ATLANTA FIREFLY PROJECT: USING COMMUNITY SCIENCE TO EXPLORE THE EFFECTS OF LAND MANAGEMENT ON THE LOCAL ABUNDANCE OF THE BIG DIPPER FIREFLY (*PHOTINUS PYRALIS*) IN CITY PARKS AND RESIDENTIAL YARDS

by

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(Under the Direction of JOHN PAUL SCHMIDT)

ABSTRACT

As human populations have become increasingly urbanized, residential landscapes and parks become correspondingly important locations for the experience of nature, a vital ecosystem service. Fireflies, globally distributed beetles in the *Lampyridae* family, while sensitive to the effects of urbanization, are charismatic and much enjoyed in residential landscapes. I present a set of guiding steps, useful for future community science projects involving fireflies or studies of residential landscapes more broadly. These steps were developed for the Atlanta Firefly Project, a community science effort to relate the effects of land management on the abundance of *Photinus pyralis*. I found firefly abundance increased with parcel vegetation, whereas artificial lighting at night, insecticides targeting mosquitoes, removal of leaf litter, municipal irrigation, and fertilizers reduced firefly abundance. Surprisingly, herbicides were associated with an increased *Photinus pyralis* numbers, but the connection is unclear. Based on these findings, I recommend conservation measures for municipalities and residential properties.

INDEX WORDS: Conservation ecology, Cumulative effects, Community science, Citizen science, *Lampyridae*, Urbanization, Fireflies, Lightning bugs

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DEDICATION

This thesis is dedicated to all the participants of the Atlanta Firefly Project, without you this project would not have been possible, thank you for everything.

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CHAPTER 1

INTRODUCTION

Background

Since the 1950s, anthropogenic processes have altered global ecosystems at unprecedented rates, and continue to transform ecological processes with evidence persisting in the geological record (Gibbard et al., 2022). One transformative anthropogenic process is urbanization which is increasing across the globe (United Nations, 2019). Urbanization transforms natural lands into developed lands with intense anthropogenic use. This process has ecological consequences including changes to landscape structure that results in both declining species abundance and richness across multiple spatial scales (Piano et al., 2020) and decreasing the production of ecosystem services (Grafius, Corstanje, & Harris, 2018).

Ecosystem services are benefits from the natural environment humans rely on for physical health, wealth, and well-being. The Millennium Ecosystem Assessment (2005) outlines four categories of ecosystem services: cultural services, the non-tangible benefits humans obtain from ecosystems that improve human happiness and societal well-being (e.g., experiencing the beauty of nature); regulating services, are benefits humans obtain from the regulation of ecosystems (e.g., air pollutant filtration primarily by vegetation), provisioning services, are products that people obtain from ecosystems (e.g., food and timber are products provided by nature); and supporting services, which are ecological processes that support whole ecosystems or control the functioning of ecosystems (e.g., forest habitat supporting ecosystem processes). The Millennium Ecosystem Assessment (2005) found that 60% out of twenty-four ecosystem services examined are degraded or being used unsustainably and furthermore, there are declines or degradation in all types of analyzed cultural services (i.e., spiritual, and religious, aesthetic, and recreation) with urbanization accounting for some of the declines.

Currently, 55% of the world's human population lives in urban areas with a projected increase of two-thirds of the population by 2050 (United Nations, 2019). In North America, the most urbanized continent with over 80% of the population living in urban areas, much of the human experience with nature is based in residential landscapes, public parks, or greenways. It is even more limited for children, who have restricted home ranges, and experience nature primarily in private gardens instead of parks (Hand et al., 2018). Given these trends, the need for urban systems to cultivate cultural services is increasing (McGranahan et al., 2005) with special considerations needed for residential landscapes. Yet studies examining ecosystem services in residential landscapes are lacking (Larson et al., 2016), (Andersson, Tengö, McPhearson, & Kremer, 2015).

Cultural ecosystem services tend to be the most valued services in residential landscapes (Camps-Calvet, Langemeyer, Calvet-Mir, & Gómez-Baggethun, 2016) and can include recreation for children and pets (Barnes, Nelson, & Dahmus, 2020) (Beumer & Martens, 2016), relaxation where gardens act as a "refuge" (Barnes et al., 2020), (Camps-Calvet et al., 2016), (Cox & Gaston, 2018) and aesthetic experiences such as bird-watching (Belaire, Westphal, Whelan, & Minor, 2015) and garden-watching (Andersson et al., 2015), (Biernacka & Kronenberg, 2019) . One example of the degradation of these cultural ecosystem services is described as the extinction of experience in which humans suffer due to a lack of exposure, interactions, and experiences with nature (Soga & Gaston, 2016), (Cox, Hudson, Shanahan, Fuller, & Gaston, 2017). One such culturally significant nature experience that is desirable in urban landscapes is those involving adult bioluminescent fireflies (Hosaka, Sugimoto, & Numata, 2017).

Fireflies or lightning bugs are globally distributed bioluminescent beetles in the *Lampyridae* family, well known for sparking wonder and curiosity in people around the world. While fireflies play important ecological roles as invertebrate predators (Fu & Meyer-Rochow, 2013) and as prey (Alcock, 2018), have contributed significantly to the advancement of biological research through the use of the firefly enzyme luciferase (Li, Ruan, Zhang, & Xu, 2021), are models in the study of evolutionary sexual signaling (Stanger-Hall, Lloyd, & Hillis, 2007), and have roles in economic markets through ecotourism, art, and literature (Fallon et al., 2019), (S. M. Lewis et al., 2021) but they are perhaps most widely recognized by the public for their cultural value.

There are over two thousand species of *Lampyridae* around the world and more than 160 species in North America with ample opportunities for humans and fireflies to interact as several *Lampyridae* species occur in urban and urbanizing areas (Lloyd, 2018). Habitat-specialist *Lampyridae* species are particularly vulnerable to the effects of urbanization (Heckscher, Walker, & Fallon, 2021) and when specialized habitat is in close proximity to urban areas these species are threatened (Fallon et al., 2021), yet even still there are anecdotal reports of population decline within adaptable species considered generalists and that frequent urban landscapes (Lewis, 2016), (Bauer, Nachman, Lewis, Faust, & Reed, 2013) but these claims are relatively unexplored. Assessing *Lampyridae* population decline for most species is challenged by a lack of data, with more than 50% of 132 North American species recently assessed classified as data deficient (Fallon et al., 2021).

The same review identified the top conservation threats to North American *Lampyridae* as 1) habitat loss and degradation, 2) light pollution, and 3) pesticide use (Fallon et al., 2021) - all three are anthropogenically driven threats associated with urbanization yet the impact on local urban *Lampyridae* populations is unknown. Given anecdotal reports of *Lampyridae* declines in urban areas and supported with documented *Lampyridae* threats because of urbanization, it is reasonable to consider *Lampyridae* populations in urban areas are in decline and nature experiences with these culturally significant species are reduced.

In urban areas, the impacts from habitat loss and degradation, light pollution, and pesticide use are cumulative, meaning a series of uncoordinated, independent, land management decisions that are spatially dispersed yet connected through successive effects (Odum, 1982). Community science, which engages the public in research, is an advantageous strategy for researching these cumulative effects. Using fireflies as an easily visually detectable species, residential land managers can directly participate in the study and contribute data that is difficult for researchers to collect independently, and, in exchange, researchers can provide residential land managers with knowledge that can aid land managers in decision making. Residential community science can thus generate powerful bottom-up shifts in land management that might lead to measurable ecological impacts (Cooper, Dickinson, Phillips, & Bonney, 2007) such as an increase in local *Lampyridae* populations in residential landscapes. In addition, under abundant conditions of local *Lampyridae* populations, urban residents have greater likelihood of nature experiences with fireflies.

Atlanta, Georgia, ranked number four in population growth among metropolitan statistical areas in the United States between 2010-2019 (Metro Atlanta Chamber, 2020) and with past records of at least 30 *Lampyridae* species it is also an excellent city for studying threats to firefly populations from urbanization. *Photinus pyralis*, the big dipper firefly, is an adaptable, common species of least concern which should be abundant and frequently encountered in residential landscapes in Atlanta, but like for most *Lampyridae* species, the species population trend for *P. pyralis* is unknown, and individual threats are not well documented (Walker, 2021). In this project, I am utilizing community science to assess the impact of habitat loss through loss of vegetation and habitat degradation through land management practices on *P. pyralis* local abundance in Atlanta. This research has implications for *Lampyridae* conservation at large and for the benefit of cultural ecosystem services management.

Project Objectives

There are three overall goals of this thesis, 1) to provide guiding steps for designing and executing effective community science projects, especially for those conducting research on *Lampyridae* or in residential landscapes and public parks more broadly, 2) assess the effects of habitat loss and land management on local abundances of *Photinus pyralis* in Atlanta, and 3) provide *Lampyridae* conservation recommendations for *P. pyralis* and possibly other *Lampyridae* species facing threats from urbanization.

In Chapter 2, I present guiding steps for the design of community science projects alongside a case study of the Atlanta Firefly Project. I describe 8 steps: 1) identify desired outcomes, participants, and approach, 2) establish research question, 3) project design, 4) training, 5) recruitment, 6) project monitoring, 7) post-collection evaluation, 8) communicating results. I expect this information to aid future community science studies involving either *Lampyridae* species or other research in residential landscapes more broadly.

In Chapter 3, I use the data collected in Chapter 2 to assess how the amount of available habitat (vegetated area) and how land management practices correlate with the local abundance of *Photinus pyralis*. I specifically will use remote imagery that measures the amount of healthy vegetation present on the landscape and nighttime satellite imagery that records measurements of radiance (brightness); land management information about mowing practices, irrigation practices, pesticide use, fertilizer use, artificial light at night use, and leaf litter management; and abiotic data including temperature, precipitation, date, and time (as a function of sunset). Based on evidence from previous studies and *Lampyridae* biology, I hypothesize that vegetation and irrigation would be positively associated with *Photinus pyralis* abundance while artificial light at night, mowing, removal of leaf litter, pesticides, and fertilizers would be negatively associated. Furthermore, I expected these correlations to have a greater positive or negative effect the longer these landscape managements are practiced.

In Chapter 4, I present my conclusions from the project and translate these conclusions to specific conservation recommendations for researchers conducting community science and for municipalities and residential land managers. Specifically, the chapter recommends 1) a nationally coordinated methodology for collecting *Lampyridae* community science data and an public agenda for communicating *Lampyridae* conservation, 2) strategies for municipalities to support firefly conservation both immediately and in the long term, and 3) best practices for the management of residential landscapes in support *P. pyralis* populations.

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CHAPTER 2

GUIDING STEPS FOR COMMUNITY SCIENCE PROJECTS: A CASE STUDY OF ATLANTA FIREFLY PROJECT[1]

[1] Ridenhour, K.R., & Schmidt J.P. To be submitted to Sustainability

Abstract

The use of community science is increasing with powerful benefits for researchers, participants, and social-ecological systems. Yet there is a lack of methodological approaches for organizing community science projects and for recruiting, training, and communicating with participants. Recent literature calls for moving community science towards theoretical frameworks and, specifically within entomology, a need for coordinated taxa-specific approaches. Here I establish a set of eight guiding steps, evaluation criteria, and analytical questions to prompt community science organizers into a methodological approach and present the Atlanta Firefly Project as a case study in the application of these guiding steps. These eight steps: 1) identify outcomes, participants, and approach; 2) establish research question; 3) project design; 4) training; 5) recruitment; 6) monitoring; 7) evaluation; and 8) communicate results along with the associated case study are broadly applicable for community science projects yet are most useful for studies involving *Lampyridae* or those collecting data in residential landscapes.

Introduction

The history of modern science is rooted in amateur research and observations, with career opportunities as a professional scientist not emerging until the second half of the 19th century (Silvertown, 2009). Today scientists distinguish between expert and non-expert research whereby expert research is conducted by professional scientists and in academic institutions, while non-expert science is conducted by different groups of amateurs. The term community science specifically refers to the voluntary and intentional participation of non-experts in scientific methods that result in new scientific knowledge. This process is also commonly described as citizen science yet in this paper, I use the term “community science.”

Foundational work by Shirk et al. (2012) defines five categories of community science delineated by varying degrees of public participation; 1) Contractual, where communities ask professional researchers to conduct research and share results on their behalf, 2) Contributory, led by professional researchers with communities primarily participating through contributing data, 3) Collaborative, led by professional researchers with communities participating in other stages of the scientific method in addition to data collection, 4) Co-created, led by both scientists and the community with active community participation in all research stages, and 5) Collegial, led independently by community members and advances scientific knowledge to a similar degree as professional researchers.

I accept these categories with the addition of one new category, crowdsourced, a necessary addition to describe the use of existing community science datasets sourced horizontally by a third party such as social media applications (Gutiérrez-Estrada et al., 2021). In this crowdsourced scenario, researchers have no engagement with the community, and simply co-opt pre-existing data that was collected by the public for some other purpose than the research question. While the main role of the community scientists in both crowdsourced and contributory models is data collection alone, the main difference between the two is that participants in contributory models collect data intentionally to assist the researcher in a vertical pathway but in a crowdsourced model, researchers horizontally source data gathered by participants for some other reason. A crowdsourced model involves public participation the least, since the participants might not be aware of the research, there is no interaction between the data gatherers and researchers, and no researcher responsibility to disseminate results back to data gatherers.

The use of community science is increasing, especially within ecological and environmental sciences, with the potential of becoming its own discipline (Spasiano, Grimaldi, Braccini, & Nardi, 2021). Accounting for the increase in community science is, in part, due to the many benefits it offers researchers. Community science provides researchers access to big data in a cost and resource-effective manner (Beeker, Millenbah, Gore, & Lundrigan, 2013) resulting in quick advances in science (Reed, Rodriguez, & Rickhoff, 2012), facilitates novel discoveries, and contributes to positive outcomes for conservation action and legislation (Gardiner & Roy, 2022). Community science is often presented as a win-win scenario with many accounts of community science benefits to the public including access to scientific knowledge (Silvertown, 2009) increased social capital, social cohesion, or a sense of community belonging (Conrad & Hilchey, 2011), (Reed et al., 2012), (Spasiano et al., 2021), (Wang, Guo, Wu, Goh, & Wang, 2022) and simply having fun through taking part in a pleasurable experience (Spasiano et al., 2021).

Yet, community science in research is not without its criticisms and/or logistical challenges. One of the biggest concerns from researchers is a perceived lack of credibility in the eyes of other researchers or decision-makers due to concerns about sampling bias (e.g., spatial autocorrelation), timing bias (e.g., data clustering at the beginning of a project that wanes as participate interest drops), observer bias (e.g., occupancy data for charismatic species only), and errors from inaccurate reporting (Conrad & Hilchey, 2011), (Riesch & Potter, 2013), (Gardiner & Roy, 2022), (Vasiliades, Hadjichambis, Paraskeva-Hadjichambi, Adamou, & Georgiou, 2021). The use of community science is also criticized for relying on experimental design and lacking theoretical approaches (Conrad & Hilchey, 2011), (Spasiano et al., 2021). By default, community science projects often must rely on experimental design to “reinvent the wheel” in the absence of implicit methodological approaches. Lastly, at the logistical level, community science experiments often struggle with initial participant recruitment and/or lack of funding which destabilizes long-term data collection efforts (Conrad & Hilchey, 2011), (Riesch & Potter, 2013) (Jennett & Cox, 2014).

Some of these concerns may be unwarranted. Community science does not appear to act as a publication barrier with many papers published over the past ten years using community science data. Impressively, Ries & Oberhauser (2015) found that 17% of new results from monarch butterfly-focused publications between 1940 and 2014 used community science data. Concerns of poor data quality can be mitigated by community scientist training (Ratnieks et al., 2016), and bias, a common problem also shared with data collected by professional researchers, can be addressed through statistical methods (Kosmala, Wiggins, Swanson, & Simmons, 2016). Logistical challenges of organizing projects, recruiting, training, and communicating with volunteers while sustaining projects over the long-term are perhaps the greatest remaining obstacles for researchers, because much of the community science literature commonly publishes results from community science data rather than detailing the methodology used to collect data. Recent literature moves community science towards theoretical frameworks (Spasiano et al., 2021) alongside calls for scalable taxa-specific standardized approaches to benefit conservation (Gardiner & Roy, 2022).

Fireflies, bioluminescent beetles in the *Lampyridae* family, being charismatic microfauna, are well suited for community science (Chow, Chong, Cook, & White, 2014) (Koken et al., 2022). Comprehensive works in firefly conservation call for using community science to address data gaps in firefly knowledge through documenting species distributions and population trends, assist with locating threatened or data deficient species, and by boosting public awareness to benefit *Lampyridae* conservation (Fallon et al., 2019), (Fallon et al., 2021). Additionally, there are many forms of firefly-specific community-science projects around the globe. In North America alone there is a list of six projects compiled by the Xerces Society website (https://xerces.org/endangered-species/fireflies/community-science) including Mass Audubon's Firefly Watch, Western Firefly Project, Atlanta Firefly Project, Southwestern Firefly (a project on iNaturalist), Light up West Virginia, and Fireflyers International Network (FIN) (another project on iNaturalist).

Yet there are surprisingly few *Lampyridae*-focused published works presenting new research because of community science data and none presenting a set of best methods or theoretical guidelines. My review identified only six journal articles: 1) Picchi, Avolio, Azzani, Brombin, & Camerini (2013) presented a negative correlation between urbanization and firefly abundance with a collaborative approach; 2) Chow et al. (2014) presented a summary of the activities of the Vanishing Firefly Project, a collaborative initiative in Clemson, SC but no results were presented; 3) Evans, Salvatore, van de Pol, & Musters (2019) found a link between adult firefly abundance and weather (temperature and precipitation) during the firefly larval stage using data from the contributory Firefly Watch project; 4) a collegial paper Faust, Hughes, Zloba, & Farrington, (2019) was able to update knowledge on and records of Photinus scintillans; 5) Fallon et al. (2021), a co-created paper, used crowdsourced data in the International Union for Conservation of Nature (IUCN) North American *Lampyridae* red list assessment; and 6) Koken et al. (2022) tracked the spread of an introduced species, *Photinus signaticollis*, also using crowdsourced data. I would like to distinguish that only two of these papers present new results from data collected in contributory or collaborative methods but interestingly, the overall body of firefly literature and conservation efforts have benefited from significant collegial and co-created contributions.

For example, Lynn Faust, a self-taught firefly expert, has been an author on at least 18 journal articles, 1 book, and various forms of other literature. Candace Fallon, a senior conservation biologist with the Xerces Society, has been an author on at least 2 journal articles in addition to other literature. The recent International Union for Conservation of Nature *Lampyridae* red list assessment is an exemplary example of a co-created form of community science involving immense collaboration between non-academic experts (namely Anna Walker, Candance Fallon, Lynn Faust, Ben Pfeiffer, Jason Davis, and Sarina Jepsen) and professional academics (namely Sara Lewis, Joe Cicero, Kitt Heckscher, Cisteil X. Pérez-Hernández, Ron Lyons, and Laura Hughes) with an additional element of utilizing crowdsourced iNaturalist and BugGuide data sourced from Global Biodiversity Information Facility (GBIF) (C. Fallon, personal communication, March 31, 2022). In addition to these efforts, the professional network Fireflyers International Network, unites more than 200 members across 20 countries and proudly features contributions from scientists across many disciplines in addition to conservationists and artists with the goals of working together to protect threatened species. For example, Radim Schreiber, an artist talented at capturing firefly photos, flash patterns, time-lapse, and videos of synchronous displays, makes his art available to researchers in publications and outreach efforts through the Fireflyers International Network.

With a strong and capable community of fireflyers, I conclude that the lack of research studies employing contributory and collaborative methods is a product of the lack of standardized methods for facilitating effective community science involving *Lampyridae*. New *Lampyridae* knowledge and firefly conservation would benefit from a set of method steps for effective community science and this paper aims at taking this initial step. I propose these steps, followed by an evaluation of effectiveness of the Atlanta Firefly Project, a community science effort to relate the effects of land management on the local abundance of *Photinus pyralis*. While these methods are intended as initial work towards advancing coordinated taxa-specific community science initiatives for *Lampyridae*, the study scope of the Atlanta Firefly Project focused on urban parks and residential landscapes, given this, these guidelines are broadly applicable to other fields of research operating at similar extents. These guiding steps, presented below, are organized by first the guiding step, second evaluation criteria, and third a self-check list of analytical questions written in language to guide a project developer (i.e., ‘we’ or ‘you’). These guiding steps, evaluation criteria, and analytical questions are provided in table form included in Appendix A.

Guiding Steps

Step 1 Identify Desired Outcomes, Participants, and Approach

Driving the distinctions between the six community science categories; 1) Crowdsourced, 2) Contractual, 3) Contributory, 4) Collaborative, 5) Co-Created, and 6) Collegial, is the quality of public participation sorted in order from least to greatest. As explored by Shirk et al (2012), the quality of participation can influence three different measurable outcomes 1) outcomes for science, 2) outcomes for participants, and 3) outcomes for social-ecological systems. Outcomes for science are traditional outcomes resulting from scientific studies such as published works. Outcomes for participants are often ones of environmental education and community engagement while social-ecological outcomes might include changes to policy or conservation support.

Project facilitators must identify the level of participation needed to meet all desired outcomes. In addition to identifying targeted participants, meaning the group of non-academics separate from academics that make up the body of the project contributors. For example, if the desired outcomes are for participants to learn more about an endangered species threatened by urbanization, the participants might be residents living in proximity to the species and a contributory or collaborative model might work best. Or if the intended outcomes are for social-ecological systems to establish a designated firefly sanctuary, participants might be the corresponding municipal partners or land managers and a collaborative or co-created model might be best suited. Defining the desired outcomes, selecting a model, and identifying the targeted participants early in the process will inform subsequent method guidelines.

For Lampyrids, we desired to fill gaps in scientific knowledge by documenting species distributions, population trends, and locate threatened, data deficient and species of concern (outcomes for science), boost public awareness by increasing public knowledge of *Lampyridae* biology and ecology (outcomes for participants), and further *Lampyridae* conservation through better resource management to benefit fireflies and make gains in conservation legislation (outcomes for social-ecological systems). To achieve all three of these goals simultaneously, contributory, collaborative, co-created, and collegial models are theoretically preferred to galvanize active participant involvement (Spasiano et al., 2021).While crowdsources and contractual models are effective at achieving outcomes for science, they are ineffective for participant and social-ecological outcomes.

As collegial and co-created models are well represented in the *Lampyridae* field, I focused here on approaching community science from contributory and collaborative (or hybrid) models that engage public participants through active data collection and other steps of the research process with intended outcomes for science, participants, and social-ecological systems. These steps are developed for these specific approaches.

Step 2 Establish Research Question

The research question will drive the design of the whole system and it must be relevant to a significant portion of the participants for the community science project to succeed. Vasiliades et al., (2021) explains this well by expressing the need to consider the "community" over the "science" in community science. Contributory and collaborative models might approach a research question with varying degrees of community participation. In contributory models, the research question is typically established independently by the researcher reserving participants as "data collectors" and relating participants to the research question might be more challenging. While in collaborative models, the community might be involved in the establishment of the research question, securing participant interest. Yet whether participants collaborated on the research question, it can be evaluated with five criteria developed here. If the research question does not fit the five criteria it might be challenging to successfully conduct research and the research question should be revised.

2.1 Scale

For the participants to succeed in their task(s), the research question must be compatible with consideration of scale. Local participants might struggle with gathering data from increasing distances, especially if frequently requested. Ask these questions about the project to evaluate if it is scaled appropriately: Can the research question be answered with data provided by the participants? What sort of spatial and time scales does it require participants to operate under? Is this true for a reasonable portion of participants? Does this place limits on the participants?

2.2 Relevance

The research must be significant to the participants in some capacity. Human interests are heterogeneous, with many different interests, motivations, skills, and needs. It is impossible to address every interest, but the research question must be a relatively appropriate match to motivate participants. Ask these questions about the project to evaluate how it relates: What does this project benefit? Who is it significant for? Why does that matter? What connection do participants have to this research?

2.3 Participant Investment

Often, community science projects ask for involvement without financial compensation. Keeping in mind, community science is voluntary and uncompensated, the commitment required by the participants should be appropriately scaled. Ask these questions about the project to evaluate participant investment: How much participant time might this take? Do participants receive anything? Is the activity unpleasant or uncomfortable? Are there risks for participants? Is specialized skill, knowledge, or resources needed?

2.4 Clarity

The research question and desired project outcomes drive the project design and are the main goals to communicate to participants. Given this, it should be written in familiar and clear language for the participants. Ask these questions about the project to evaluate research question clarity: Are words and terms understandable to those without subject matter expertise? Is the language inclusive of the participants? Do participants speak multiple languages?

Step 3: Project Design

Using the research question and desired outcomes as the driving force behind the design, evaluate the data collection design needs with four criteria. Involving participants in this step is not typically part of the contributory model but participants can be involved in this step in a collaborative model.

3.1 Data Needs

Data needs from participants must be clearly identified on a granular level. Ask these questions to identify data needs: What variables are specifically needed from the participants? Is it quantitative or qualitative? Can the data needs be easily listed?

3.2 Format compatibility

A specific data format will be required to conduct analysis and answer the research question. Data is often compiled, cleaned, or transformed between collection and analysis and these methods will vary widely from study to study but determining the data format required for analysis is productive. Ask these questions to identify format compatibility: How does the data look when received from participants? What kind of work will it take to prepare the data for analysis? If applicable, how might this data be validated?

3.3 Collection methods

Using the list of data needs, evaluate all the ways these types of variables can be submitted. A few data submission methods, searchable in the literature, include sending in physical data, submitting data into a third-party source (e.g., iNaturalist), digital data submission through forms, submission of vocal recordings, custom smartphone applications or gaming applications. Ask these questions to identify possible methods: What is the list of possible methods participants can use to submit the needed data? Are these methods compatible with the required analysis format? Do the project facilitators and participants have (or will have) access to these methods?

3.4 Simplicity

While the data submission method must ultimately be a compatible format for final analysis, it is best to choose the method that is the simplest for participants as opposed to the researcher. The researcher possesses more resources and technical skills with options for transforming data into a final format for analysis. Evaluate all the possible methods for data collection and choose the option most simple for the participants. Ask these questions to identify simple methods: Do participants need special skills for this? Can participants be trained on this method? Are there opportunities for miscommunication? Are there tedious steps for participants? Where might participants be frustrated or bored?

Step 4: Training

Training on the collection system must be developed along with communicating the importance of training. While time-intensive, data training is a proven technique for producing high quality community science data and should be an essential step. In contributory models, data training is primarily conducted by the researcher while in collaborative models, some participants might also be involved in conducting training. A few data training methods, searchable in the literature, include training events, workshops, and training videos. List all the options for training participants on the data collection scheme and evaluate all the possible methods for participant training using four criteria.

4.1 Effective

Participant training is necessary to cope with data inaccuracies, especially with large-scale community science (i.e., population monitoring) or more technical project components (i.e., cryptic species identification). Selecting a method that is highly effective at training for the requested task is important while maintaining awareness of learning styles and participant demographics and skill levels. Ask these questions to identify effective training methods: Which methods can be used for training? Will these methods to communicate the research question? Will these methods teach participants to collect all the needed data? If applicable, will these methods teach the participants any specialized skills necessary? Will these methods be consistent? Are multiple training methods required?

4.2 Accessible

Training is not effective if it is not accessible to the project participants. The project must consider how participants will access training. Ask these questions to identify accessible methods: Is this training method compatible with most of the participants? Will the audience need access to training during data collection? Is training available as a reference? Are training opportunities limited (by time, location, or other)?

4.3 Timeline

The project must consider the project timeline and what constraints it places on training methods. A training method that does not fit the project timeline is incompatible. Ask these questions to identify timeline compatibility: Is there time to both develop the training materials and promote the training before data needs to be collected? Is there time for most of the participants to complete the training prior to data collection?

4.4 Feasibility

Research projects are often constrained by project resources, which limits training options. Ask these questions to identify training practicality: Does the research project have (or can gain access to) the needed equipment, funding, space, and training facilitators? Is there additional support to rely on should it be required?

Step 5: Recruitment

Recruiting your participants requires examining the mechanisms that connect your participants. The participants might be established, organized, or connected through various pre-existing communication networks. While there is heterogeneity in any group of participants, the goal here is to find the ways in which they connect. Once again distinguishing between contributory and collaborative models, in contributory models researchers recruit participants while in collaborative models, participants are also involved in recruitment. Identifying and reaching these networks effectively requires three main criteria:

5.1 Incentivization

Project incentives influence community participation and include a wide variety of cultural or physical motivations (Wehn & Almomani, 2019). Ask these questions to identify project incentives: Why is participation in this project interesting (cultural incentive)? How can participants receive recognition or be thanked (cultural incentive)? Do participants receive any products or compensation from this project (physical incentive)? Do participants obtain new knowledge or skills because of this project (cultural incentive)?

5.2 Promotion

Project promotion is centered around the research question and its relation to the participants. Developing promotions familiar to participants is critical. For a local community, these promotions might be event advertisements, press releases, or project announcements which are common and easily understood. Whichever type of promotion is chosen, ask these questions to prompt the project: How will the promotion explain project goals and objectives? What is the project's call for action (who is needed, where, and when)? How can the incentives be communicated?

5.3 Active Recruitment

Actively recruit additional participants and do not passively wait for them to come to you. There are three common categories of existing communication networks relating to local communities that can be actively engaged with: governmental networks, social networks, and press networks. To utilize these networks, ask these questions to identify active recruitment pathways: What are the governing parties (Neighborhood Planning Units, Neighborhood Associations, Homeowners Associations, Schools, Park Conservancies, etc.) acting in the study scale? What are the social elements (Non-profits, churches, gardening clubs, beautification groups, sports clubs, local businesses, events, etc.) present at the study scale? What are the press sources (Non-profits, churches, gardening clubs, beautification groups, sports clubs, local businesses, events, etc.) relevant to the study scale? How can the project promotion be distributed to these networks?

Step 6: Monitoring

The project should be monitored across the duration of the study and avoid leaving data review until the conclusion of data. Monitoring the active data collection must be considered to effectively manage the moving parts of a study, address the potential questions your participants may have, and correct any errors in your collection system. Once again, the role in involving participants in project monitoring can be another distinguishing characteristic between contributory and collaborative, and project monitoring is well suited to include participants in the process if they are instructed to answer questions or check for specific errors. The monitoring plan should consider two main criteria:

6.1 Tracking

Tracking the data during the study is necessary to make sure the data is collected as intended. Ask these questions about the project to evaluate data tracking needs. What are the most important parts of the data? What are the most difficult components of the data? How can the data be checked in real-time? How can expected errors be quickly identified?

6.2 Two-Way Communication

During active data collection, participants may have questions and they might want to further recruit for a project, or the project might need to communicate an error or update. These are all cases in which a communication plan for the participants to reach the facilitator and the facilitator the participants would be critical. Ask these questions about the project to evaluate two-way communication. How can the project communicate with participants directly and quickly? How can participants find answers to questions? How can participants leave feedback? Can participants share their activities? How should project updates be communicated?

Step 7: Evaluation

Evaluating the success of the study is recommended at the conclusion of each data collection cycle. The most important steps to evaluate are Steps 3 - 6. The evaluation should consider four main criteria which can be addressed quantitatively or qualitatively:

7.1 Collection System

Ask these questions about the collection system to evaluate effectiveness: Did project feedback include grievances or errors with the collection system? Did participants use the communication system to ask questions about the data collection system? How much data was collected? Was the collection system burdensome to the researcher?

7.2 Training

Ask these questions about the training methods to evaluate effectiveness: Was the training well attended or well used? Did project feedback include grievances or confusion at training? Did participants use the communication system to ask questions about instructions? How much data was collected? Was the data accurate? Was the data complete? Was the data received in expected quantities?

7.3 Recruitment

Ask these questions about the recruitment methods to evaluate participant recruitment success: How many participants were there? Are there returning participants? How much data was collected? Where were participants recruited? What communication networks (government, social, press) engaged with the promotion? Did participants use the incentives?

7.4 Monitoring

Ask these questions about the project monitoring to evaluate success: Were errors discovered during active data collection? Were errors discovered after active data collection? Were the communication pathways used? Were new methods or novel observations encountered?

Step 8: Communicate Results

The project participants, to a degree, own part of the work and the project must consider how the project participants will learn about research results. The communication of results should consider two main criteria:

8.1 Recognition

When communicating project results, the project contributors should be recognized. Ask these questions about how recognition can be given to the participants. Are there any contributors who should be included as an author? Can participants be reasonably thanked by name? Is it clearly documented (in manuscripts, papers, or other documentation) how the participants contributed to the project? How were participants thanked? Was there anything the participants asked for that was not provided?

8.2 Access

Aside from recognition, the participants should be provided with access to this recognition and, if possible, access to products from the study. Ask these questions to understand the access needed. How will the participants access the results? Will the participants have access to the original data or materials? Will results be communicated specifically to the participants in some format?

Case Study: Atlanta Firefly Project

1 Identify Desired Outcomes and Participants

The Atlanta Firefly Project desired to achieve outcomes for science, participants, and for social-ecological systems: for science by resulting in published work; for participants by boosting interest in and knowledge of local fireflies; and for social-ecological systems by influencing the management of residential land to benefit fireflies. To collect the needed data to achieve these goals, I identified the desired participants to be residents in the Atlanta-Metropolitan area and I preferred to reach adults over children as adults are more likely to have control over and knowledge of local land management. I desired a collaborative approach. However, constrained by the timeline of a two-year MS thesis and challenges presented by Covid-19, I employed a contributory model with collaborative elements detailed in this case study.

2 Establish Research Question

The research question was driven, in part, by public anecdotal reports of declines in fireflies, explained in Chapter 3, resulting in the research question “How do common land management practices in Atlanta’s residential landscapes and city parks affect local abundances of *Photinus pyralis*?” This research question was partially collaborative as the question was asked by the community rather than exclusively pushed by project facilitators.

Scale

The research question required the collection of data across the *P. pyralis* peak season ~2 months. While not an insignificant amount of time, it was scaled to spaces in which the participants reside and play (residential landscapes and parks). I believed I could likely answer the research question given enough data, and as there are many people residing in Atlanta, I believed it possible to collect enough residential data. My participants were generally, any Atlanta resident. To avoid participant exclusion, I encouraged anyone from any Atlanta location to submit data regardless of housing situation, for example, I explicitly stated observations from public areas at apartment complexes was desired and included an option for participants to monitor at parks.

2.1 Relevance

While the research question benefits *Lampyridae* conservation at large, it also benefits *Photinus pyralis* populations locally. This matters to participants because there are unexplored anecdotal declines within this species, and participants might have the ability to alter land management practices to benefit *Photinus pyralis*.

Participant Investment

I asked participants to contribute data a maximum of four times on days of their own choosing over a course of two months, requiring an average of 1 hour per submission. For the sake of a valuation example, according to the National Low Income Housing Coalition (https://reports.nlihc.org/oor/georgia) $19.42 is the minimum wage required to afford average Atlanta housing, minimally valuing participants time at $77.68. For this investment, the audience will receive 1) general information about *Lampyridae* biology, 2) engage in a pleasant activity, 3) will be presented with scientific results, and 4) some volunteers will receive a sticker. Accessing these benefits through other methods would likely cost the volunteers to purchase books, materials, attend a workshop, pay to access journal articles, or purchase stickers. From their perspective, the cost incurred by the participant is reasonably matched to the benefits. Additionally, contributing is not unpleasant or uncomfortable, with minimal risks of exposure to the sun and biting insects (no more than what the audience is already exposed to when recreating outdoors at their residence). No specialized skill or resources are needed except access to the internet on any device, which is now, commonplace in Atlanta, Georgia.

2.2 Clarity

The research question “How do common land management practices in Atlanta’s residential landscapes and city parks affect local abundances of the big dipper firefly?” was stated in general terms that are familiar to most adults. The use of “residential landscapes” was selected because it does not exclude any kind of housed individuals, but it does exclude unhoused individuals whose experiences are not captured in this project. Despite the use of many different languages among communities in Atlanta, English is the primary language and given the initial project scope and quick turnaround, materials were only produced in English.

3 Project Design

3.1 Data Needs

The project needed a minimum list of variables to be collected by the participants (the full questionnaire can be found in Appendix B) including geographic local (latitude/longitude), address, quantitative measurement of firefly abundance, and a qualitative description of the species while the land management questionnaire was optional.

3.2 Format compatibility

The data inputs from participants would be received as a collection of letters and numbers (translating to both character and numeric fields). I knew, ultimately, the data would need to be in one csv file for analysis in R Studio but would need to undergo data validation, data cleaning, and transformation to convert character fields into numeric data. For example, I wanted to confirm that participants completed the training as part of the data validation, and it prompted me to include a survey question asking volunteers whether they watched the training materials.

3.3 Possible collection methods

After a review of literature, I determined possible collection methods for the Atlanta Firefly Project were digital submission forms, physical submission forms, and custom smartphone applications. While each of these methods would be compatible with the eventual required format however, physical forms would take the most effort to prepare. The project time and access constraints make a custom phone application infeasible. Thus, I opted for a digital submission form. The Atlanta firefly project chose to utilize digital submission forms provided on the ArcGIS service called Survey123. The merits of these readily available yet powerful tools should not be overlooked as it provides almost as much flexibility as a custom app but with less facilitator investment and expertise needed.

3.4 Simplicity

While specialized skills are not required for participants to use any of the three submission methods (digital submission form, physical forms, and custom application) there are opportunities for miscommunication with all these methods. Keeping track of a physical paper can be tedious and is difficult to keep clean in the field and remitting physical forms through the mail or scanned submissions is another frustrating step. Furthermore, facilitators might struggle to interpret writing on the physical forms. Custom applications are highly flexible in design but challenging to streamline functionality between all devices. Downloading and updating new applications can be tedious for participants and even more frustrating if participants cannot access the application from their preferred device. Simple digital submission forms are a familiar tool and, through a robustly designed service like Survey123, are embeddable in any browser, eliminating the problem of incompatible devices.

4 Training

4.1 Effective

The Atlanta firefly project broke training up into two categories 1) residential sites and 2) park sites with all participant training first coordinated through a website which acted as a central training hub (www.atlantafireflyproject.org). While some park sites were chosen by the researcher, participants were allowed to submit park sites of personal interest for monitoring, a collaborative component.

Residential Sites: All participants in this group monitored at their place of residence and were offered training with a digital video, in addition to written instructions. Given the Covid-19 pandemic and only a single researcher, training all participants in-person at their homes was impractical.

Park sites: 46 park sites were monitored by either the researcher (15 parks), or trained participants (31 parks). The park participants were either trained through hybrid in-person and digital methods or digital methods alone. There was a total of 29 park participants. 12 park participants were first sent a park training video, then met on-site to be trained in-person, 2 park volunteers were first sent a park training video, then were followed up with training over the phone, and the remaining 15 park volunteers were first sent a park training video and followed up with via email. The specific monitoring location for each park was pre-selected by the researcher and shown to each park volunteer either in person, or via photos and maps, and confirmed verbally via phone or email.

Digital methods in the form of a training video were effective as they could communicate the research question, include educational components, use visuals to teach how to collect the variables, and it was consistent training that was easy to distribute to all participants.

4.2 Accessible

These training methods were effective in ensuring compatibility for the participants. At least 1 park participant uses a wheelchair and was able to access the monitoring location and the training methods both in person and digitally. All participants were given access to the training during data collection along with written reminders, and repetitive links to the training video were provided on the digital submission form. All of this prevented time and location limitations on training.

4.3 Timeline

The research project had a rapid timeline, and it was challenging to complete digital training materials with enough time to recruit participants, however it was possible and succeeded in recruiting participants. It was necessary to limit the number of park participants I could meet in person and required more reliance on digital training for parks. Without digital training, the number of monitored park sites would have been fewer. Website materials were prepared in March 2020, but the website was not launched until April 2020. Training videos were released on May 18th, 2020, giving audience members a couple of weeks to watch the video prior to data collection and park volunteers were trained in the second half of May 2020.

4.4 Practicality

Atlanta Firefly Project received 2 small grants: $ 970 from the University of Georgia Graduate School Communication of Research and Scholarship Award to fund the training website fee, microphone, camera tripod, logo design fee, sticker printing, plus stamps and $2,810 from University of Georgia Odum School of Ecology Small Grants to fund miles traveled for research, a few red headlamps for facilitators and to lend volunteers, two years of website fees, and to cover other miscellaneous fees associated with data analysis at a later stage.

5 Recruitment

5.1 Incentivization

Photinus pyralis is desirable in residential landscapes and is a pleasant experience enjoyed by the participants and many people feel fireflies are declining with Atlanta. I knew this from anecdotal data prior to project initiation but results from project data confirm these reports. From a survey of 208 people living in the same location for at least 5 years or more with many participants (33%) indicated a perceived overall decline in abundance at their location additional participants (20%) indicating a decline except for a noticeable increase in the last 1-2 years only. 24% of participants indicated no change, and only 13% described a perceived overall increase while the remaining 10% were unsure of any changes.

In addition to these cultural incentives, 1) the first 500 participants to sign-up were offered a free sticker of the project logo, 2) participants were thanked through digital methods, 3) participants are acknowledged in the results, 4) participants received general training on firefly biology with the training video, and 5) participants are invited to attend a free talk presenting the results held in person at a convenient local facility, Trees Atlanta, to be held on May 6th, 2022 with a summary of results posted online.

5.2 Project Promotion

The project was named The Atlanta Firefly Project and a logo was designed (see figure 2.1). The project goals and objectives were explained through the press release and reiterated on the project website and social media. The project website can be found at www.atlantafireflyproject.org and social media can be accessed on Instagram @atlantafireflyproject. The press release was also a call for action through the statement "Atlanta Firefly Project is a community initiative that assists researchers in studying firefly conservation in Atlanta. You can help from your own home, whether you live in an apartment, townhome, detached home, or wherever you call home, your observations are valuable! All it takes is a commitment to monitor outside your home ideally for two evenings in June and two evenings in July during 2021 (if you cannot do that many it is OK - do what you can) and submit information using our entry form documenting whether you see fireflies! Check out atlantafireflyproject.org to sign-up and follow them on Instagram at @atlantafireflyproject. The first 500 volunteers to sign-up get a free Atlanta Firefly Project sticker!" The full press release can be found in Appendix C.

Figure 2.1: Atlanta Firefly Project Logo (which was included in the press release).

5.3 Active Recruitment

The Atlanta Firefly Project utilized primarily government networks, but also social and press communication networks. For governing networks, the original press release was sent to 67 Neighborhood Associations, 22 Neighborhood Planning Units, 7 Park Conservancies, 4 County/City Departments and 1 State University, while for social networks, 15 contacts were reached from social groups, private universities, and local non-profits. Each contact in the government and social groups were asked to redistribute the press release on their personal networks. This is another collaborative element, allowing participants to contribute to project recruitment.

The Atlanta Firefly Project generated its own press on Instagram which engaged over 1000 followers and through an email listserv which has more than 1,500 subscribers. Participants were motivated to sign-up for the listserv by offering the incentive of a sticker. The original press release was reshared on at least 16 known sources, the largest being WABE's Fresh Air in a two-minute story by reporter Molly Samuel (WABE 90.1 FM, Ga.; 6/21/21) and then adapted for a three-minute national story on NPR's Here & Now (NPR & WBUR 91.9 UIS.; 7/5/21) which airs on over 450 stations across the country and reaches an estimated 5 million weekly listeners.

6 Project Monitoring

6.1 Project Tracking

The most important components of the Atlanta Firefly data for analysis were the geographic location, measure of firefly abundance, and land management survey. The most difficult component of the data was submitting the correct geographic point location. I could monitor for these errors by plotting the data by location as it came in and validate location by systematically checking the point location against the address. Furthermore, the point location defaulted to the center of downtown Atlanta when the point location was not updated by the participant, making it immediately clear on the plot when an inaccurate point was submitted.

6.2 Two-Way Communication

The email listserv acted as one form of communication and reached ~1,500 participants. The listserv sent out a total of 5 email campaigns in a 3-month period. 1 in May notifying participants of training materials, 2 participation reminders in June and 2 participation reminders in July, with links to instructions and training materials provided each time. The Atlanta Firefly Project also utilized Instagram and engaged over 1,000 followers by encouraging participants to post about observations and ask questions there. Participants were able to access a set of Frequently Asked Questions on the website and send inquiries to a project email address (info@atlantafireflyproject.org).

7 Evaluation

7.1 Collection System

The Atlanta Firefly Project collected 925 samples in the residential data set and 97 samples in the park data set. The collection system collected all the types of data needed for the analysis, but the raw data sheet included 85 variables while only 17 variables (provided by participants) were used in analysis. Filtering the data into a usable set of predictor variables took significant investment of researcher time.

Only a few instances of errors with the collection system arose in the communication. For example, on June 6th, one participant used the email to inform the facilitator to explain the survey timed out on them as they tried to take a photo. The tone of the initial email seemed frustrated, yet after being followed up with, the participant's tone changed positively and stated "...I will try again soon and see what happens. I love the idea of this study. I'm a retired scientist and this is right up my alley 😊." While a park participant notified the researcher, "FYI- I had trouble each time I got to the map portion of the submission form and usually ended up resetting the info I had just put in. Maybe it was because I was doing it from my phone?"

7.2 Training

The Atlanta Firefly Project training received 925 samples in the residential data set and 97 in the park data set. 888 of the 925 residential samples answered "yes" that they watched the training video. It is believable that these participants watched the training with records of the training website page accessed 6,706 times in May - July 2021. The video accessed separately via youtube had 596 views and the email listserv with instructions had a combined click total of 1,155.

Participants were also using the contact form to confirm data submission. Specifically, a few participants checked for their data to appear on the public facing map, yet when their data did not appear, they sent an inquiry via email. In these few cases there was no error as the public map was filtered to only display residential data, yet the participants were checking for park data. I include this as an example as it was an example of participants following through to ensure the accuracy and acceptance of their data.

The data was largely accurate and complete. A scoring system to validate data was implemented with 57 samples removed from the set based on a set of four criteria: 1) participants watched the training video, 2) the location tool was accurately used, 3) flash counts did not appear evenly rounded on all three counts, and 4) the participant was descriptive when describing flashes (as opposed to a 1- or 2-word answer). Samples needed to meet 3 out of the 4 criteria to be kept. Additionally, while the land management questionnaire was optional, most of the participants answered the questionnaire. However, there was some confusion from the audience when answering the question "How long have you [enter land management practice] for?" The answer options were offered as multiple-choice representing years. There was a trend where individuals who were not implementing a management practice (e.g., using fertilizer) skipped answering the "How long" question presumably because they were not implementing that practice. These types of questions were largely answered by only those who were implementing the practice. This could be improved by training clarification and by altering the survey question to say, "How long have/haven't you [enter land management practice] for?"

7.3 Recruitment

Recruitment was successful with 13,000 website visits from 8,900 unique visitors on the Atlanta Firefly Website and >1,500 participants signing up to participate with 1022 samples received. Notably, there is a great difference between the number of potential participants exposed to the project (8,900) and number of samples received (1,022) from 482 sites indicating further barriers preventing individuals with interests, knowledge, and access from following through. Governing pathways, specifically neighborhood associations and city/county government engaged the most by resharing materials on their networks along with social pathways, primarily non-profits. Sticker incentives were desired by participants with >500 people signing up and the audience received the sticker by their preferred choice: pick-up or via mail.

7.4 Monitoring

Maps to monitor the data identified errors in geographic location quickly and easily because they defaulted to the center of downtown Atlanta. With a quick visual inspection of the map, we were able to catch many geographic errors this way during the collection period. Yet I still chose to manually validate geographic location for each sample by checking the point against the address. A notable number of samples had some type of geographic error.

Facilitator directed communication with the participants via email had a listserv size of (1,500) and an averaged open rate of 45% ranging from 40.5% - 72.8% from the five email campaigns. The website, email contact, and Instagram (over 1,000 followers) were used for communication by the participants and the researcher. The direct email address sent a total of 299 emails directly between April 2020 and April 2022 with 91 two-way conversations. Most conversations were around general inquiries, miscellaneous questions, comments, or requests to monitor at parks. The audience was also able to leave thoughts, comments, or memories on the data submission form along with an optional contact email and phone number.

Through monitoring social media, a novel tool was discovered and recorded by a participant Chandler Coats. Chandler submitted photos taken with a simple phone application called NightCap Camera designed for photographing star trails. Chandler found it was excellent at capturing firefly flashes. Upon review of these photos, I believe tools such as this would be useful quantitative data in the future as it can capture firefly flash trains and useful for identifying *Lampyridae* species and also a possible tool for measuring abundance. Examples can be seen in figures 2.2 and 2.3. Photography has been a commonly employed tool for documenting *Lampyridae* species, with even new techniques intended to monitor swarms for species of interest (Sarfati & Peleg, 2021) but in all those cases, special tools, software, or more advanced camera skills are needed. This is a previously unconsidered simple application that anyone can use without camera knowledge available at a relatively low cost ($2.99) but currently only available for iOS. Without two-way project monitoring, novel techniques such as these would remain undocumented.

Figure 2.2: Firefly Photo (taken with NightCap Camera, photo by Chandler Coats)

Figure 2.3: *Photinus pyralis* photo (taken with NightCap Camera, photo by Kelly Ridenhour)

8 Communicate Results

8.1 Recognition

The project website communicated the value of the participants' efforts and thanked the participants in some way on almost every page. Additionally, the email campaigns intentionally thanked participants for their time with each email. Stickers were distributed and I strived my best to answer all questions submitted through digital methods. I also dedicate this thesis to the Atlanta Firefly participants. Without them, this work would be impossible. There are too many volunteers to reasonably thank by name but with special thanks to those 29 park participants who spent time away from their homes to monitor a city park.

8.2 Access

A set of best management practices result from this project, developed, and intended for the project participants and the participants are offered a custom in-person presentation of the results, to be held in the community, for free, at the non-profit Trees Atlanta on May 6th, 2022. In addition, these results will be shared on the website, distributed on the listserv, and social media. The raw data will be anonymized and available for download on the website (www.atlantafireflyproject.org).

Discussion

The guiding steps identified in this paper can be applied for isolated projects or scaled up to a coordinated national level. For example, work has already begun by the Xerces Society, on the Firefly Atlas, a new initiative to educate and engage researchers, land managers, and community scientists in filling data gaps. The methods proposed in this paper are timely to assist Firefly Atlas facilitators in their efforts. Given the Firefly Atlas's challenge of covering a wide initial spatial scope across three regions (Mid-Atlantic, Southeast, and Southwest), these methods serve as a starting point to organize, structure, and recruit participation with local community scientists in areas of interest. The initial Firefly Atlas scope focuses on high priority data deficient species and in some cases adjacent residential zoning areas are sources of pollution that threaten populations. Using community science to engage communities living in proximity to these species would be one productive conservation and education approach. These efforts could be strategically planned and coordinated through the Firefly Atlas but facilitated through local organizations. This sort of bottom-up engagement might improve the quality of land management in the matrix surrounding critical firefly habitat, culminating in positive outcomes for biodiversity and social-ecological systems.

In addition, if the Firefly Atlas is successful at guiding local organizations in standardized methods, it could result in a significant body of data for researchers. This effort could perhaps be scaled further, to the international level, and coordinated through Fireflyers International

Network. When sustained through time, this type of data set would allow researchers to track long-term trends in species populations and equip conservationists to keep tabs on species of interest before an alarm is sounded at a critical stage.

Not only can the steps discussed here be used in the implementation of a firefly-specific community science program, but they provide a framework for quantifying the successes of community science and critically evaluating community science outcomes. For example, the Atlanta Firefly Project is not the only community science effort, with one such project, Firefly Watch, having collected *Lampyridae* data since at least 2008. Between 2008-2016 Firefly Watch was facilitated by The Museum of Science in Boston and was clearly successful at collecting data with an impressive 25,478 samples within the 2008-2016 data set. Since 2016, the project has been facilitated by Mass Audubon and similar training methods and tools are used. Data from these efforts is an immense body of data with potentials of providing outcomes for science, outcomes for participants, and outcomes for social-ecological systems. To quantify this potential and inform future *Lampyridae* efforts, it would be useful to evaluate the efficiency of their data collection system using the analytical questions in my Step 7. This process encourages data exploration to uncover if the data is usefulness for researchers, uncovers process burdens, reviews participant feedback (if any), examines data accuracy and completeness, evaluates best recruitment strategies, explores long-term participant engagement, and unveils if there were any novel discoveries by participants (highly likely given the sheer number of participants).

Furthermore, this quantification of successes is useful in securing future participant interest, funding, and resources that contribute to long-term project sustainability. While project sustainability in terms of funding or resources was not explicitly addressed in these steps, they are implicitly prompted when considering scale, timeline, and feasibility. In the case study of the

Atlanta Firefly Project, the project will transition to a student organization EcoReach which will continue the project's community science activities. For future projects, these types of collaborations between academic institutions, non-profits, local organizations, and even local businesses can be sought out to improve project sustainability.

While grants, donations, and municipal funds might be monetary opportunities it is worth noting that individual participants might be a source of funding. For example, from a poll of Atlanta Firefly Project participants 142 indicated they would purchase a project t-shirt, 72 indicated they would purchase additional stickers, 61 vehicle stickers, and 57 hats. While this might amount to miniscule funds when pulling from a participant size of the Atlanta Firefly Project (at time of writing), it could have potential when scaled. For example, this poll represents about 22% of the Atlanta Firefly Project email listserv, with each participant spending ~$25 on goods resulting in $8,250 before expenses. Yet, at the Firefly Watch scale, which has 20x the number of samples, could 20x the goods be sold? A speculative potential of $165,000 (before expenses) for *Lampyridae* conservation. At these numbers, project sustainability is much more feasible.

To conclude, I intend these guiding steps to be useful in both critically evaluating existing *Lampyridae* community science projects and guiding future studies towards a coordinated methodology to benefit researchers, the public, and *Lampyridae* conservation.

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CHAPTER 3

GUIDING STEPS FOR COMMUNITY SCIENCE PROJECTS: A CASE STUDY OF ATLANTA FIREFLY PROJECT[1]

[1] Ridenhour, K.R., & Schmidt J.P. To be submitted to Biological Conservation

Abstract

As human populations globally have become increasingly urbanized, residential landscapes and urban green spaces become correspondingly important locations for the experience of nature, a vital ecosystem service. Fireflies, globally distributed beetles in the *Lampyridae* family, while sensitive to the effects of urbanization, are at the same time charismatic and much enjoyed in residential landscapes. Here, I analyzed data from the Atlanta Firefly Project, a community science effort to relate the effects of land management on the local abundance of *Photinus pyralis*. I found that firefly abundance increased with the quality of landscape greenness at the parcel level, whereas artificial lighting at night, mosquito spraying (pyrethroids), removal of leaf litter, and fertilizers reduced firefly abundance while mowing, use of other insecticides (various chemical applications), and fungicides had no effect. Surprisingly, the use of herbicides increased *Photinus pyralis* numbers, but the relationship is unclear. From these findings, I recommend conservation measures for municipalities and residential property managers.

Introduction

In North America, over 80% of the population lives in urban areas, where there is a decrease in the production of ecosystem services (Grafius, Corstanje, & Harris, 2018). One of the most significant ecosystem services to people are cultural services (Larson et al., 2016), the non-tangible benefits humans obtain from ecosystems that improve human happiness and societal well-being. One concerning consequence from the loss of cultural services in urban areas is the extinction of experience where humans suffer from a lack of exposure, interactions, and experiences with nature (Soga & Gaston, 2016), (Cox, Hudson, Shanahan, Fuller, & Gaston, 2017).

Providing opportunities for memorable nature experiences is a method for reducing this consequence (Soga & Gaston, 2016) yet is challenged by urban declines in species abundance and richness (Piano et al., 2020). One memorable nature experience is those involving fireflies (*Lampyridae*) (Hosaka, Sugimoto, & Numata, 2017), and are often based in residential landscapes and public parks. The need for urban systems to cultivate cultural services is increasing (McGranahan et al., 2005) yet studies examining ecosystem services in residential landscapes are lacking (Larson et al., 2016), (Andersson, Tengö, McPhearson, & Kremer, 2015). This same trend is true for fireflies, with few studies exploring *Lampyridae* in urban areas (Picchi, Avolio, Azzani, Brombin, & Camerini, 2013) and none that explore land management practices on abundance dynamics.

Yet, despite the lack of data on urban firefly abundance, distribution, and land management associations in residential areas, there is no lack of "firefly-friendly" land management recommendations accessible to the public and targeted primarily for residential landscapes. A google search for the exact phrase "firefly friendly" or "firefly-friendly" returns more than 8,000 results from gardening blogs, magazines, newspaper articles, and published books. These results feature recommendations such as "leave the leaves," "mow less often," "reduce or eliminate pesticide use," "do not use chemical fertilizers on lawn," and "reduce or eliminate unnecessary outdoor lighting" among many other guidelines. The volume of available resources is likely driven by strong cultural desire for nature experiences, anecdotal reports of population declines, and fireflies being a charismatic microfauna.

These recommendations aim to generate supporting services for fireflies through provisioning suitable habitat in residential landscapes; however, supporting services (such as habitat provisioning) are the least explored ecosystem service for urban areas and in one metaanalysis of urban ecosystem services only a few examples were found (Haase et al., 2014). Additionally, it is unclear how effective these bottom-up “wildlife-friendly” approaches are at this scale without a species-specific approach (Goddard, Dougill, & Benton, 2010).

In Atlanta, interest in habitat provisioning in residential landscapes is high with local participation in several programs; The National Wildlife Federation’s certified wildlife habitat with 5,233 certified locations as of 2022 in metro Atlanta counties of Fulton, DeKalb, Cobb, and Gwinnett (National Wildlife Federation, 2021), Georgia Audubon’s wildlife sanctuary program with more than 600 certified Atlanta locations (Georgia Audubon, n.d.), and certified Monarch waystations with 61 Atlanta locations as of 2022 (Monarch Watch, 2022). While there is some evidence that this type of habitat provisioning is effective in building structural habitat (Widows & Drake, 2014) and can increase local abundance of birds (Belaire, Whelan, & Minor, 2014) the effects of urban land management on insect populations are under-researched, even more so, studies involving private residential landscapes and none involving fireflies.

To assess fireflies at the residential scale, interactions between local abundance and *Lampyridae* threats must be understood. Using Rabinowitz’s rarity classification, as many as 99.4% of 168 North American species demonstrate some type of rarity (Reed, Nguyen, Owens, & Lewis, 2020). Rabinowitz’s rarity classification relies on three criteria of assessment; geographic distribution (narrow or wide), habitat requirements (specialist or generalist), and population (occurs in small populations everywhere or one large population somewhere). Reed et al. (2020) argues Rabinowitz’s rarity classification alone is insufficient for assessing *Lampyridae* extinction risk. Instead, firefly risk factors (light-based mating signals, diet specialization, activity time, dispersal ability, etc.) along with threats (overharvest, artificial light at night, catastrophic events, pesticides, climate change, etc.) would strengthen the assessment of firefly extinction risks.

In Atlanta, Georgia *Photinus pyralis*, the big dipper firefly, is an adaptable, common species of least concern and it is not threatened with extinction, yet ideas from Reed et. al. (2020) for assessing local abundances of *P. pyralis* is useful. *P. pyralis* should be abundant and frequently encountered in residential landscapes in Atlanta, but like most *Lampyridae* species, the species population trend is unknown, and threats are not well documented (Walker, 2021). The top conservation threats to North American *Lampyridae* are anthropogenically driven, greatest in areas undergoing rapid urbanization and listed as 1) habitat loss and degradation, 2) light pollution, and 3) pesticide use (C. E. Fallon et al., 2021).

Habitat loss is most detrimental to *Lampyridae* habitat-specialists such as Photuris bethaniensis, a species limited to interdunal freshwater swales vulnerable to residential development (C. E. Fallon et al., 2021). Even still local populations of *Lampyridae* generalists experience small-scale habitat loss, with possible extirpations documented in Pyractomena borealis, a widely distributed species of least concern, from forest clearing and habitat degradation (Walker and Lewis., 2021) and once locally abundance species Photuris eureka and Pyractomena angustata from groundwater extraction at Mallory Swamp near Gainesville, Florida, USA (Lloyd, 2018).

P. pyralis, a habitat generalist with preferences for open areas and ecotones including yards, county parks, cemeteries, orchards, and fields will also occupy woodlands near rivers and streams (Barrows, Arsenault, & Grenier, 2008), (Lewis, 2016), (Faust, 2017). *P. pyralis* adults have been documented to nectar on milkweed flowers (Asclepias spp.) (L. Faust & Faust, 2014) which are found in meadow habitats. Photinus larvae spend most of their time under leaf litter or under the soil and use earthworms and other invertebrates as food sources (Buschman & Faust, 2014), (Koken et al., 2022). In urban areas, much of the available habitat for *P. pyralis* is developed into impervious surfaces. Impervious surfaces such as buildings, roads, and pavement are all forms of local habitat loss for *P. pyralis* as it prevents access to the soil.

Consequences from habitat degradation in urban areas are cumulative, meaning a series of uncoordinated, independent, land management decisions that are spatially dispersed (Odum, 1982). These cumulative effects are heterogeneous and a result of a spectrum of residential land management practices such as artificial light at night, pesticide use, fertilizer use, management of leaf litter, mowing, and irrigation. Evidence suggests that some of these practices might threaten local populations of *P. pyralis*. Additionally, these cumulative effects are not constant, and shifting temporarily with changing ownership.

Artificial light at night (ALAN) is one of the biggest conservation concerns for *Lampyridae* locally and globally (C. E. Fallon et al., 2021), (Lewis et al., 2020), (Vaz et al., 2021) with a growing body of studies to support this claim. Adult flashing *Lampyridae* species courtship communication is disrupted under ALAN (Bird & Parker, 2014), (Costin & Boulton, 2016), (Firebaugh & Haynes, 2016), (Owens, Meyer-Rochow, & Yang, 2018) at all intensities and colors for both males and females (Owens & Lewis, 2021a) with higher light intensity being more disruptive than dim lights (Owens & Lewis, 2021a), (Van den Broeck, De Cock, Van Dongen, & Matthysen, 2021) and females typically more sensitive to disruption than males (Owens & Lewis, 2021a) especially at longer exposures of light (Elgert, Lehtonen, Kaitala, & Candolin, 2021).

While the effects of ALAN on *Lampyridae* larvae are less explored, there is evidence that ALAN disrupts larval dispersal with some *Lampyridae* species choosing to burrow deeper in the soil instead of dispersing across it (Owens & Lewis, 2021b) while in other species, larvae exposed to intense downwelling light were stationary, perhaps unable to detect a change in photoperiod (Mbugua, Wong, & Ratnayeke, 2020). Both disruption in courtship communication and a potential reduction in larval dispersal due to ALAN can lead to declines in population abundance, especially under bright amber light conditions, where rapid extirpation of small populations of *Lampyridae* with brief mating seasons is possible (Owens & Lewis, 2021a).

One study conducted across the urban landscape of Turin, Italy found a negative correlation between ALAN and adult *Lampyridae* presence at an illuminance of 0.2 lux or greater and proposed that habitat colonization might be limited in urban environments under experiencing ALAN (Picchi et al., 2013). It has also been proposed that crepuscular *Lampyridae* species, such as *P. pyralis*, are less sensitive to ALAN (Lewis & Owens, 2019), (Owens & Lewis, 2021a) yet several studies documented a reduction in flashing *P. pyralis* under ALAN conditions (Costin & Boulton, 2016), (Firebaugh & Haynes, 2016). While *P. pyralis* can be seen displaying under ALAN conditions (Faust, 2017),the effect of ALAN on urban populations of *P. pyralis* is unknown.

The effects of pesticides and fertilizers on *Lampyridae* are much less researched. The earliest study found the commercial insecticides on Fenthion highly toxic to larvae of *Luciola cruciata* when applied as a concentrate, but when diluted to recommended application rates fenitrothion, fenthion, and difenphos were non-toxic (Tabaru, Kouketsu, Oba, & Okafuji, 1970). This was echoed when high concentrations of clothianidin (a neonicotinoid insecticide commonly used in seed treatments) were found to be toxic to *Photuris versicolor* complex and *Photinus pyralis* larvae, yet non-toxic at low application rates (Pearsons, Lower, & Tooker, 2021). Pearsons et al., (2021) expressed concerns from residual clothianidin which can accumulate to acutely toxic and lethal rates, especially in turf applications or when Lampyrids consume prey exposed to clothianidin. For adult *Lampyridae*, a study of the arthropod community in clothianidin-treated corn seed field against control fields found a 70.4% reduction in adult flying *Lampyridae* within clothianidin-treatments but all arthropod groups trended toward recovery at later in the growing season (Disque, Hamby, Dubey, Taylor, & Dively, 2019).

In a controlled lab study on *Luciola lateralis* Lee, Kim, Lee, Song, & Nam, (2008) found ten insecticides (5 organophosphates, 2 insecticide mixtures, 1 insecticide growth regulator, 1 Neonicotinoid, and 1 Phenylpyrazole) to be highlight toxic to both larvae and adults and significantly decreased egg hatchability. This is highly concerning as the classes of organophosphates are some of the most widely used chemicals and readily available to land managers with mortality ranging from 80-100% in larvae and 100% in adults with a 100 - 67% reduction in egg hatchability. Fipronil, a broad-spectrum insecticide commonly used for cockroaches and termites, resulted in mortality for larvae (83%) and adults (100%) with a 34% reduction in egg hatchability.

Two lab studies have documented *Lampyridae* luminescent responses under chemical exposures, Hollingworth & Murdock (1980) documented changes in adult *Photinus pyralis* luminesce output when exposed to formamidine insecticides and Trajkovska, Tosheska, Aaron, Spirovski, & Zdravkovski (2005) documented a suppression of luciferase response under exposures to three common herbicides fenoxaprop-p-ethyl, diclofop-methyl, and metsulfuron methyl. These two studies were exploratory with unclear implications for *Lampyridae* however, as adult bioluminescence species use light to attract conspecific mates (Lloyd, 1971), (Stanger-

Hall & Lloyd, 2015), (Stanger-Hall et al., 2018), any alterations in luminescent abilities would be concerning for *Lampyridae*.

Perhaps most concerning is the lack of knowledge on fertilizers. Only one study in a controlled lab experience found *Luciola lateralis* larval mortality within 72 hours following exposure in three out of six common fertilizers. Urea fertilizer (27% mortality), ammonium sulfate (56% mortality), and potassium chloride (73% mortality) (Lee et al., 2008). All three are common additives in lawn, landscaping, and general fertilizers, especially urea and potassium chloride. While easily accessible, ammonium sulfate is a common additive for soil acidification. There is enough evidence to consider residential applications of pesticides detrimental for local abundance of *P. pyralis*.

Other commonly cited "firefly-friendly" land management practices of leaving the leaves, mowing, and irrigation are less studied. Within *Lampyridae* conservation literature, emphasis is placed on the importance of protecting *Lampyridae* larval habitat as adult stages are short for *Lampyridae* (Lewis, 2016), (Faust, 2017), (Fallon et al., 2019) and in a staggering review, it was concluded that larval life stages have not been studied in 94% of *Lampyridae* species (Riley, Rosa, & da Silveira, 2021) and out of the larval studies, they were taxonomically and geographically biased with morphology being the most frequently research trend, with larvae interactions the least studied.

Like most *Lampyridae* larva, there is still much unknown about the larval behavior, habitat, physiology, and interactions of *P. pyralis* but larvae in the *Photinus* genus are fossorial, spending most of their time under the soil or under leaf litter and are gastropod-eating with some species specializing in earthworms (Buschman & Faust, 2014). Moisture is necessary for all life stages of most Lampyrids as they are not tolerant of desiccation at any stage (Lewis, 2016), (Faust, 2017), (Fallon et al., 2019). Two expert interviews in Lewis et al., (2020) indicated that in some instances irrigated landscapes could be beneficial for some populations with examples in Spain and Texas. Therefore, the management of leaf litter, mowing, and irrigation could be significant for *P. pyralis* larvae locally. Figure 3.1 below is provided to communicate the number and type of studies used as evidence used to make my predictions. The papers referenced in figure 3.1 are organized in Appendix D.

To my knowledge, this study is the first to assess the effects of habitat affinities and land management variables on local abundances of *Photinus pyralis*. Using community science data gathered from the Atlanta Firefly Project in Atlanta, Georgia, this project has three main aims 1) to assess the following variables commonly promoted for wildlife habitat provisioning in urban areas: landscape greenness, artificial light at night, mowing practices, irrigation practices, pesticide use, fertilizer use, and leaf litter presence where I predict that the abundance of *Photinus pyralis* will be positively correlated with landscape greenness, and irrigation while negatively correlated with artificial light at night, mowing, pesticides, loss of leaf litter, and fertilizer, 2) serve as baseline data useful for future population monitoring for *Photinus pyralis*, and 3) provide habitat provisioning recommendations for fireflies for both bottom-up and top-down conservation approaches.

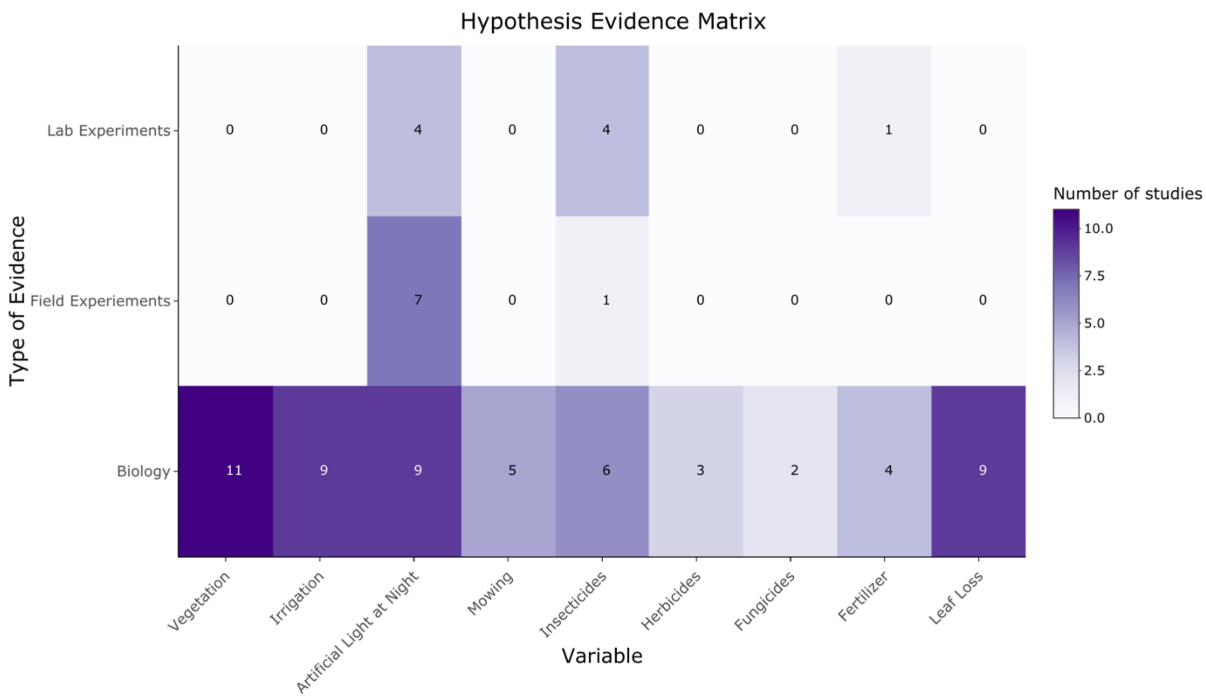

Figure 3.1 Hypothesis Evidence Matrix: which shows the 9 management variables sorted in columns and labels on the bottom (vegetation, irrigation, artificial light at night, mowing, insecticides, herbicides, fungicides, fertilizer, and leaf loss) with the three categories of research papers listed by row with labels on the left-hand side (lab experiments, field experiments, and biology). The number of studies used to make our hypothesis is shown in each cell and illustrated with color with more students being darkest purple and the fewest studies showing up as white.

Methods

1 Study Site

Atlanta (33.753746, -84.386330), the capital of the State of Georgia, has a population of 4,692,000 as of 2020 in the Atlanta-Metropolitan region, which is composed of multiple, interconnecting municipalities (Atlanta Regional Commission, 2020). One of the largest defining environmental features of Atlanta is its presence of tree canopy with the highest canopy cover out of any major city in the United States (Giarrusso, 2014) and 47.9% canopy cover in the City of Atlanta boundary with forest patches commonly serving as city parks. Most of Atlanta's land is zoned single-family residential, covering more than 60% of the city area. While there are 357 city parks covering 4.5% of Atlanta.

Atlanta is a temperate forest the most recent climate normals reporting 4.54 inches of rain with an average temperature of 77.9°F in June and 4.75 inches of rain with an average temperature of 80.9°F in July (NOAA Online Weather Data, 2022). Georgia is rich in *Lampyridae* with The International Union for Conservation of Nature Red List of Threatened Species database indicating records of at least 49 species within the state of Georgia with 29 species having been observed in the region where Atlanta is located.

2 Study Design

A community science data collection project was promoted as The Atlanta Firefly Project. The scope of this project targeted the City of Atlanta municipal area but did not prohibit anyone from contributing samples from anywhere; therefore, samples were received across the metropolitan statistical area. Volunteers were recruited through promoting the project to all neighborhood associations, neighborhood planning units, and various local nonprofits and community organizations.

Faust (2017) recorded peak activity for *P. pyralis* in June approximately 30 minutes before sunset and typically ending by 60 minutes after sunset, depending on habitat and levels of ambient light. We cross references all adult-flashing species recently occurring in the Atlanta area with records of activity time overlapping the activity time of *P. pyralis*. A total of 8 species were selected and one additional species with a continuous glow with a later activity time and rarely observed in Atlanta was added to demonstrate *Lampyridae* variability. In June and July 2021, volunteers from the Atlanta Firefly Project submitted a combined total of 1,022 samples from two different data sets, residential and parks.

For residential monitoring, volunteers were asked to collect data from their homes twice in June and twice in July. The observation period began 60 minutes before sunset and volunteers waited 15 minutes after the first flash was observed before recording data. If no fireflies were observed, they were instructed to remain until 30 minutes past sunset to confirm no fireflies were seen. The volunteers were trained on data collection with a digital training video and provided with written instructions for each question on the data submission form. Volunteers submitted the data described in the next section utilizing a Survey123 data submission form which was accessible on any device. These methods gathered 925 residential samples from 435 locations and are shown in figure 3.2.

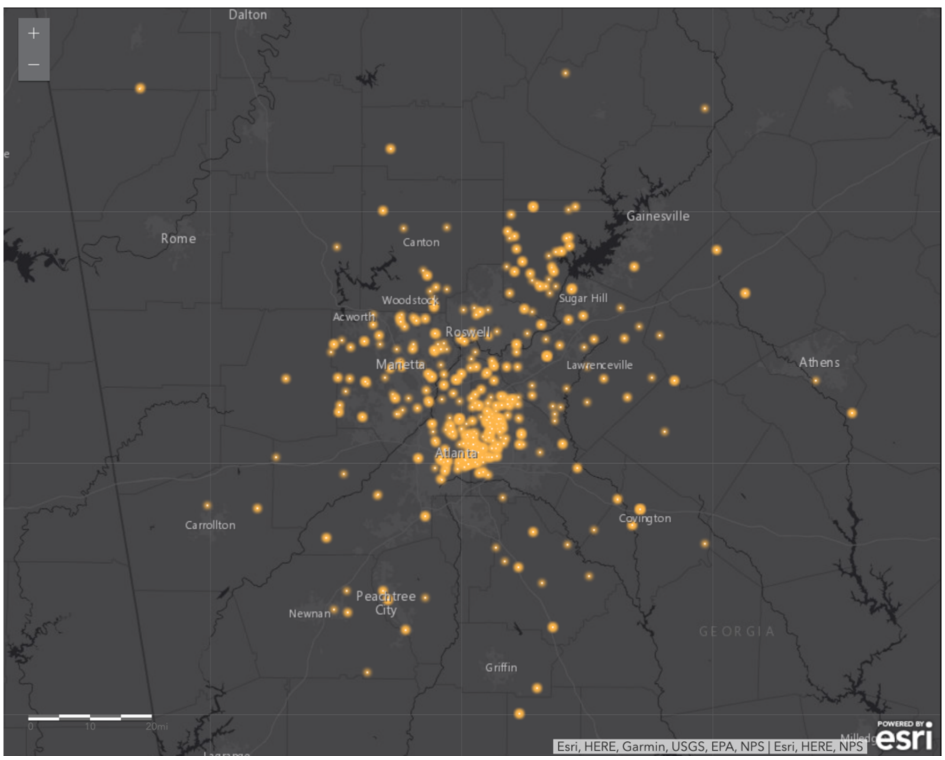

Figure 3.2 Map of Observations (showing the residential point locations in yellow that were submitted in 2021).

For park monitoring, 46 parks were observed with a single researcher observing 15 parks and trained volunteers observing 31 parks. Volunteers were asked to collect data from city parks and public spaces at least once in June and once in July. The observation period began 60 minutes before sunset and volunteers waited 15 minutes after the first flash was observed before recording data. If no fireflies were observed, they were instructed to remain until 30 minutes past sunset to confirm no fireflies were seen. Each park site was standardized by pre-selecting a monitoring location stationed at an ecotone (the buffer between forest patches and open lawn or field). There was a total of 29 park volunteers who were all first trained with a park training video followed by at least one additional training method: 12 park volunteers were met on-site and trained in-person, 2 park volunteers were trained over the phone, and the remaining 15 park volunteers were trained via email instructions. Volunteers were also provided with written instructions for each question on the data submission form. Volunteers submitted the data described in the next section utilizing a Survey123 data submission form which was accessible on any device. These methods gathered 97 parks samples from 46 locations.

3 Data Collected

The survey form included required and optional data. The required data included the date, time, latitude and longitude of the observation, home address or park name, flash counts repeated three times (volunteers were trained to stand in one location and only looking one direction, to count all the flashes observed within 60 seconds), and the direction faced. Optional data included project notes, memories, photos, a survey about if changes in firefly abundance had been observed, and a land management questionnaire that questioned participants about mowing, irrigation, pesticide, fertilizer, lighting, and leaf management. For each type of management, the questions systematically asked where it is treated, how much is treated, how frequently it is treated, for how many years it has been treated, and what kinds of treatments they were applying.

For management information from parks, the same questions were asked of park management. For the full questionnaire see Appendix B.

4 Remote Data

10 freely available color infrared image tiles were downloaded from the National Agriculture Imagery Program (NAIP) covering 10 metropolitan Atlanta counties from 2019 accessible at https://datagateway.nrcs.usda.gov/GDGHome_DirectDownLoad.aspx. NAIP provides color infrared products at < 1 meter resolution in three bands (infrared, red, and green bands) (USDA, 2013). Color infrared refers to near infrared wavelengths (NIR) which are longer than visible red wavelengths (Red) and invisible to the human eye. NIR wavelengths are necessary for analysis using the normalized difference vegetation index (NDVI). The index normalizes the difference between visible red wavelengths (which vegetation absorbs) and near infrared wavelengths (which vegetation reflects) using the formula:

$$NDVI = (NIR - Red) / (NIR + Red)$$

NDVI values range from -1 to 1 where values closest to (1) indicate dense, healthy, green leaves and values closest to (-1) indicate water or snow and moderate values indicate bare areas like dirt, rock, buildings, and other impervious surfaces. Each NAIP tile was processed separately in ArcGIS Pro using the NDVI function. 40 random latitude and longitudes of known lawns were selected. The lowest NDVI value from 40 lawns was selected as the minimum value for available greenness for *P. pyralis*. Values lower than the threshold were reclassified as 0 to eliminate negative numbers and remove any values lower than the lawn. All firefly monitoring latitude and longitudes were projected and buffered using a 30-meter diameter zone to measure parcel level greenness and 100-meter diameter zone to measure block greenness. The values of each pixel within the buffer were summed using zonal statistics and if any diameter zone was only partially contained inside the 10-county area, it was removed from the sample set.

To measure levels of artificial light at night, one freely available nighttime light image from the Luojia 1-01 satellite was downloaded from the Hubei Data and Application Network for High Resolution Earth Observation System (http://59.175.109.173:8888/app/login.html) covering a spatial area of 250 km x 250 km across metropolitan Atlanta. Luojia 1-01 provides products at 130-meter resolution as a panchromatic band (Li, Li, Li, He, & Jendryke, 2019). The panchromatic band is a combination of the visible red, green, and blue bands allowing for a greater spatial resolution. The satellite measures wavelengths between 460 nm and 980 nm and translates light measurements to a digital number (DN). DN values range from 0 to upwards of 4,000 where values closest to 0 indicate darkness and high values indicate the highest levels of measurable light capable for Luojia 1-01. The DN values of Luojia-1 image can be converted to radiance values, a measurement of observed light by the instrument, using the formula provided by the satellite provider:

$$r = 10\text{-}10\ d3/2$$

Where r = radiance, d = DN value of a pixel. Radiance units are measured in watt per steradian per square meter (W·sr−1·m−2). All firefly monitoring latitude and longitudes were projected and the maximum value of the DN at that point location was calculated using zonal statistics and then converted into radiance.

Temperature and cloud cover can influence the activity time or *Photinus pyralis* with flash intervals speeding up at very high temperatures and intervals slowing down at very low temperatures (Faust, 2017) while cloudiness can alter activity time (Lloyd, 2006). Precipitation and minimum daily temperatures were chosen to account for influences of weather and data was downloaded from five weather stations covering the study site. Weather data was pulled in RStudio using the RANN package with code written to pair each sample's latitude and longitude to the nearest weather station.

5 Data Transformation

Raw data for both residential and park data were exported as a CSV file from Survey123 and underwent transformation and cleaning prior to analysis. Raw data in character form and was systematically converted into numeric data in excel:

1. Date was converted to the number day-of-the-year (chronological number out of 365 days)
2. Search and replace to convert yes and no answers were converted to 0 or 1
3. Flash pattern descriptions along with photos were reviewed and a 0 or 1 was assigned for each of the 9 species on the flash chart (*P. pyralis*, *P. australis*, *P. hebes*, *P. macdermotti*, *P. marginalis*, *P. lucicrescens*, *P. marginellus*, *P. frontalis*, *P. reticulata*). If the descriptions were unclear or indicated uncertainly it was assigned "species unsure."
4. The "Memories" text field was reviewed, and 6 categories were generated based on trends including (Positive Experience, Additional Observations, Learned Something, Memory, Population Comment, Shared with Others). There were 0 negative comments or complaints and most comments fell within only one of these 6 categories, some comments in multiple categories. A 0 or 1 was assigned per comment for each of these categories.
5. The "Briefly describe what sort of changes have you seen over time" question was reviewed, and 5 categories were generated based on trends. This question was only answered by those who have lived in the same location for a minimum of 5 years and the

trends included (perceived increase, perceived decrease, no change, short term increase: within last year only, unsure).

6. Observation time was imputed as hours minutes seconds in Eastern Daylight Time and converted to Eastern Standard Time in fractional time. As *P. pyralis* responds to levels of light rather than the time of the day, we calculated the observation time as a function of sunset on that day by collecting daily sunset time using the "suncalc" package in RStudio which pulls sunset time according to the latitude, longitude, and date for each observation. The sunset time was then converted to fractional time and subtracted from the observation time to represent time elapsed past sunset (a positive number) or time until sunset (a negative number).
7. A park field was generated and a 1 entered for park samples and a 0 for residential samples

Analysis

Model 1: The park data and residential data was combined into one set and was filtered to only select samples that observed at least some *P. pyralis* flashes. To test my prediction that *P. pyralis* abundance would be positively correlated with available landscape greenness and irrigation while negatively correlated with artificial light at night, mowing, pesticides, leaf loss, and fertilizer, I used the highest flash count from each sample as a measurement of abundance. Flash counts have commonly been employed to visually assess firefly abundance (Firebaugh & Haynes, 2016). I took the natural logarithm of the abundance value (highest flash count) to look for large differences in count numbers. This abundance measurement served as the response variable and predictor variables were the land treatments filtered into 10 categories selected to represent heaviest uses of that treatment. All samples that fell into these categories were scored a 1 while all other samples were scored a 0.

- Mowing: Representing samples that were mowing >50% of their property at a frequency of every two weeks or more frequent
- Irrigation: Representing samples that were irrigating lawn, aesthetic landscaping, or natural areas at a frequency of every week or more frequent
- Mosquito Service: Representing samples that were using a mosquito spraying service at a frequency of once a season or more frequent
- Insecticides: Representing samples that were using any other type of insecticides (except for treatments on buildings only) at a frequency of once a season or more frequent
- Herbicides: Representing samples that were using herbicides on lawn, aesthetic landscape, or natural areas at a frequency of once a season or more frequent
- Fungicide: Representing samples that were using herbicides on lawn, aesthetic landscape, or natural areas at a frequency of once a season or more frequent
- Landscape Service: Representing samples that were used a third-party to maintain their landscaping
- Fertilizer: Representing samples that were using fertilizer in lawns, aesthetic landscape, or natural areas at a frequency of once a season or more frequent
- Leaf Loss: Representing samples that had no leaves found on the property or bagged up and removed all leaves
- Artificial Light at Night: Representing samples that leave outdoor lights on all night and are located near adjacent lighting.

- Lastly, a few variables were included in this category as controls. As flash rates vary between species of *Lampyridae*, I chose to include *P. australis*, *P. hebes*, and *P. frontalis*, which all have at least double the flash rate of *P. pyralis* and whose observations would artificially inflate the abundance measurement. Landscape Service was included to account for any differences between some samples self-managing land versus a paid service.

Location (latitude and longitude) was included to account for spatial autocorrelation and repeating of sample locations throughout the season. Numeric values of date, time (as a function of sunset), light measurement (natural logarithm of value of radiance), parcel greenness (log10 NDVI value taken at 30 meters), neighborhood greenness (log10 NDVI value taken at 300 meters), minimum temperature, and daily precipitation were also selected as non-linear predictor variables and splined.

Model 2: To test my prediction that the effect would be greater the longer the management was used, the same process as model 1 was repeated except the 10 categories of land treatment were filtered again to only the samples who had been implementing the same treatment for at least 3 years or longer (except mowing practiced were filtered to 5 years or longer). All samples that fell into these categories were scored a 1 while all other samples were scored a 0.

Generalized Additive Models (GAMs) were selected because the relationship between some predictor variables and the response variable is non-linear. Furthermore, GAMs can uncover the relationships among predictor variables in easily interpretable ways. Tests were run in the RStudio Team (2020) R programming language using the “mgcv” package in RStudio with the smoothing of splines by the s and te functions.

Results

For model 1 *Photinus pyralis* abundance (estimate) was negatively correlated with the variables mowing (-0.06166), irrigation (-0.26349), mosquito service (-0.55300), fertilizer (-0.10781), leaf loss (-0.40561), and artificial light at night (-0.30075) with artificial light at night, mosquito service, and leaf loss being the most statistically significant at the 0.01 level. Insecticides (0.03942), herbicides (0.23993), fungicide (0.08515) all showed a positive correlation with *Photinus pyralis* yet were not significant. Furthermore, the standard deviations overlapped with zero for mowing, insecticides, and fungicides and essentially have no effect on abundance.

For model 2 the variables mowing (-0.07010), irrigation (-0.35884), mosquito service (-0.77887), fertilizer (-0.20830), leaf loss (-0.41092), and artificial light at night (-0.34203) continued a negative trend (estimates). Fungicides (0.09932) and herbicides remained positively correlated (0.27045) yet insecticides (-0.01830), previously positive, displayed a negative correlation. Again, mosquito service and artificial light at night being the most statistically significant at the 0.001 level followed by leaf loss and mosquito spraying at the 0.01 level. The negative relationship to irrigation was significant at the 0.05 level while fertilizer at the 0.1 level. Results for models 1 and models two are summarized in figure 3.3.

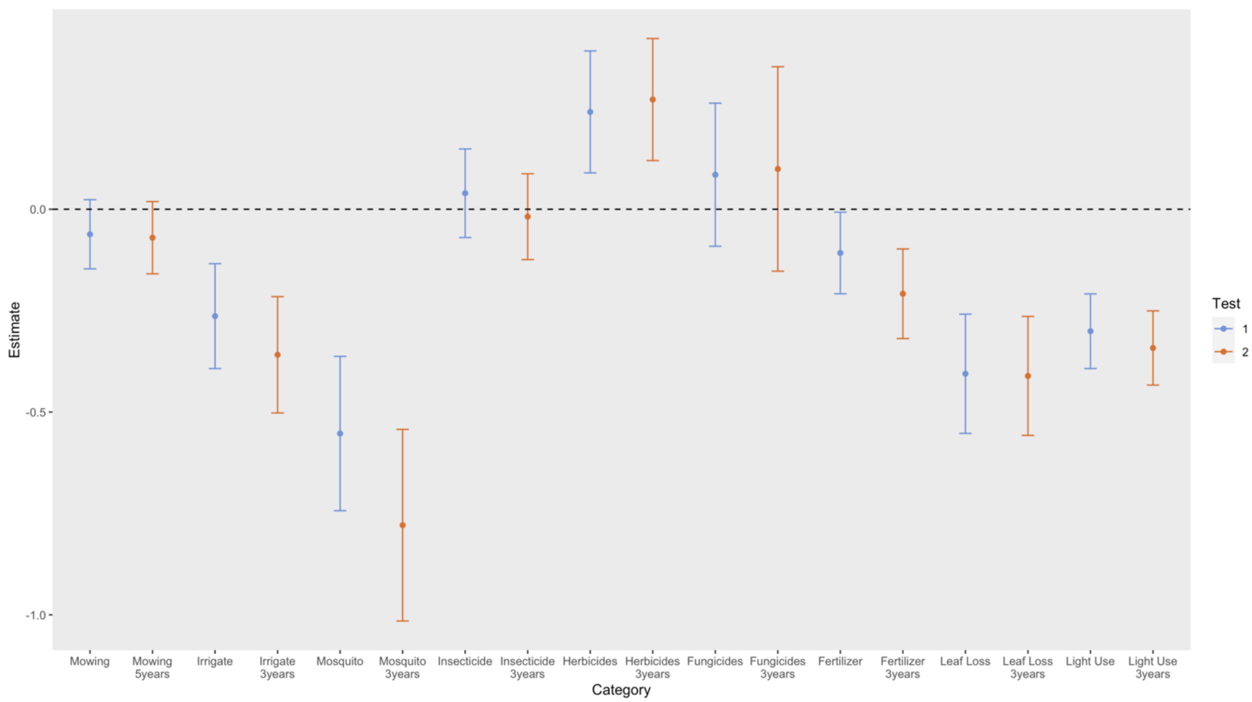

Figure 3.3 Management Results illustrates model 1 in blue and model 2 in orange. The management practices are labeled on the x-axis along the bottom and the effect on firefly abundance is shown on the y-axis with points showing the estimated effect along with standard deviations. When points fall below the zero on the y-axis it can be interpreted as a negative effect and when points fall above the zero on the y-axis it can be interpreted as a positive effect. When standard deviations cross the zero, there is no effect of the management on firefly abundance.

For both groups, plots of abiotic smoothed terms revealed similar trends with date, time, levels of remotely sensed light, and amount of available greenness at the parcel level were significant predictors of abundance. Plots revealed a peak abundance close to June 25thth as shown in figure 3.4 typically about 15 mins before sunset as shown in figure 3.5. For light, a negatively correlated linear relationship is seen between increasing levels of light shown in figure 3.6. There is almost a linear increase in abundance at increasing values of greenness at the parcel level shown with figure 3.7 with a strongly negative effect at very low levels of greenness but no effect was detected at the neighborhood levels of greenness shown with figure 3.8. The indicator variables of the three species with higher flash counts (*Photinus australis*, *Photuris hebes*, and *Photuris frontalis*) were all positively correlated in addition to parks.

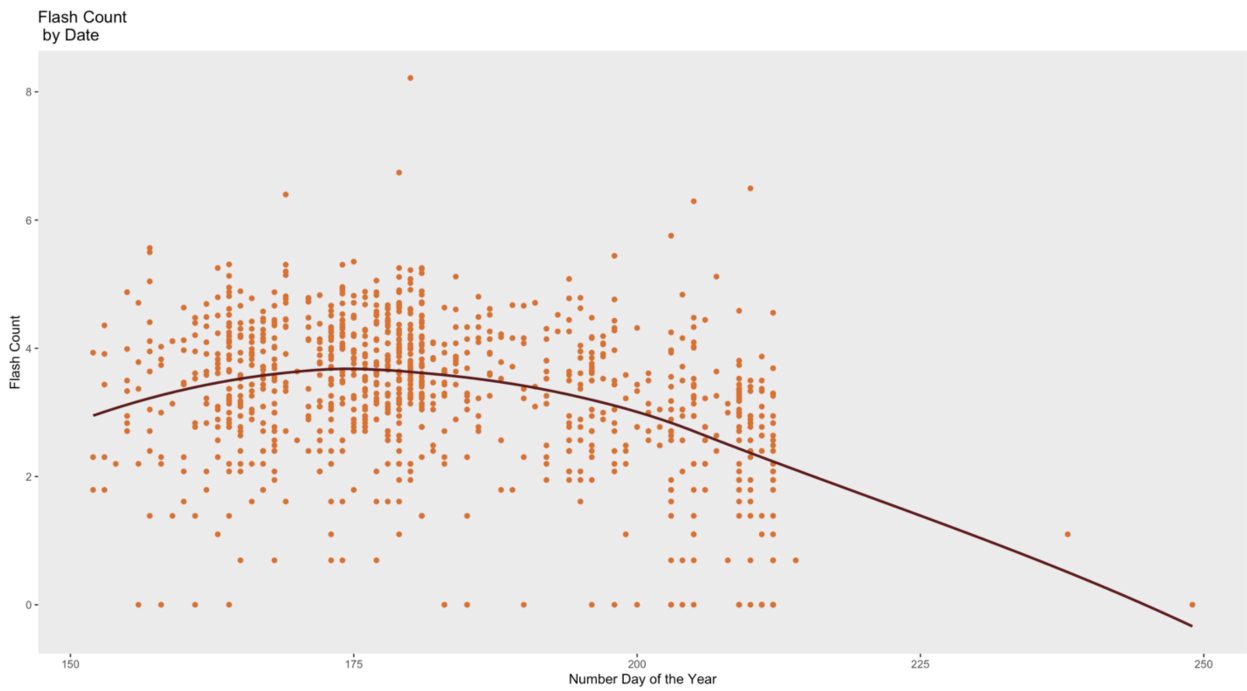

Figure 3.4 Flash Counts by Day displays the highest flash count on the y-axis plotted by number day of the year on the x-axis

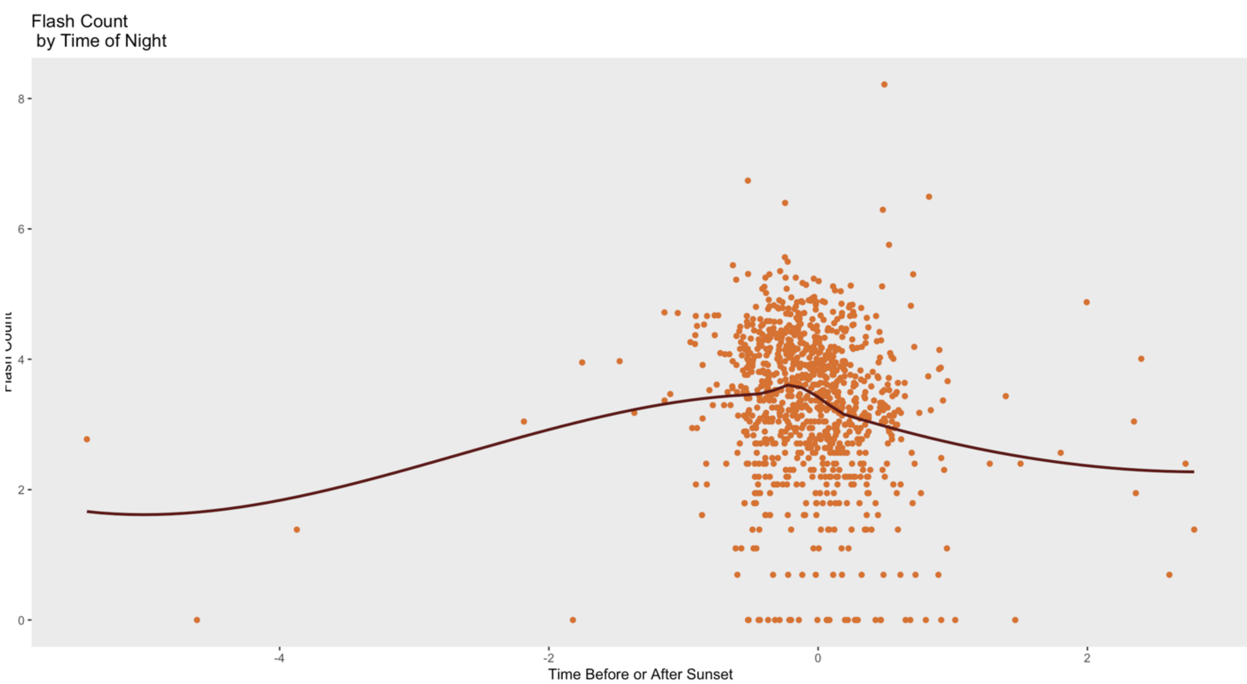

Figure 3.5 Flash counts by Time displays the highest flash count on the y-axis plotted by time of night as a function of sunset on the x-axis with 0 marking sunset. Negative values on the x-axis show the time (in hours) before sunset followed by positive values on the x-axis for time (in hours) past sunset.

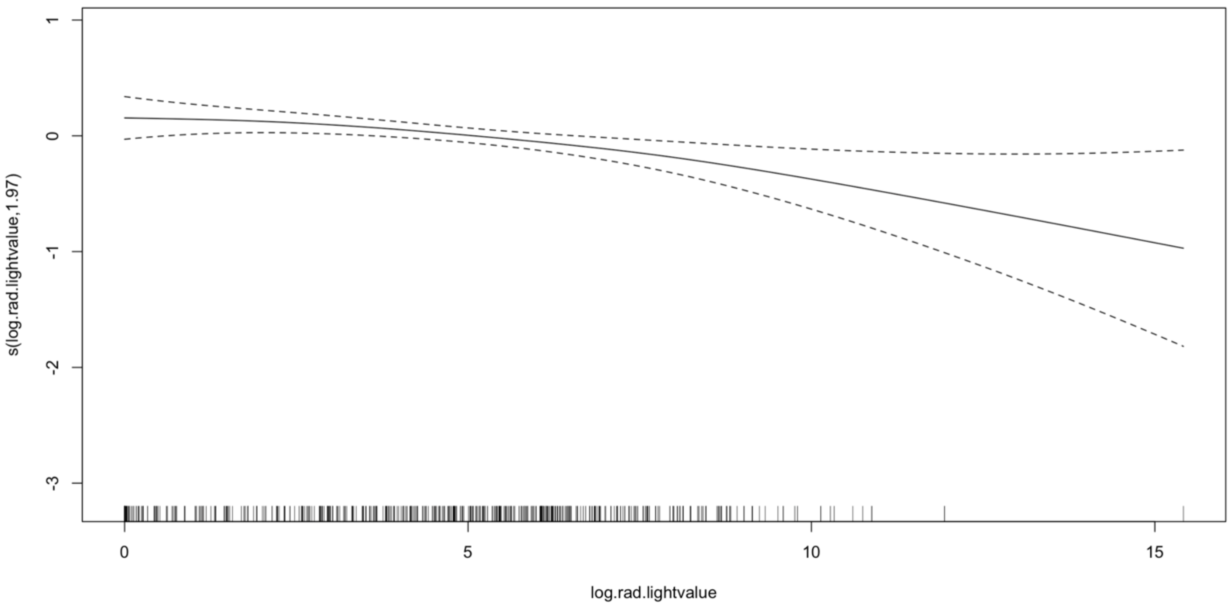

Figure 3.6 Flash counts by Brightness plots brightness (measured in radiance) on the x-axis with darker areas closer to 0 and the normalized natural logarithm of the highest flash count on the y-axis with negative correlations represented under the zero value on the y-axis and positive correlations falling above zero on the y-axis.

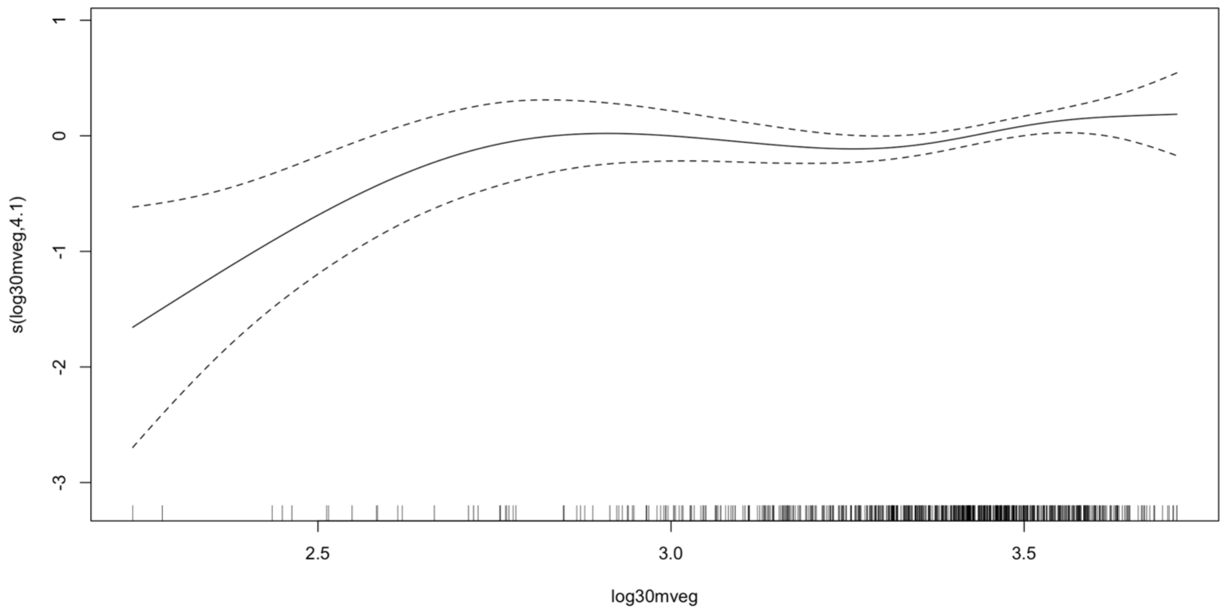

Figure 3.7 Flash Counts by Parcel Vegetation plots the sum of the greenness in a 30-meter diameter buffer around the observation (measured by adding together the minimum value of lawn and greater for all pixels within the buffer) on the x-axis with low amounts of vegetation under 3 and higher amounts of healthy green leaves above 3.5. The normalized natural logarithm of the highest flash count is shown on the y-axis with negative correlations represented under the zero value on the y-axis and positive correlations falling above 0.

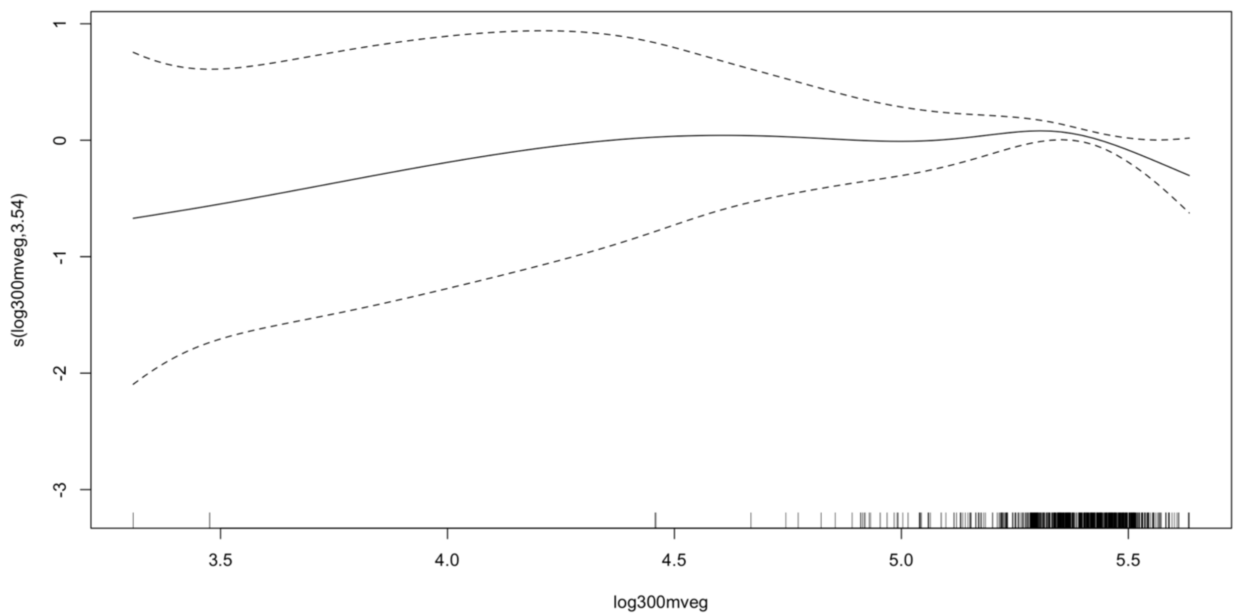

Figure 3.8 Flash Counts by Neighborhood Vegetation plots the sum of the greenness in a 300-meter diameter buffer around the observation (measured by adding together the minimum value of lawn and greater for all pixels within the buffer) on the x-axis with low amounts of vegetation under 5 and higher amounts of healthy green leaves above 5.5. The normalized natural logarithm of the highest flash count is shown on the y-axis with negative correlations represented under the zero value on the y-axis and positive correlations falling above 0.

Discussion

Land management matters for firefly abundance in parks and residential landscapes. Most significantly, the use of artificial light at night (ALAN) and mosquito spraying. ALAN was detected both through the land management survey and remote imagery, indicating a strong correlation. Disruption in *Lampyridae* species courtship communication under ALAN, especially at longer exposures of light (Elgert et al., 2021) will lead to declines in population abundance.

The chemicals used in mosquito spraying are most commonly organophosphates and pyrethroids. Lee et al., (2008) found organophosphates to be highly toxic to eggs, larvae, and adults in one *Lampyridae* species which is in line with the clear negative correlation between mosquito spraying and abundance. I expect population abundance to further reduce with continued spraying and emphasis should be brought to the cyclical use of mosquito-control chemicals. While mosquitoes can present public health concerns, before default spraying is established in residential landscapes, self-preventative measures should be the first line of defense and coupled with municipal disease monitoring programs.

The frequent and long-term use of fertilizers is also cause for concern. From lab studies, we know at least three common fertilizers result in high rates of larval mortality for at least one species of *Lampyridae* and my results show a negative correlation with a greater effect over time. I expect local population abundance to further reduce with continued applications of fertilizers. Leaf loss or lack of leaf litter is highly concerning given the importance of protecting habitat for *Lampyridae* larvae, and the significant negative effects we observed. The remaining negatively correlated variables of mowing were not significant and while mowing may have an influence on local populations of *Lampyridae*, it may be less significant for the fossorial larvae who live under the soil.

While the effect is not significant and overlaps with zero, the change in effect from insecticide from positively correlated in model 1 to negative in model 2 is notable. Earlier lab research presents mixed effects from insecticides on *Lampyridae* with toxicity of some insecticides observed at concentrated levels yet absent when used at recommended application rates. Even still, there is cause for concern that residuals from repeated insecticide applications might accumulate to toxic rates (Pearsons et al., 2021) and the negative trend in our data might reflect this process but more research is warranted. Previous research tells us little about the connection between fungicides and *Lampyridae* and I found an insignificant positive correlation that changed little between the two models. The fungicide group was the least common treatment with only 20 samples, while all other treatments were at least four times more common. Upon review, most of the fungicide samples indicated they either did not know the chemical but used it to treat their lawn, were using something to treat white flies or black mold, or Thiophanate.

The significant negative trend in irrigation was a surprise given the critical importance of moisture in all stages of *Lampyridae* lifecycles and with irrigated agricultural systems sometimes providing suitable *Lampyridae* habitat. It would be of interest to explore differences between agricultural irrigation sources and municipal ones. In our samples, most samples are on city water, which is a treated drinking water system. The City of Atlanta's Department of Watershed Management pre-treats water with sodium permanganate followed by two stages of chlorine treatment. The mixing of chlorine and sodium permanganate can form DBPs (trihalomethanes and haloacetic acids) when these chemicals react with organic materials. The Department of Watershed Management monitors and tests for DBPs within the system, but there is no tracking in place once the water enters the environment. Lonigro, Montemurro, & Laera (2017) found soil accumulations of similar compounds were directly related to the chlorine concentration in irrigation. Furthermore, soil structure was a significant factor and silty-clay soil bioaccumulated 300% over sandy soils. Atlanta is primarily clay soil and *Photinus pyralis* larvae are likely fossorial, positioning the larvae to potentially high accumulations chlorine and their by-products, yet the relationship between irrigation of treated drinking water and negative abundance on *Lampyridae* is unclear and is cause for further research.

Most surprising was the overall positive correlation between herbicides and abundance, another unclear connection. Previous research tells us little to nothing about the effect of herbicide exposure on *Lampyridae*. Most participants who use herbicides indicated they use some form of glyphosates with a trend in either 1) lawn treatment or 2) applications for poison ivy and English ivy. It is possible that there is an unexplored interaction resulting from this dynamic, for example, one study found mildly toxic effects of glyphosate in a different beetle species, yet the beetle was found in higher abundance in glyphosate treated fields compared to control fields (Pereira et al., 2018). This points to another unclear observable effect, but Pereira et al. (2018) speculated that it might be a result of reduced predation as predators were more sensitive to glyphosate. Yet this is unproven.

More generally, the best time in Atlanta to enjoy watching *Photinus pyralis* is on warm nights with low precipitation around 20 to 5 minutes before sunset during the second half of June based on one season of data. This is in line with literature by Faust, 2017, who uses modified degree days to predict peak abundance. Developed from twenty-four years of observations, Faust provides estimated peak numbers for *Lampyridae* species derived from modified degree days (mGDD). For *Photinus pyralis* Faust calculates mGDD 1700 as about the peak. In Atlanta Georgia, mGDD 1700 calculation according to Faust's method fell on June 16th, 2021, and we observed a peak abundance of our data near this window, with the highest peak on June 25th.

For remote data, it is challenging to make useful inferences from the radiance value. While plots of the radiance revealed an almost negative linear trend, the units in which Luojia 1-01 provides data is converted into radiance. Radiance is a radiometric measurement of radiation energy measured on the electromagnetic spectrum received by the satellite sensor at a specific angle and is generally described as "brightness." However, brightness measured in radiance units is not readily convertible into familiar photometric units, which measure visible light perceived by the human sensor (eyeball). Therefore, we are unable to translate these measurements into familiar lighting terms such as "lumens" or "lux". Additionally, as the radiant light travels great distances between emitter (reflected or emitted light source) and receiver (satellite sensor) much light is diminished and scattered along the way, and if anything, the radiance measurement is understated.

Another limitation of Luojia 1-01 data is its reduced ability to detect light-emitting diode (LED) wavelengths. Luojia 1-01 best detects wavelengths of light at 460 nm and 980 nm. In (Owens & Lewis, 2021a), cool white LED had a peak wavelength: 453.2 nm and blue LED had a peak wavelength of 455.31 nm. While both LED sources still emit light at longer wavelengths detectable by Luojia 1-01, cool blue LED lights are under detected. Even still with these limitations a negative correlation is observed, which is highly concerning as the true effect is likely greater.

There are continued hindrances of using the Normalized Differences in Vegetation Index (NDVI) derived from NAIP imagery in our data. NAIP imagery was chosen for its ability to measure the landscape at an impressively fine scale (<1 meter) and can detect even small amounts of vegetation (individual newly planted small trees and strips of grass between the sidewalk and street) at a scale suitable to accurately analyze an individual residential property (parcel level). Yet, each pixel has a value that relates to how green the property is, a function of the visible red and near-infrared wavelengths. I reclassified the data so that any value lower than lawn was 0 but as more robust and healthier vegetation reflects more near-infrared wavelengths, healthy trees and large-leaved plants have higher values than short grass (lawn) and unhealthy plants (dying trees) as they reflect less near-infrared. I calculated a sum of all the pixel values within a 30-meter buffer (representing the parcel). From this I cannot distinguish between plant types and vegetation coverage since a fewer number of green pixels with higher values (i.e., smaller area of trees) and a larger number of green pixels with lower values (i.e., lawn) might add up to similar numbers. Overall, the plot has a positively skewed trend which can be generally translated to more vegetation and less impervious surfaces and better for *P. pyralis* populations with some presence of healthy trees likely being important.

Due to the fine-scale nature of the NDVI imagery, it grows less useful as we scale up to a 300-meter buffer. The NDVI value only presents a sum and reveals nothing about the landscape structure such as patch size, fragmentation, and connectivity. Given this mismatch in scale, other landscape metrics would be more effective at evaluating landscape structure at scales beyond the parcel-level. However, we can infer that while big dipper populations do positively respond to the amount of available greenspace on an individual property, as the landscape extent is expanded, landscape composition likely matters more than the indiscriminate cumulative amount of available green habitat. Using different methods, Picchi et al. (2013) found that landscape structure influenced L. italica abundance at the 250-meter extent by observing a negative correlation between abundance and the proportion of urban land and available vegetated land cover. This supports our theory that an examination of landscape structure might be better suited than a cumulative value of uncritical green pixels and why our data revealed no significant relationship at this scale.

My data also showed significant positive correlations for park sites, with high firefly abundance found in parks. Parks might be autocorrelated with suitable habitat such as wet meadows or more connected to suitable habitat, another indication that evaluating landscape structure with different landscape metrics would be of interest for fireflies. However, we can state that parks are important locations in Atlanta for fireflies, and to some degree, could potentially act as sources for surrounding areas. To examine this further, future research could examine if distance to parks is a significant predictor of firefly abundance.

Lastly, all three of the higher flashing species *Photinus australis*, *Photuris hebes*, and *Photuris frontalis* were positively correlated. The inclusion of these variables was to control for higher flashing species to prevent the artificial inflating of abundance and positive correlation was expected. It would be concerning if this were not observed as all these species have at least double the flash rate of *Photinus pyralis*, our focal species. I take this as further evidence of the community scientists' ability to correctly identify species when provided training and references such as a flash chart and I encourage further research to approach well-designed community science data with confidence.

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CHAPTER 4

CONSERVATION CONCLUSIONS

Summary

Here I outline three conservation approaches. Presented first are recommendations for the future of firefly community science projects in the United States; second, strategies for municipal governments to utilize in the protection of urban *Lampyridae* populations; third, best management practices for residential landscapes in the support of *P. pyralis* populations.

Firefly Community Science

Recent *Lampyridae* conservation literature calls for at least three main aims for community science: 1) address data gaps in firefly knowledge through documenting species distributions and population trends, 2) assist with locating threatened or data deficient species, and 3) public education and awareness about firefly biology, ecology, and conservation (C. E. Fallon et al., 2021), (Lewis et al., 2021). I provide each of these aims with strategic goals below.

Address data gaps in firefly knowledge

For *Lampyridae*, Fallon et al., (2021) makes clear the shortage of survey efforts and population monitoring and cites the lack of standardized methodology as partly the cause. Fallon et al., (2021) also makes the case that success in documenting species distributions and population trends may hinge on the integration of community science across wide geographic areas. The case for standardized *Lampyridae* community science methods is echoed more broadly by Gardiner & Roy, (2022) who call for taxa-specific community science methods to gather population data and benefit entomological conservation globally.

Lampyridae community science is well-suited to a systemized approach through contributory and collaborative community-science methods with at least 3 currently operating projects (Atlanta Firefly Project, Firefly Watch, and Western Firefly Project) in addition to various projects on iNaturalist. Each project utilizes varied methods to train community scientists, collect data, and measure firefly abundance while iNaturalist is fairly limited to the collection of occupancy data alone. Once again, due to the lack of methods and varied approaches, combining each of these data sets into a population analysis would prove challenging for researchers.

For example, all three projects collect a relative measurement of abundance by using flash counts for adult bioluminescent species but employing variations on similar methods: the Atlanta Firefly Project asks participants to count all flashes seen across a 1-minute period and repeated 3 times; Firefly Watch asks for all flashes seen within a 10 second period and repeated 3 times; and lastly Western Firefly Project asks for 1 count of all flashes seen across 10 seconds. Similarly, Atlanta Firefly Project and Firefly Watch aim to understand more about the species observed through flash descriptions but once again with different methods: Atlanta Firefly Project asks for specific flash descriptions and referencing a flash chart key and while Firefly Watch asks participants for the number of different flashes seen. Once again, training methods between projects have varied approaches: Atlanta Firefly Project trained some park monitoring volunteers in-person, but primarily used a 30-minute training video in addition to detailed written instructions on the data collection form while Firefly Watch uses a 2-hour training video in addition to more-detailed digital training through what is called “Firefly Watch Pro.”

Aside from these differences in data collection, there are many conservation concerns for *Lampyridae* including habitat loss and habitat degradation, especially artificial light at night and pesticide use. All three projects use different informal approaches to educating participants about these issues. Establishment of a strong, baseline message for science communication would promote the political agenda of *Lampyridae* conservation.

I propose the development of toolkit of standardized *Lampyridae*-specific methods for 1) collection of location, time, and date, 2) collection of abundance data, 3) collection of species identification, 4) training participants on data collection and 5) public education curriculum concerning *Lampyridae* conservation. Standard methods can be incorporated into existing projects and allow for researchers nationally (or globally) to combine, compare, and analyze datasets more readily. Not only would these further outcomes for scientists and produce new research, but the guiding conservation curriculum would also help organize and direct public conservation policy support. Projects can incorporate unique research elements informed by local experts that address local issues (e.g., land management data collected for the Atlanta Firefly Project or the wet meadow habitat monitoring for the Western Firefly Project) but standard methods to collect location and time, abundance data, species data, train volunteers, and communicate conservation concerns, would not limit project scope but rather improve upon it. Under this consistent approach, combining multiple sets of data across a broad spatial and time scale becomes less burdensome to researchers.

A potential coordinator at the National level for the toolkit initiative is the Xerces Society, which, at time of writing, is in development of a national firefly initiative called the Firefly Atlas launching in May 2022. The initiative has a nationwide scope, beginning with three priority regions of the Mid-Atlantic, the Southeast, and the Southwest with goals to "educate and engage researchers, land managers, and community scientists in filling data gaps that can then help inform firefly conservation efforts" (www.xerces.org/endangered-species/firefly-atlas). The

Firefly Atlas has established expert working groups in each of these three regions. Utilizing this network of knowledge and by collaborating with existing community science projects, it is possible to develop a co-created toolkit. Methods promoted in the toolkit can be adopted by existing projects and distributed to community partners and universities who can establish and facilitate new projects locally.

Assist with locating threatened or data deficient species

Fallon et al., (2021) identified surveying and monitoring as key conservation actions for all species classified as threatened and data deficient. While some of these species are located near urban areas, others are found in specialized habitats that are difficult to access, particularly during nocturnal fieldwork, and further troubled by the short activity window of species. While the existing *Lampyridae* community-science data collection schemes are most useful in easily accessible locations, these projects have networks which can be co-opted to recruit participants' assistance in targeted surveys for known threatened species. Training a subset of community scientists to conduct targeted surveys in tandem with experts expands the spatial area monitored during a brief temporal window and boosts nocturnal safety by allowing groups to work together in the field rather than individually.

Furthermore, as lethal collection of specimens belonging to threatened species is not recommended, equipping community scientists with tools such as simple dark-adapted time-lapse photography applications such as the NightCap iphone application (www.nightcapcamera.com/), or similar software, can help community scientists document the species observed when participating in specialized surveys. Streamlining the collection of this type of data into digital forms aids both survey organizers in managing data and researchers in the systematic analysis of data later.

One limitation of the existing community-science projects is their focus on adult flashing species. Uncovered by Fallon et al., (2021), non-flashing (diurnal) fireflies make up a large portion of the data deficiency with 68% of diurnal fireflies classified as data deficient compared to 38% of adult flashing species. These diurnal species, just like habitat-specialist adult flashing species, require targeted surveys. As previously mentioned, community science networks can be used to recruit participants in assisting experts in these efforts. However, as community scientists may be less culturally connected to non-flashing species, it may be challenging to successfully recruit community scientists for non-flashing species only. When possible, combining survey events to monitor for both flashing and non-flashing species may prove more successful in recruiting community scientists on targeted surveying.

Public education and awareness

The benefits of establishing coordinated conservation curriculum for community-science projects is noted in the section Address data gaps in firefly knowledge where a baseline agenda of conservation curriculum would be included in the community science toolkit. Yet this conservation curriculum should not be limited to the toolkit in application. For example, this strategic conservation curriculum would be particularly useful when distributed to all known *Lampyridae* tourism sites.

Lewis et al., (2021), estimated that from at least twelve countries, over one million tourists traveled annually for firefly-watching in recent years. In the United States alone, significant events are documented in: Tennessee, South Carolina, and Pennsylvania with an upward estimate of 40,000 visitors combined (Lewis et al., 2021)and this does not include several new, small-scale firefly tourism sites or future sites. I propose two outreach efforts for *Lampyridae* tourism sites 1) distributing the conservation curriculum toolkit so that firefly tourism sites are equipped to educate the public on the major firefly conservation agenda and 2) distribute a community-science project contact sheet informing tourists of potential firefly monitoring efforts in their home locations. Lewis et al., (2021) proposed the development of training programs for tourism site guides in addition to educational materials for visitors and referenced the existing materials such as Conserving the Jewels of the Night (Fallon et al., 2019). The availability of existing conservation materials aimed at the public is encouraging and makes the task of compiling a toolkit for community science projects and tourism sites easier.

Municipal Strategies for Firefly Conservation

Municipalities can implement several practices to support existing firefly populations. I have divided these actions into 1) immediately actionable and 2) long-term goals.

2.1 Immediately Actionable

Park Management

Many of the city parks in the Atlanta Firefly Project data are managed as low impact parks, a compatible management approach for healthy firefly populations, yet the most concerning practice for fireflies is the use of artificial light at night at a frequency of all night long. 40% of the park samples were using artificial light at night, somewhere in the park, all night long with an additional 67% of parks experiencing adjacent light sources. Some parks are heavily used, highly urban, and have paved trails used as public transit corridors by the public. In these cases, artificial light at night is needed for safety, yet many of the parks close after dark yet lighting infrastructure at parking areas remain on all night and are often aged lighting systems with unshielded light fixtures that scatter light in all directions, which results in a greater negative impact of artificial light at night.

Mosquito spraying is rarely employed as routine park management (only in one park) and continuing with little to no-use of mosquito-spraying insecticides is beneficial for the existing firefly populations as we observed a significant negative correlation. The management of leaves in parks typically follows a leave-in-place model or a mowed over model and we recommend continuing with these practices to minimize removing leaves from parks and we encourage the planting of native trees in parks with low canopy cover. Fertilizers (11%) and insecticides (10%) were not frequently applied in parks yet long-term use of these chemicals (specifically fertilizers) is harmful to firefly abundance and we recommend limiting their use to only when necessary. Mosquito spraying is rarely employed as routine park management (only in one park) and little to no-use of mosquito-spraying insecticides is beneficial for the existing firefly abundance as we found a significant negative correlation.

The use of mowing (>50%) and herbicides (46%) were frequently employed in parks yet mowing had little effect on *P. pyralis* abundance and the use of herbicides did not have a negative correlation with *P. pyralis* abundance, therefore no change in management is suggested. Uncommonly used in parks was irrigation (5%) and fungicides (4%), fungicides had little effect on *P. pyralis* populations and while irrigation was negatively correlated, the relationship is unclear and no changes in management are suggested. Recommended applications of these results are summarized in this following set of actionable park management items.

1. Complete a lighting audit at city parks following standards set forth by the International Dark Sky Association (www.idsw.darksky.org/activities/dark-sky-friendly-home/)
    a. Confirm the lights serve a clear and necessary purpose
    b. Confirm the light falls only where needed

c. Confirm the intensity of light is appropriate for intended purpose

d. Confirm the light is connected to a control

e. Reduce the frequency of light to the lowest necessary use (preferably avoid using it all night long)

f. There is no universal “nature-friendly” light color yet discovered. Different color wavelengths have varying effects between firefly species and even within species, male and females respond differently (Owens & Lewis, 2021). Keeping this in mind, generally, there are two best practices for *Lampyridae* concerning light color

    i. Avoid warm white light

    ii. Choose the dimmest possible red light

2. Establish a set of best land management practices for parklands. These best land management practices should be co-created with the park operations and maintenance staff and, at minimum, clearly document artificial light at night practices, leaf litter practices, protection of existing trees, use of insecticides, and use of fertilizers. Ideally, this documentation will also explain the connection between these managements and firefly abundance. This documentation will work to limit uncoordinated and indiscriminate uses of these managements in the future.

Promote bottom-up land management

Several well-established third-party programs encourage residential land managers to practice low-impact management through certified yard habitat programs. For example, a few major existing programs active in the Atlanta area include Native Plant Habitat Certification via the Georgia Native Plant Society (www.gnps.org/conservation/native-plant-habitat-certification-2/), Monarch Waystation via Monarch Watch (www.monarchwatch.org/waystations/), Certified Wildlife Habitat via the National Wildlife Federation (www.nwf.org/CERTIFY), and a Certified Wildlife Sanctuary with Georgia Audubon (www.georgiaaudubon.org/wildlife-sanctuary-program.html). An upcoming local program is City Forest Certified facilitated by Trees Atlanta, notably for the development of a specific firefly-stewardship track.

Municipalities can work to support these bottom-up initiatives by providing these programs with funding and promotional support. Funding would help these programs expand and offer communities services and technical assistance and promotional support would encourage program awareness by exposing more municipal residents to information about these programs. Promotion support might include education and outreach events in addition to digital promotions. While each of these programs have specific focuses separate from fireflies, many of these programs encourage practices that might benefit local firefly populations, according to research. The following ordered list of programs are what I hypothesize would be the most effective program for provisioning suitable habitat for local fireflies.

- City Forest Certified Firefly Stewardship Track via Trees Atlanta which requires participants to get involved with firefly community science, limits the amount of impervious surface, requires no fertilizer use, caring for existing trees, leaving the leaves, requires no mosquito spraying, and reduces outdoor light use.
- Certified Wildlife Sanctuary via Georgia Audubon which requires a minimum garden size, demands little to no pesticide use (insecticide, herbicide, and fungicide), and places limits on leaf blowing. Additionally, it is the only other certification that asks for minimal outdoor lighting use.

- Native Plant Habitat Certification via the Georgia Native Plant Society requires the user to choose 4 out of 8 sustainable landscape practices including: Avoiding using herbicides and pesticides and allowing leaves to remain.
- Certified Wildlife Habitat via the National Wildlife Federation encourages applicants to eliminate chemical pesticides and fertilizers
- Monarch Waystation via Monarch Watch asks certified locations to have a sustaining plan for the garden including eliminating insecticide use yet it does encourage irrigating and fertilizing, two practices we would not attempt to encourage.

2.2 Long-Term Goals

Park Surveys

Park lands near urban areas that are also located within ranges of threatened or endangered species or species of concern should be priority areas to survey. If threatened species are discovered in those locations, given their proximity to urbanization drive threats, it would require the need for a species-specific park management plan co-developed between experts and municipalities.

Policy

Municipal Lighting Plan

Municipalities control much of the artificial light at night through city facilities and public streets. While artificial light at night is necessary for human safety and mobility, the municipal lighting plan should be reviewed and updated to ensure it is minimizing the ecological harm from use of artificial light. This includes reducing unneeded lights, employing the lowest level of light needed, and shielding lights to prevent light leak and trespass.

Conservation Commission

Conservation commissions are sometimes used by municipalities to protect a significant resource. Made up of citizens, often appointed by the government (Mayor or City Council) their duty is to assist the city in the protection and management of natural systems. For example, in Atlanta, the Tree Conservation Commission is made up of 15 members who have specialized knowledge of trees, and they oversee the city tree protection, including appeals for tree removal. Conservation commissions can be used to help assist with projects such as updating lighting plans, conducting education and outreach events, promoting residential land certification programs and community science projects, and coordinating with experts to conduct park firefly surveys.

Firefly Best Management Practices for Residential Landscapes

These best management practices were developed from analyzing and interpreting data gathered by the Atlanta Firefly Project in 2021. These management practices are presented as effective managements for local big dipper firefly populations based on previous research, *Lampyridae* biology, and the positive correlations between big dipper firefly abundance and these land managements.

- Reduce the frequency of outdoor lights, do not keep them on all night
- Use the least intense (dimmest) possible light needed and shield the light source so that the light rays only fall where you need it.
- To the extent possible, reduce adjacent light. This might include protecting and caring for trees that can act as a buffer between habitat and light source.
- All colors of light impact fireflies but the dimmest possible red light is the least harmful for some species of fireflies. It is best to reduce the frequency of light

use, reduce the intensity of your light source, and shield your light first before considering changing the bulb color.

- Avoid mosquito spraying, especially across multiple years
- Leave some of the leaves on the land and if you have no leaves, plant trees
- The greater area of vegetation you can provide the better, especially made up of healthy green plants like tall grasses, shrubs, and trees.
- Avoid using fertilizers in lawns, natural areas, and landscaping with particular emphasis on using fertilizer less frequently, less extensively, and not every year.
- Take caution when using other insecticides, especially on lawns, natural areas, and landscaping over a period of multiple years.
- Contribute to *Lampyridae* community science near you

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APPENDIX A

COMMUNITY SCIENCE GUIDING STEPS

GUIDING STEPS	EVALUATION CRITERIA	ANALYTICAL QUESTIONS
Step 1: Identify Desired Outcomes, Participants, and Approach	Desired Outcomes	Are there outcomes for science?
		Are there outcomes for participants?
		Are there outcomes for social-ecological systems?
	Participants	Who are the participants?
	Approach	Which community-science approaches are applicable for achieving the outcomes?
Step 2: Establish Research Question	Scale	Can the research question be answered with data provided by the participants?
		What sort of spatial and time scales does it require participants to operate under?
		Is this true for a reasonable portion of participants?

		Does this place limits on the participants?
	Relevance	What does this project benefit?
		Who is it significant for?
		Why does that matter?
		What connection do participants have to this research?
	Participant Investment	How much participant time might this take?
		Do participants receive anything?
		Is the activity unpleasant or uncomfortable?
		Are there risks for participants?
		Is specialized skill, knowledge, or resources needed?
	Clarity	Are words and terms understandable to those without subject matter expertise?
		Is the language inclusive of the participants?
		Do participants speak multiple languages?
Step 3: Project Design	Data Needs	What variables are specifically needed from the participants?

		Is it quantitative or qualitative?
		Can the data needs be easily listed?
	Format Compatibility	How does the data look when received from participants?
		What kind of work will it take to prepare the data for analysis?
		If applicable, how might this data be validated?
	Collection Methods	What is the list of possible methods participants can use to submit the needed data?
		Are these methods compatible with the required analysis format?
		Do the project facilitators and participants have (or will have) access to these methods?
	Simplicity	Do participants need special skills for this?
		Can participants be trained on this method?
		Are there opportunities for miscommunication?

		Are there tedious steps for participants?
		Where might participants be frustrated or bored?
Step 4: Training	Effective	Which methods can be used for training?
		Will these methods communicate the research question?
		Will these methods teach participants to collect all the needed data?
		If applicable, will these methods teach the participants any specialized skills necessary?
		Will these methods be consistent?
		Are multiple training methods required?
	Accessible	Is this training method compatible with most of the participants?
		Will the audience need access to training during data collection?
		Is training available as a reference?
		Are training opportunities limited (by time, location, or other)?

	Timeline	Is there time to both develop the training materials and promote the training before data needs to be collected?
		Is there time for most of the participants to complete the training prior to data collection?
	Feasibility	Does the research project have (or can gain access to) the needed equipment, funding, space, and training facilitators?
		Is there additional support to rely on should it be required?
Step 5: Recruitment	Incentivization	Why is participation in this project interesting (cultural incentive)?
		How can participants receive recognition or be thanked (cultural incentive)?
		Do participants receive any products or compensation from this project (physical incentive)?
		Do participants obtain new knowledge or skills because of this project (cultural incentive)?

	Promotion	How will the promotion explain project goals and objectives?
		What is the project's call for action (who is needed, where, and when)?
		How can the incentives be communicated?
	Active Recruitment	What are the governing parties (Neighborhood Planning Units, Neighborhood Associations, Homeowners Associations, Schools, Park Conservancies, etc.) acting in the study scale?
		What are the social elements (Non-profits, churches, gardening clubs, beautification groups, sports clubs, local businesses, events, etc.) present at the study scale?
		What are the press sources (Non-profits, churches, gardening clubs, beautification groups, sports clubs, local businesses, events, etc.) relevant to the study scale?
		How can the project promotion be distributed to these networks?

Step 6: Monitoring	Tracking	What are the most important parts of the data?
		What are the most difficult components of the data?
		How can the data be checked in real-time?
		How can expected errors be quickly identified?
	Two-Way Communication	How can the project communicate with participants directly and quickly?
		How can participants find answers to questions?
		How can participants leave feedback?
		Can participants share their activities?
		How should project updates be communicated?
Step 7: Evaluation	Collection System	Did project feedback include grievances or errors with the collection system?
		Did participants use the communication system to ask questions about the data collection system?

		How much data was collected?
		Was the collection system burdensome to the researcher?
	Training	Was the training well attended or well used?
		Did project feedback include grievances or confusion at training?
		Did participants use the communication system to ask questions about instructions?
		How much data was collected?
		Was the data accurate?
		Was the data complete?
		Was the data received in expected quantities?
	Recruitment	How many participants were there?
		Are there returning participants?
		How much data was collected?
		Where were participants recruited?
		What communication networks (government, social, press) engaged with the promotion?

		Did participants use the incentives?
	Monitoring	Were errors discovered during active data collection?
		Were errors discovered after active data collection?
		Were the communication pathways used?
		Were new methods or novel observations encountered?
Step 8: Communicate Results	Recognition	Are there any contributors who should be included as an author?
		Can participants be reasonably thanked by name?
		Is it clearly documented (in manuscripts, papers, or other documentation) how the participants contributed to the project?
		How were participants thanked?
		Was there anything the participants asked for that was not provided?
	Access	How will the participants access the results?

		Will the participants have access to the original data or materials?
		Will results be communicated specifically to the participants in some format?

APPENDIX B

COMMUNITY SCIENCE GUIDING STEPS

Required Data

1. Date
2. Time of observation (eastern daylight time)
3. Answered yes or no to the question “Did you watch the training video for how to submit information?
4. If fireflies were observed or not
5. Geographical location, recorded as latitude and longitude
6. Address number and street name
7. If fireflies were seen flying in the air
8. A description of the flash color and pattern seen flying in the air (with a provided flash chart as a reference guide)
9. If flashes were seen coming from the ground
10. If flashes were seen up in the trees
11. Facing in one direction without moving, a count of all flashes seen in a normal field of vision within 1 minute, repeated three times.
12. Direction faced when observing fireflies

Optional Data

1. Photographs of fireflies

2. Memories from the project
3. Land Management Questionnaire
    a. Is the property mowed? (Yes/No)
        i. How much is mowed? (0-25%, 25-50%, 50-75%, 75-100%)
        ii. How frequently is it mowed? (Weekly, every other week, once a month, every other month, 1-4 times a year)
        iii. How long have the mowing practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)
    b. Is the property irrigated? (Yes/No)
        i. How frequently irrigated? (Daily, Weekly, Every Other Week, Monthly, Seasonally)
        ii. What is irrigated? (Lawn, vegetable garden, Landscape plants, natural areas, only specific plants, other)
        iii. How is the property irrigated? (Sprinklers, drip, by hand, other)
        iv. How long have the irrigation practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)
    c. Is mosquito control used on this property? (any type of control) (Yes/No)
        i. Does this property have a mosquito service? (Yes/No)
        ii. Which service?
        iii. Are mosquitos controlled with products other than a mosquito service? (Yes/No)
        iv. Which products?

v. Do you use other mosquito control methods other than apply bug spray on yourself/clothes? (Treat standing water, use mosquito traps, mosquito barriers, other).

vi. What on this property is treated for mosquitoes? (Vegetable gardens, landscape plants, lawn, natural areas, standing water, other)

vii. How frequently is this property treated for mosquitoes? (weekly, monthly, once a season, once a year, not every year)

viii. How long have the mosquito practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

d. On this property, are insecticides (other than for mosquitoes) used? (Yes/No)

i. Please list which insecticides

ii. What are the insecticides used on? (Vegetable gardens, landscape plants, lawn, natural areas, spot treat specific plants, other)

iii. How frequently are insecticides used? (Weekly, monthly, once a season, once a year, not every year)

iv. How long have the insecticide practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

e. Are herbicides used on this property? (Yes/No)

i. Please list which herbicides

ii. What are the herbicides used on? (Vegetable gardens, landscape plants, lawn, natural areas, spot treat specific plants, other)

iii. How frequently are herbicides used? (Weekly, monthly, once a season, once a year, not every year)

iv. How long have the herbicide practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

f. Are fungicides used on this property? (Yes/No)

i. Please list which fungicides

ii. What are the fungicides used on? (Vegetable gardens, landscape plants, lawn, natural areas, spot treat specific plants, other)

iii. How frequently are fungicides used? (Weekly, monthly, once a season, once a year, not every year)

iv. How long have the fungicide practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

g. Is there a landscape service for this property? (Yes/No)

i. Please list which landscape service and briefly describe services provided

ii. How long has the landscape service been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

h. Are fertilizers used on this property? (Yes/No)

i. Please list which fertilizers

ii. What are the fertilizer used on? (Vegetable gardens, landscape plants, lawn, natural areas, spot treat specific plants, other)

iii. How frequently are fertilizers used? (Weekly, monthly, once a season, once a year, not every year)

iv. How long have the fertilizer practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

i. Does this property have leaf litter? (Yes/No)

i. How is the leaf litter managed? (Removed, partially removed, relocated, remains in place, other).

ii. How long have the leaf litter practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

j. Is there outdoor lighting at this property? (Yes/No)

i. What kind of outdoor lights? (String lights, holiday lights, house/porch lights, garden/path lights, decorative lighting, floodlights or security lights, other)

ii. What kind of bulbs are used in the lighting?

iii. How frequently are the outdoor lights in use? (On all night, turn off when going to sleep, motion activated, timer operated, only when in use)

iv. How long have the lighting practices been utilized? (<1 year, 1-3 years, 3-5 years, 5-10 years, 10-15 years, >15 years)

k. What would you be willing to change, if anything, about this property if you know it would help fireflies? (Remove lights, reduce frequency of light use, change the type of light bulb, change light color, keep leaf litter on your property, plant trees or add leaf litter or reduce light, mow less, mow more, change the type of vegetation, water more, water less, use less fertilizer, stop fertilizer, reduce lawn size, reduce mosquito treatment, stop mosquito treatment, reduce another insecticide/fungicide/herbicide, stop another insecticide/fungicide/herbicide, reduce paved surfaces)

l. Have you lived in the same location for at least 5 years or more and are willing to talk to us about the change (increase or decrease) in the amount of fireflies you have seen over time? (Yes/No)

   i. How long have you lived in your location? (5-9 years, 10-19 years, 20-29 years, 30-39 years, >40 years)
   ii. Email address
   iii. Phone number
   iv. Briefly describe what sort of changes have you seen over time?

APPENDIX C

ATLANTA FIREFLY PROJECT PRESS RELEASE

Hello [enter name],

I am reaching out from the Odum School of Ecology. I am a graduate student [title/program] and [enter connection to location/place] I am reaching out to [enter NPU, School, Neighborhood organization, non-profit] to seek your help! The Atlanta Firefly Project, the first of its kind, has put out a call for volunteers to participate in a community science opportunity in Atlanta this summer!

The project is the Atlanta Firefly Project, a community science initiative that assists researchers in studying firefly conservation in Atlanta. I think this might be of interest to [enter residents, community members, etc] in [enter place]. Please feel free to forward this to any appropriate parties, but I would be grateful if you can help share this volunteer opportunity on your networks such as social channels, forward the email to your staff, add to it your newsletter, and/or share it with friends, family, and neighbors. Also following @Atlantafireflyproject on Instagram is helpful! Any word that can be spread about this project will greatly contribute to its success. Below is a description of the project and included at the bottom of the email is some social copy drafted, along with a photo for your use, in case that's helpful. Let me know if you need any more information from me!

Project Description:

This project is part of the data collection initiative at the Odum School of Ecology and anyone can help, right from their own home. Whether at an apartment, townhome, detached home, or wherever you call home, everyone's observations are valuable! **If you do not see any fireflies, the information is just as valuable to us as if you do see fireflies**. Firefly species worldwide face threats such as habitat loss, artificial light at night, pesticide application, overcollection, water pollution, and climate change. This project's data will help us understand the threat of habitat loss, artificial light at night, and land management practices on our common Eastern Firefly known as the Big Dipper (Photinus pyralis).

By getting involved in this project, your observations will directly influence firefly conservation research and you will have the option to attend a follow-up with a talk where we will present you the outcome of the work. Our goal is to provide individuals with the information needed to make informed decisions about the land we live on. This is a unique project with the hopes that many will contribute!

Head to atlantafireflyproject.org for more information about this project and to access the training information and data submission form. Now you can also monitor a park near you! To monitor a park please email us at info@atlantafireflyproject.org with the park name and we will send you further instructions!

Instagram:

Would you like to get involved in firefly conservation? Check out the Atlanta Firefly Project for community science opportunities in Atlanta this summer! The project is looking for as many volunteers as possible to sign up to monitor your yard, whether apartment, townhome, single-family or wherever you live, your observations are valuable! Don't have fireflies at home? That is OK, they still need your help! They need all types of properties monitored so they can understand where fireflies are located in Atlanta, how many fireflies Atlanta has, and what threats they are facing. Check out atlantafireflyproject.org for the training information and follow them on Instagram at @atlantafireflyproject! You can even help monitor a park near you. If you are interested in park monitoring, email them the park name at info@atlantafireflyproject.org for further instructions!

Or

[Your organization/You] are so excited about more community science opportunities benefiting Atlantans and our environment. Check out our friends at the Atlanta Firefly Project for community science opportunities in Atlanta this summer! The project is looking for as many volunteers as possible to sign up to monitor your yard, whether apartment, townhome, single-family or wherever you live, your observations are valuable! Don't have fireflies at home? That is OK, they still need your help! They need all types of properties monitored so they can understand where fireflies are located in Atlanta, how many fireflies Atlanta has, and what threats they are facing. Check out atlantafireflyproject.org for the training information and follow them on Instagram at @atlantafirefly project! You can even help monitor a park near you. If you are interested in park monitoring, email them the park name at info@atlantafireflyproject.org for further instructions!

Twitter:

Check out the Atlanta Firefly Project for community science opportunities in Atlanta this summer! The project is looking for volunteers to sign up to help monitor fireflies in Atlanta. Find them at atlantafireflyproject.org or @atlantafireflyproject on Instagram.

Facebook:

Maybe you have noticed a decline in the firefly populations throughout your life, or maybe you remember catching them when you were young, or perhaps you have fireflies at home and want to keep them around, or maybe you have never seen fireflies before and are interested in learning more! Whatever your reason, check out the Atlanta Firefly Project for community science opportunities in Atlanta this summer! The project is looking for as many volunteers as possible to sign up to monitor your yard, whether apartment, townhome, single-family or wherever you live, your observations are valuable! Don't have fireflies at home? That is OK, they still need your help! They need all types of properties monitored so they can understand where fireflies are located in Atlanta, how many fireflies Atlanta has, and what threats they are facing. Check out atlantafireflyproject.org for the training information and follow them on Instagram at @atlantafireflyproject.org! You can even help monitor a park near you. If you are interested in park monitoring, email them the park name at info@atlantafireflyproject.org for further instructions!

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[Your organization/You] are so excited about more community science opportunities benefiting Atlantans and our environment. Check out our friends at the Atlanta Firefly Project for community science opportunities in Atlanta this summer! The project is looking for as many volunteers as possible to sign up to monitor your yard, whether apartment, townhome, single-family or wherever you live, your observations are valuable! Don't have fireflies at home? That is OK, they still need your help! They need all types of properties monitored so they can understand where fireflies are located in Atlanta, how many fireflies Atlanta has, and what threats they are facing. Check out atlantafireflyproject.org for the training information and follow them on Instagram at @atlantafireflyproject.org! You can even help monitor a park near you. If you are interested in park monitoring, email them the park name at info@atlantafireflyproject.org for further instructions!

Thank you!

APPENDIX D

LITERATURE REFERENE MATRIX

	Biology	Field Experiments	Lab Experiments
Vegetation	1, 2, 3, 4, 27, 30, 33, 34, 35, 36, 38	0	0
Irrigation	1, 2, 3, 27, 28, 29, 31, 38, 40	0	0
Artificial Light at Night	24, 25, 26, 28, 29, 33, 37, 41, 42	7, 8, 9, 10, 15, 16, 17	11, 12, 13, 14
Mowing	1, 27, 35, 36, 38	0	0
Insecticides	2, 3, 27, 28, 39, 40	21	18,19, 20, 22
Herbicides	27, 28, 38	0	0
Fungicides	5, 27	0	0
Fertilizer	27, 28, 29, 39	0	20
Leaf Loss	1, 3, 5, 16, 27, 29, 31, 32, 36	0	0

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