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ASSESSMENT OF SPATIAL DISTRIBUTION PATTERNS AND INFESTATION RISK OVER TIME OF SPOTTED LANTERNFLY (LYCORMA DELICATULA) IN NEW YORK STATE

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ASSESSMENT OF SPATIAL DISTRIBUTION PATTERNS AND INFESTATION RISK OVER TIME OF SPOTTED LANTERNFLY (*LYCORMA DELICATULA*) IN NEW YORK STATE

By

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Abstract

Spotted Lanternfly (*Lycorma delicatula*) is an invasive treehopper native to Asia. It was first introduced to Pennsylvania in 2014, and as of 2020 it has expanded to New York state. Their preferred host tree is the invasive tree of heaven (*Ailanthus altissima*), but they will feed on over 173 different plants worldwide. Preferred host species in New York state include agricultural vegetation such as grape vines and fruit trees. Positive Spotted Lanternfly site data collected by the New York Department of Agriculture and Markets and iMapInvasives were analyzed using ArcGIS Pro to assess spatial distribution patterns. Spotted Lanternfly egg masses can be unknowingly spread via transportation pathways such as highways and railroads. Using a multi-scale geographically weighted regression, proximity to these pathways and tree of heaven presence were shown to be significant factors in the location of spotted lanternfly sightings in New York state. Additionally, infestation risk was geographically categorized based on proximity to these transportation pathways and agricultural regions.

Acknowledgements

I would like to thank the members of my thesis committee for their guidance: Jeff Zappieri M.S., Adjunct Faculty, University of Albany Department of Geography and Planning, Dr. Rui Li, Interim Chair, Associate Professor and Program Director, University of Albany Department of Geography and Planning, and Michael Sarnowski, Horticultural Inspector 2, New York State Department of Agriculture and Markets. Additionally, I would like to thank the New York State Department of Agriculture and Markets for providing me with data for this project.

List of Abbreviations

SLF - spotted lanternfly

TOH - tree of heaven

NYS - New York state

SBA - Significant Biodiversity Area

NYSDAM - New York State Department of Agriculture and Markets

NYSDEC - New York State Department of Environmental Conservation

New York City - NYC

Geographically Weighted Regression - GWR

Multi-scale Geographically Weighted Regression - MGWR

Introduction

Global introductions of non-native species have doubled in the past 50 years, causing both ecological and economic concerns (IPBES, 2019). A non-native species is a species that has been introduced, either intentionally or accidentally, outside of its natural geographic range. A non-native species is considered an invasive species when it causes, or has the potential to cause, ecological problems, economic problems, and/or human health concerns. This has cost North America an estimated $1.26 trillion between 1960 and 2017. After controlling for research effort within each country, the United States had the highest recorded cost of $5.81 billion (Crystal-Ornelas et al., 2021). Spotted lanternfly (SLF), a 2014 introduction to the United States from Asia, is an emerging invasive insect that can highly consume important crops such as grapes and fruit trees, as well as native hardwood trees (Ladin et al., 2023).

The majority of SLF studies have been conducted in Pennsylvania, due their initial introduction in 2014 in Berks County. Since this initial introduction SLF has spread to 14 states, entering New York State (NYS) in 2020. Little is known about SLF distribution and biology in NYS so there is a strong need to better understand their establishment and spread in this state. NYS hosts a variety of ecologically diverse and critical habitats. There are a total of thirteen unique ecoregions within NYS, as well as many designated Critical Environmental Areas designated by a local or state agency (DEC, 2023). Additionally, NYS contains 30,650 farms and 6,502,286 acres of production, employing 56,678 people (New York Farm Bureau, 2022). The presence of SLF and possibility of further spread throughout NYS puts both the ecological and agricultural health throughout the state at risk.

This assessment aims to assist NYS government agencies, land managers, and agricultural professionals in better understanding the distribution and spread patterns of SLF throughout the state. Using geographic information systems to analyze data from the NYS Department of Agriculture and Markets (NYSDAM) and iMapInvasives, this assessment will provide general information on the spatial trends over the past few years as well as provide categories of infestation risk across the state.

Background

Invasive Species

Invasive species are one of the highest contributing factors toward global biodiversity loss. A non-native species is only considered an invasive species when it causes, or has the potential to cause, ecological problems, economic problems, and/or human health concerns. The distinction between non-native species and invasive species is quite important. For example, domestic cows and many commonly grown fruits and vegetables are non-native to the United States but are not considered invasive since they are agriculturally beneficial and do not lead to any of the previously mentioned problems. Invasive species have increased in both quantity and threat level as human transport and trade has increased across the globe. They can impact native ecosystems through habitat alteration, resource competition, predation, herbivory, and spread of disease. Additionally, invasive plant species can even alter carbon and nitrogen cycles, as well as alter natural fire regimes. Invasives species pose the highest risk toward endemic island species, but mainland species are also strongly affected. A study looking at 215 extinct species from five major taxa (plants, amphibians, mammals, birds, and reptiles) found that invasive species are the second most common threat associated with extinction when considering the following threats: agriculture and aquaculture, climate change and severe weather, biological resource use, pollution, natural system modification, residential and commercial development, and invasive species (Bellard et al., 2016). It has been found that 11% of phylogenetic diversity worldwide is represented by invasive-threatened species. Projected extinction scenarios that incorporate invasive species suggest a global shift in species composition away from those with large body mass (Bellard et al., 2021). This mainly encompasses mammals which mostly feed in the lower foraging strata and have an herbivorous diet. The reduction of mammals and other larger organisms would greatly alter ecosystem function and services.

Invasive arthropod species are quite pervasive and pose significant threats to both ecosystem health and agricultural stability, often due to their herbivory of native plants and agriculture. Examples of well-known invasives insects in North America include the emerald ash borer (*Agrilus planipennis*), which consumes ash trees, and the Asian long-horned beetle (*Anoplophora glabripennis)*, which consumes a variety of native North American trees. Both species entered North America from their native habitats in Asia via human trade. Indirect effects of invasive insects' populations may include the human use of pesticides which then lead to environmental and water pollution (Vennette & Hutchison, 2021). Invasive insects often pose a significant threat toward human health by spreading disease. For example, the Asian tiger mosquito (*Aedes albopictus*) is an invasive insect introduced to the United States in the 1980s and carries a variety of deadly diseases including West Nile virus.

Spotted Lanternfly Life History

Lycorma delicatula (White) (Hemiptera: Fulgoridae), commonly known as spotted lanternfly (SLF), is native to China, Vietnam, and Japan, although the full extent of its native range is unknown. SLF is a phloem-feeding planthopper that is highly polyphagous (Urban & Leach, 2023). It was first introduced to the United States, specifically in Berks County, Pennsylvania, in 2014. Since 2014, it has spread to 14 states, as far west as Indiana and as far south as North Carolina (Liu et al., 2023). SLF can survive and develop at constant temperatures between 15 and 30°C and can survive 2 to 35 days at constant temperatures outside of this range (Krietman et al., 2020). SLF was first identified in NYS in 2020 on Staten Island and has since spread rapidly across New York state. The use of climatic niche models indicate that about half of the United States, specifically most of the states in New England, the Mid-Atlantic, and the Pacific Coast are at risk of SLF invasion (Wakie et al., 2020). SLF are univoltine and lay their eggs on the bark of a variety of tree species. However, they do not lay eggs exclusively on tree bark. They also lay their eggs on inorganic objects such as trains, motor vehicles, and stone (Cook et al., 2021). The eggs hatch in May-June and go through three intermediate instar stages until they become mature adults in July. SLF is unlike other phloem feeding insects in that it consumes both herbaceous and woody plants. During their first through third instar stages they are quite generalist in their feeding habits. Observations and records of actual feeding behavior show that SLF is associated with 103 plant taxa worldwide, 56 of which are North American host plants (Urban & Leach, 2023). However, during their fourth instar stage, SLF shows a preference for certain species. The preferred host tree is the North American invasive *Ailanthus altissima*, commonly known as tree of heaven (TOH), which is one of the most widespread invasive plant species in the United States. Other preferred hosts during this stage of their life cycle include grapes (*Vitis spp.*), black walnut (*Juglans nigra*), silver maple (*Acer saccharinum*), red maple (*Acer rubrum*), and willows (*Salix spp.*) (Urban & Leach, 2023). Mature females lay their eggs between September and November and can survive until temperatures become too cold, sometimes surviving into December. However, the SLF life cycle is variable because invasive insect species with broader geographic ranges are assumed to have wider thermal tolerance and variation in performance tolerances among populations (Keena et al., 2023).

Predation of SLF in the United States has been witnessed but is not common. The most common SLF predation sightings have been generalist arthropods and bird species. Reported sightings of mammals preying on SLF resulted in illness in one third of cases (Johnson et al., 2023).

Transportation Vectors

The first stage of a biological invasion involves the transportation of a species beyond its native geographical range. Increasing globalization has in turn increased the amount and frequency of organisms moving beyond their native ranges via anthropogenic dispersal methods. Once this introduction has occurred, organisms can travel via short-distance dispersal, which is caused by the natural movement of organisms, or long-distance dispersal, which is often caused by accidental human movement (Cook et al., 2021). SLF invasion is significantly associated with both short and long-distance dispersal. Adult SLF can travel between 3 and 4 miles throughout their lifetime through a mixture of walking, jumping, and flying (Cornell CALS, 2023). While they are generally poor flyers, mature SLF launch themselves into wind from trees or tall inorganic structures to facilitate in level or gradually descending flight. In one episode they can travel from 10m to 40m (Baker et al., 2019). Specifically, human-mediated dispersal (cars, trucks, and trains) is responsible for the observed long-distance spread dynamics and distribution of the SLF in any of its life cycle stages (mature insects, nymphs, and egg masses) throughout the eastern United States. Model simulations that controlled for SLF population growth rates, random vs. nonrandom movement behavior of individuals, and the amount of human-mediated dispersal events occurring per year, exhibit poor performance (33% true positive predictions). Meanwhile, when human-mediated dispersal was included within model scenarios, models increased to 92% true positive predictions in predicting the observed spread of the SLF (Ladin et al., 2023).

Ecological Concerns

Like many invasive species, SLF poses ecological concerns as they invade new geographic areas. Studies show that SLF likely co-evolved with TOH and grapevine in its native range, thus it can compete with grapevine sinks for resources which leads to whole-plant carbon limitation. However, little is known about its effects on the ecophysiology of plants in the U.S. (Lavely et al., 2022). Herbivores that feed on sap consume carbohydrates and nutrients from phloem and/or xylem tissue. This then leads to the reduction of available energy and nutrients in aboveground and belowground plant growth. Field observations in the U.S. indicate that SLF can result in the weakening or full death of grape vines. In a Pennsylvania vineyard study, most heavily predated vines in a vineyard did not survive winter conditions, which then resulted in only a few of the surviving vines bearing fruit in the spring (Baker et al., 2019). Another study focusing on the ecophysiology of grapevines eaten by SLF found that intensive phloem feeding late in the season by high SLF population densities can induce carbon limitation. This may lead to negative effects in subsequent years in cases of severe belowground carbon depletion (Harner et al., 2022). Although SLF feeding effects on grapevines have been studied the most due to the potential economic impacts they pose toward viticulture, a few studies have investigated how SLF impacts the ecophysiology of other host plant species. One such study focusing on red and silver maple trees found that up to 30 nymphs confined to a single branch did not have a significant effect on gas exchange, but 40 adults confined to a single branch of these trees rapidly suppressed gas exchange and reduced nitrogen concentration in leaves (Lavely et al., 2022).

Dense populations of SLF also result in a large accumulation of honeydew, the sugary excrement from the hindgut of insects, that coats surfaces below. Honeydew promotes the growth of sooty mold, an epiphytic order of fungi known as Capnodiales. Sooty mold results in a mass of black colored cells that coat leaves and/or abiotic surfaces. This is a nuisance in urban areas where the honeydew covers objects like cars and outdoor furniture. In a more natural setting this results in significant photosynthesis blockage of understory plants (de Lemos Filho & Paiva, 2006).

Climate Change

Anthropomorphic climate change further complicates the threat of increasing frequency and severity of invasive species infestations. Both climate change and invasive species are two of the most prevalent aspects contributing toward global biodiversity loss and environmental change. Most invasive species managers are concerned about how climate change will affect their respective programs. One study conducted in the eastern U.S. showed that 67% of interviewed invasive species managers were “very concerned” about how climate change will affect their management efforts (Beaury et al., 2020). This same study found that these managers had a significantly higher concern level than the organizations they worked for, suggesting their desire to incorporate climate change into their management plans may lack funding or support. Studies focusing on the South Korean infestation of SLF have shown evidence that climate change may be a factor for the occurrence and expansion of the pest. SLF was first reported in South Korea in 2006 near the capital city of Seoul. Since then, SLF has expanded across the nation. The mean winter temperatures in South Korea during the last 30 years have gradually increased to above the temperature for 100% mortality of SLF eggs (−3.44 °C). The city of Chuncheon has the lowest mean minimum winter temperatures which resulted in an egg mortality rate of 93.32%, leading to a significant survival rate (Lee et al., 2011). As temperatures rise throughout South Korea, and globally, egg survival is likely to increase. Recent studies have even indicated that the potential climatic range that SLF may occupy is larger than previously predicted. Nymphs that were exposed to greater extremes than the maximum or minimum temperature they can tolerate were still able to develop when these temperatures alternated with favorable temperatures (Keena et al., 2023). It should be said however that exposure to these extreme temperatures does slow development and sometimes lead to mortality. The incorporation of these findings into phenology modeling may increase the climactic range that SLF can survive in and globally affect invasive project management.

Economic Concerns

Studies have predicted the strong potential impacts SLF may have on Pennsylvania agriculture, thus leading to concerns about NYS agriculture. The direct economic impact of SLF on tree fruits, berries, grapes, and tree nuts is estimated to be $11.0 million throughout the entire state of Pennsylvania (Harper et al., 2019). Many of NYS's common agricultural products are similar to those grown in Pennsylvania. At risk NYS agricultural products include apples, grapes, walnuts, hops, syrups, and lumber. NYS is well known for its apple production and is estimated to produce over 30 million bushels of apples each year. Additionally, NYS grapes are valued at an annual harvest of $52.8 million (NYSDAM, 2023). The NYS Department of Agriculture and Markets' Spotted Lanternfly Control Program aims to monitor and limit the spread of this invasive pest throughout NYS, with particular emphasis on limiting infestations near agricultural districts. Horticultural Inspectors throughout the state survey sites for the presence of SLF in any of its life stages. NYSDAM employs regulatory actions to mitigate the risk of SLF spread, as well as provide outreach to the public, trade groups, and other stakeholders (NYSDAM, 2023).

Methods

Data

All SLF data collected by horticultural inspectors working for the Plant Division of NYSDAM from 2021 to the Fall of 2023 was obtained. Inspectors use the Survey 123 application to input sites they visit. This application records the geographic coordinates of the site as well as the date and time. This data was then narrowed down to only positive sightings of SLF due to the non-random method of data collection by the agency. More data was then obtained from the iMapInvasives website. This site is an online GIS-based data management system that provides public citizen science data to locate invasive species (iMapInvasives, 2024). The data downloaded was narrowed down to positive SLF sightings from 2021 to 2023 that had been verified by contributing agencies. Data from both iMapInvasives and NYSDM were then combined into one table, thus resulting in 2,899 presence points. The number of insects found at each site, the life stage of the insect(s), and vegetation type where the insect(s) were found was excluded in this study due to the inconsistencies of how data was recorded for each of these positive sites. NYSDAM inspectors and citizen scientists using iMapInvasives varied in the amount of data collected, so just the point location and the date the data was collected were used.

Additional data was collected to use in the geographic weighted regression and high concern area identification in this study. TOH is widely distributed across NYS, so data points for the presence of this preferred host tree were also collected from iMapInvasives (iMapInvasives, 2024). These presence points were narrowed down, like those of SLF, to those sighted from 2021 and 2023 and verified by contributing agencies. This resulted in 2,108 data points. NYS municipality polygon boundaries were obtained from the NYS Office of Information Technology Services GIS Program Office (2020). Agricultural District polygon data were acquired from the Cornell Institute for Resource Information Sciences (Cornell IRIS, 2023). The transportation vectors used in this study include primary and secondary roads throughout NYS and all railroads throughout NYS. Primary and secondary road line data were acquired from the United States Census Bureau (U.S. Census Bureau, 2021) and railroad line data were acquired through ArcGIS Online (NYSDOT, 2023). Hudson Valley Significant Biodiversity Areas and NYS Forested State Land polygon data were also acquired through ArcGIS Online (NYSDEC, 2022). All maps created and analyses performed were done using ArcGIS Pro (ESRI, 2024) and MGWR 2.2 (Oshan et. al, 2019) software.

Spatial Autocorrelation and Hot Spot Analysis

The *Spatial Autocorrelation (Moran's I)* tool in ArcGIS Pro was used to evaluate whether positive SLF locations show a clustered, dispersed, or random pattern. This is a popular tool used in many ecological and environmental studies. Understanding an organism's dispersal patterns allows for a better understanding of their behavior, indicating if they are generally found in clustered groups or prefer space from other individuals in their population. A positive Moran's I index value paired with a z-score or p-value showing statistical significance indicates a clustered pattern. A negative Moran's I index value paired with a z-score or p-value showing statistical significance indicates a dispersed pattern. If the z-score or p-value are insignificant the null hypothesis is accepted: the values are randomly distributed.

SLF point data was summarized by count per NYS municipality to use the *Getis-Ord Gi* Hot Spot Analysis* tool. This statistic looks at each feature in relation to neighboring features. A statistically significant hotspot (significant p-values or z-score) denotes a feature that has a high value and is surrounded by other features with high values as well, while a significant coldspot denotes a feature that has a low value and is surrounded by other features with low values as well. This is similar to the previously mention *Spatial Autocorrelation (Moran's I),* but since the data is clustered by municipality, it will reveal clusters of municipalities with high counts of SLF and/or clusters of those with low counts of SLF. The assessment was used because many of the following assessments required the SLF data to be organized into counts per polygons.

Space-Time Cube Visualization

A space-time cube allows for the visualization and analysis of spatial-temporal data through a time-series analysis. This technique is often used in biogeographically studies to investigate changes in species distributions, ecological quality, and disease spread. Resulting maps from this analysis provide a representation of how phenomena change over time within geographical space (Cao et al., 2014). The *Create Space Time Cube by Aggregating Points* tool in ArcGIS was used to visualize and analyze the positive SLF locations. This tool aggregates the input features into space-time bins. The *Visualize Space Time Cube in 2D* tool was then used to display the data by trend and confidence level.

Identifying Areas of High Concern

In addition to identifying observed geographical trends exhibited by SLF, NYS was identified and ranked by concern level. Weighted overlays are commonly used to narrow down geographic areas by certain characteristics, to either locate areas of suitability for organisms or, in this case, to locate areas at risk. This technique is easily adaptable to any organism and any characteristics of concern, thus allowing any organization to customize an overlay by the characteristics and weights deemed appropriate. The *Weighted Overlay* tool was used to create five concern level classes: Very Low Concern, Low Concern, Mild Concern, High Concern, and Very High Concern. Agricultural Districts were assigned a weight of .50, since the NYSDAM and NYS government is most concerned with preventing the spread of this pest into agricultural districts. Adult SLF can travel between 3 and 4 miles throughout their lifetime, so the *Buffer* tool in ArcGIS Pro was used to create a 3.5-mile buffer around all railroad tracks and primary and secondary roads. The railroad buffer and road buffers were each assigned a weight of .25 as they are both long-distance vectors of adult insect and egg mass transport.

Another concern level ranking was created for the Hudson Valley area of NYS that includes both agricultural concerns and ecological concerns. Significant Biodiversity Areas (SBAs) are areas with a high concentration of biological diversity or value for regional biodiversity that were identified by the New York State Department of Environmental Conservation (NYSDEC) Hudson River Estuary Program, the New York Cooperative Fish and Wildlife Research Unit at Cornell University, and the NY Natural Heritage Program (NYSDEC, 2022). The *Weighted Overlay* tool was used to create the same five concern level classes as previously described, but the weights were changed to: 0.25 for SBAs, 0.25 for Agricultural Districts, 0.25 for railroad buffers, and 0.25 for road buffers.

Multi-Scale Geographically Weighted Regression

A geographically weighted regression (GWR) is a spatial regression technique used to model the relationship between a dependent variable and independent variables while considering spatial variation in the model parameters. More recent geographic studies use a multi-scale weighted regression (MGWR). This allows each relationship to vary according to a distinct spatial scale parameter (Oshan et. al, 2019). This assessment was performed to investigate the relationship between various spatial variables and SLF count numbers. SLF count data was standardized by obtaining the log of the number of SLF occurrences per municipality divided by the human population. This was then used as the dependent variable, while the independent variables used were the following per municipality: TOH count, total square miles of railroad buffer, total square miles of road buffer, total square miles of agricultural district, and total square miles of state forested land (Figures 10a-e). Only municipalities that contain SLF presence were used in this regression. The MGWR was run using a Gaussian model in the MGWR 2.2 software, using the following formula:

$$yi = \beta 0(ui ,vi) + \sum j\ \beta k\ (ui ,vi)\ xij + \varepsilon i$$

yi is the dependent variable; xk,i *is* kth independent variable; εi si the Gaussian error at location i; (ui,vi) is the x-y coordinate of the ith location; and coefficients $\beta k\ (ui,vi)$ are varying conditionals on the location.

Results

Spatial Autocorrelation and Hot Spot Analysis

SLF sightings were primarily found in southern NYS, including NYC, Long Island, and the Hudson Valley region (Figure 1). Pockets of infestations are present in major cities further north and west, including Albany, Binghamton, Buffalo, Rochester, Ithaca, and Syracuse. SLF sightings exhibit a significantly clustered pattern (Moran's Index= 0.359009, z score = 46.653502, p value = 0). When SLF sightings are grouped by count per NYS municipality (Figure 2), areas closer to NYC generally show higher counts. Significant hotspots are located between municipalities in NYC and western Long Island, and between Minisink and Greenville in Orange County (Figure 3.)

Space-Time Cube Visualization

The space-time cube visualization indicates significant downward trends between 99% and 95% confidence near Staten Island, indicating a decrease in the amount of SLF sightings between 2021 and 2023. There are multiple areas scattered throughout NYS that exhibit upward trends between 95% and 90% confidence, indicating an increase in the amount of SLF sightings between 2021 and 2023. These areas are found in Syracuse, Binghamton, Buffalo, one location in the Hudson Valley, and a few locations on Long Island (Figure 4.)

Identifying Areas of High Concern

Based on the established criteria used in the weighted overlay, the areas of highest concern are those that have a significant amount of agricultural land near major transportation pathways. These areas are primarily located in the Finger Lakes region and western NYS, with smaller areas of high concern in the Hudson Valley, Long Island, and around the perimeter of the Adirondack Mountains (Figure 5.). The vast majority of SLF sightings (2,501) have been found in Mild Concern areas (Figure 6.). This accounted for 86.3% of all sightings. The NYC area accounts for many of these sightings, as it falls under the Mild Concern category due to its high density of transportation vectors but lack of agricultural land. Only 43 sightings (1.5%) were found in the Very High Concern category.

The weighted overlay made specifically for the Hudson Valley with the inclusion of SBAs (Figure 7.) resulted in the areas of highest concern being in a thin stretch going North to South, consistent with the major railroad and highway routes of the region (Figure 8.). A very small number of Very High Concern areas were identified and no SLF sightings were located within them (Figure 9.). Most sightings were in Mild Concern areas (587) and Low Concern areas (368). This accounted for 53.1% and 33.3% of the total sightings found in the Hudson Valley respectively.

Multi-Scale Geographically Weighted Regression

The global regression model resulted in an adjusted R-Squared value of 0.177 with an AICc value of 219.156. Independent variables with significant p-values include: TOH count (.004), square miles of railroad buffer (.004) and square miles of road buffer (.000) (Figure 11.). When local p-values were mapped for these three variables, varying patterns emerged. TOH presence had strong local significance in all but one municipality (Figure 12a). Railroad buffers showed no local significance (Figure 12b) and road buffers showed local significance in 11 municipalities (Figure 12c.)

Figures

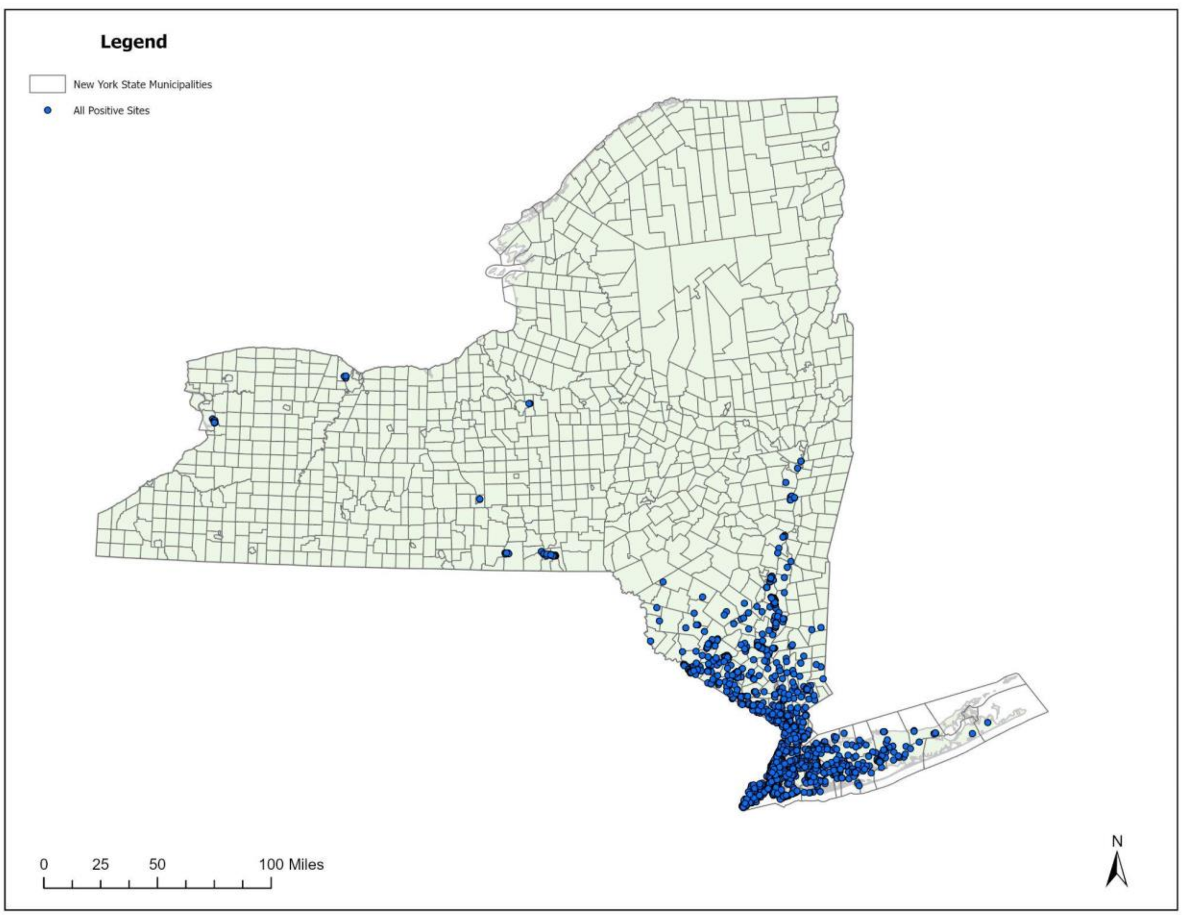

Figure 1. All positive SLF sightings.

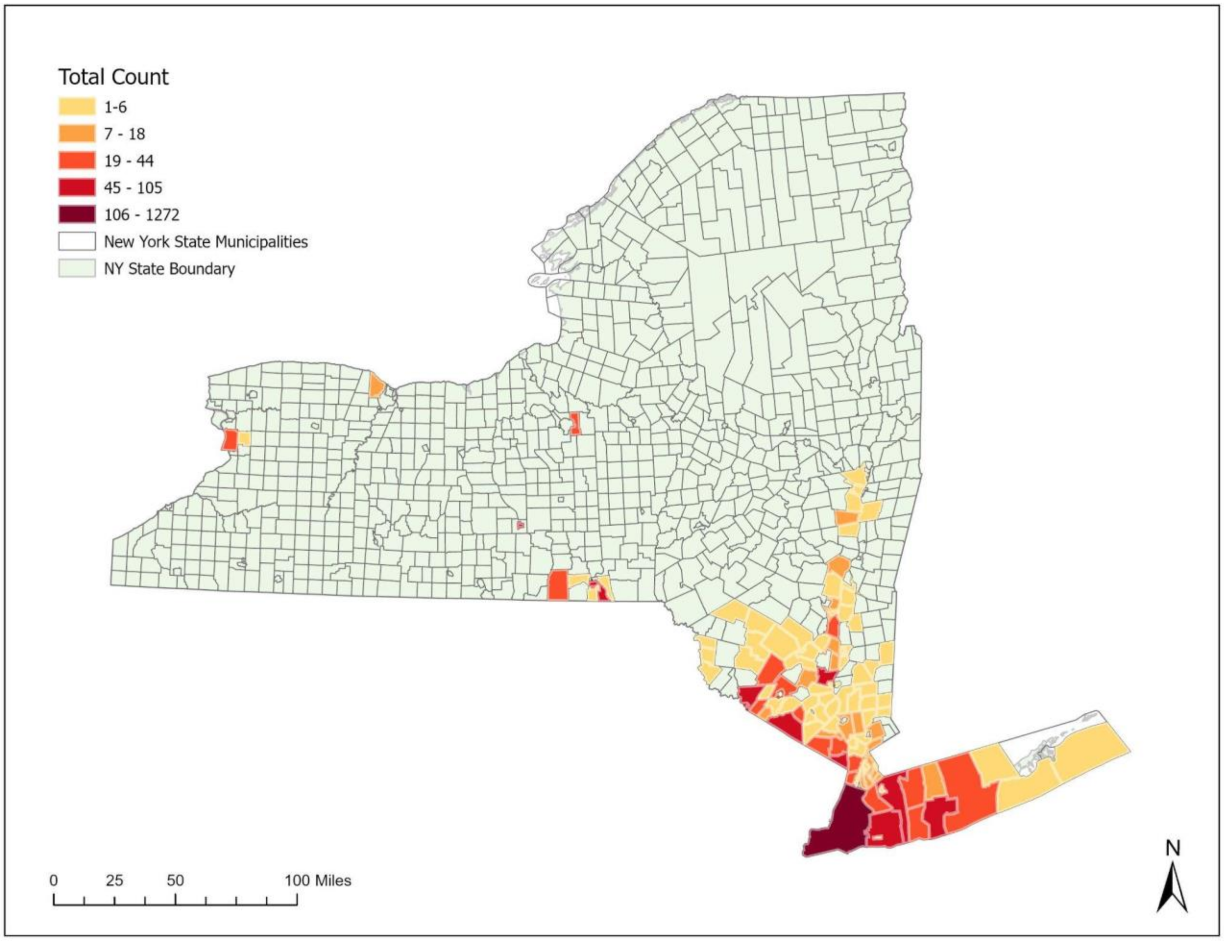

Figure 2. SLF sightings per NYS municipality.

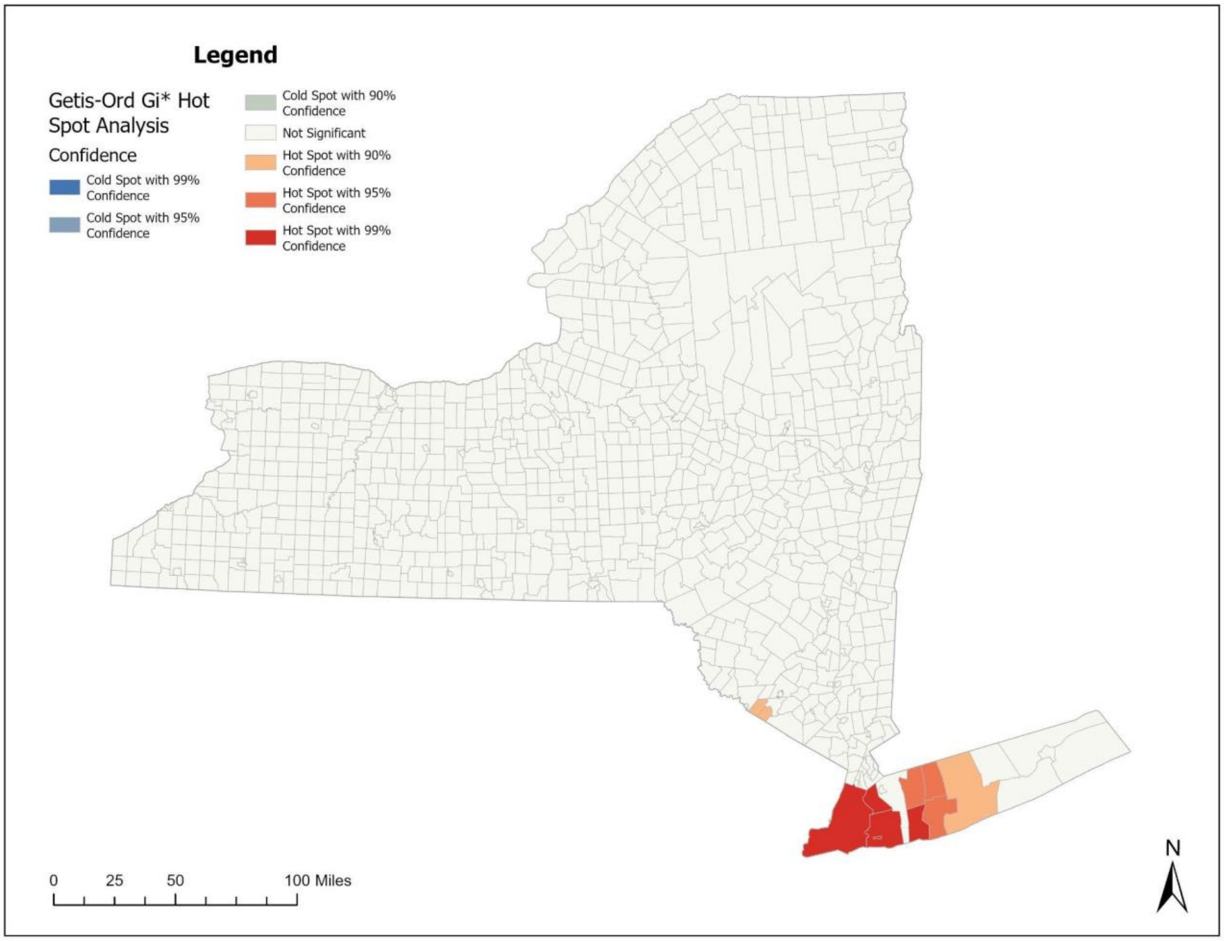

Figure 3. Getis-Ord Gi* Hot Spot Analysis.

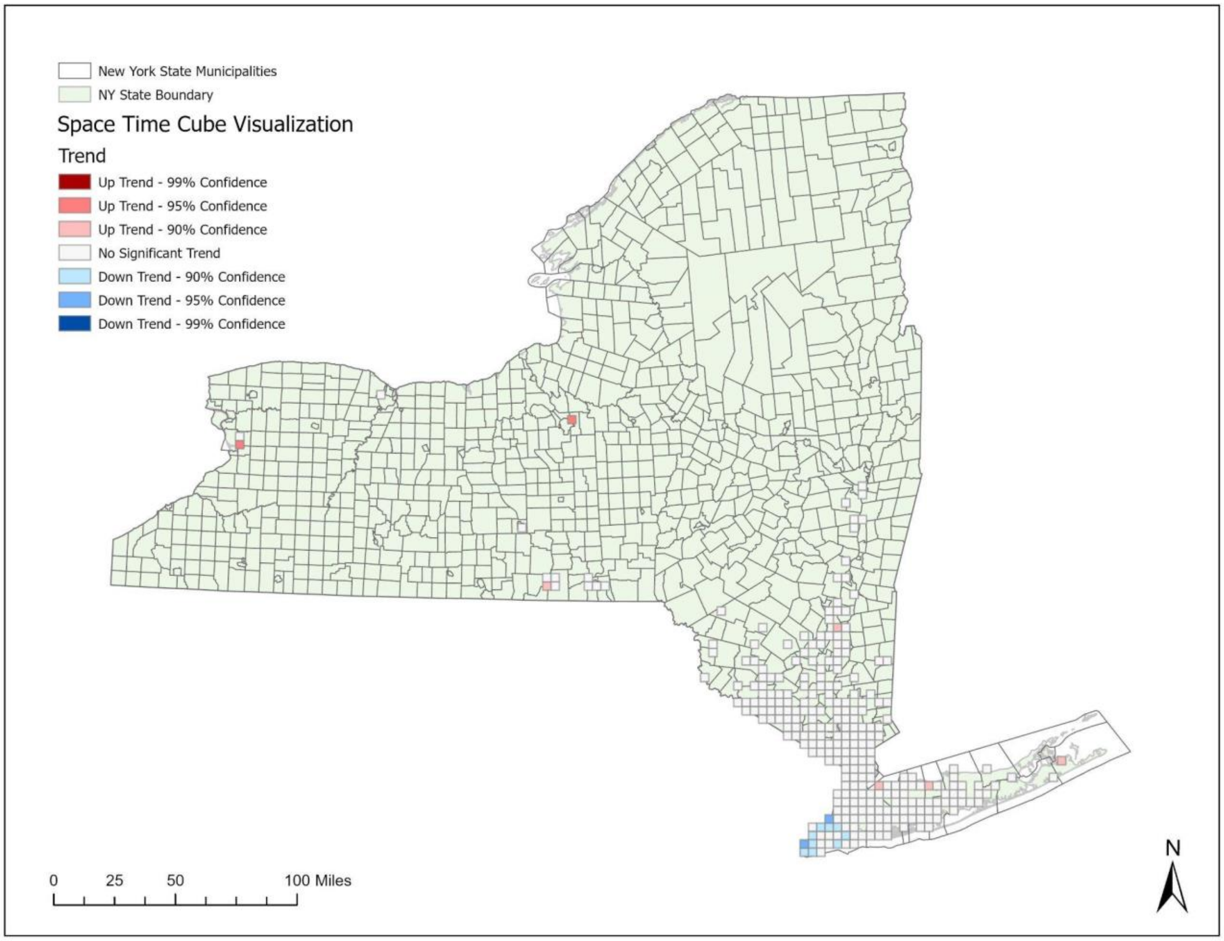

Figure 4. Space-Time Cube Visualization.

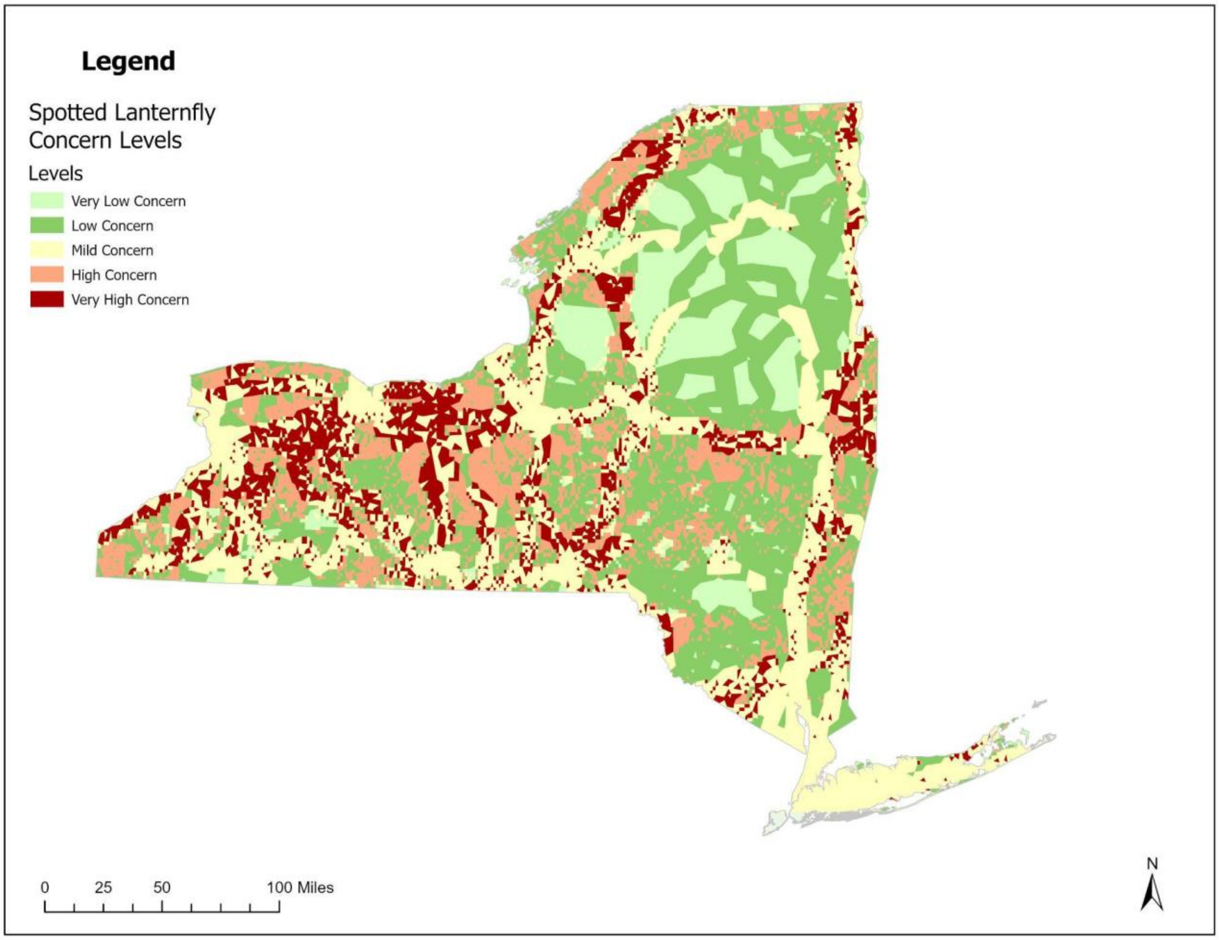

Figure 5. Geographic distribution of SLF concern levels.

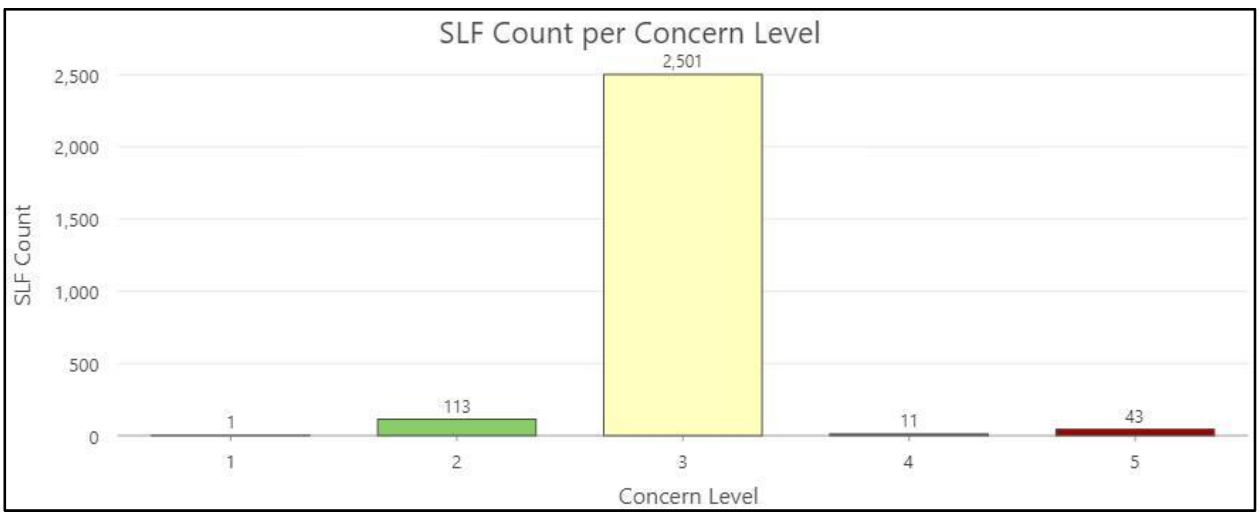

Figure 6. SLF count per concern level.

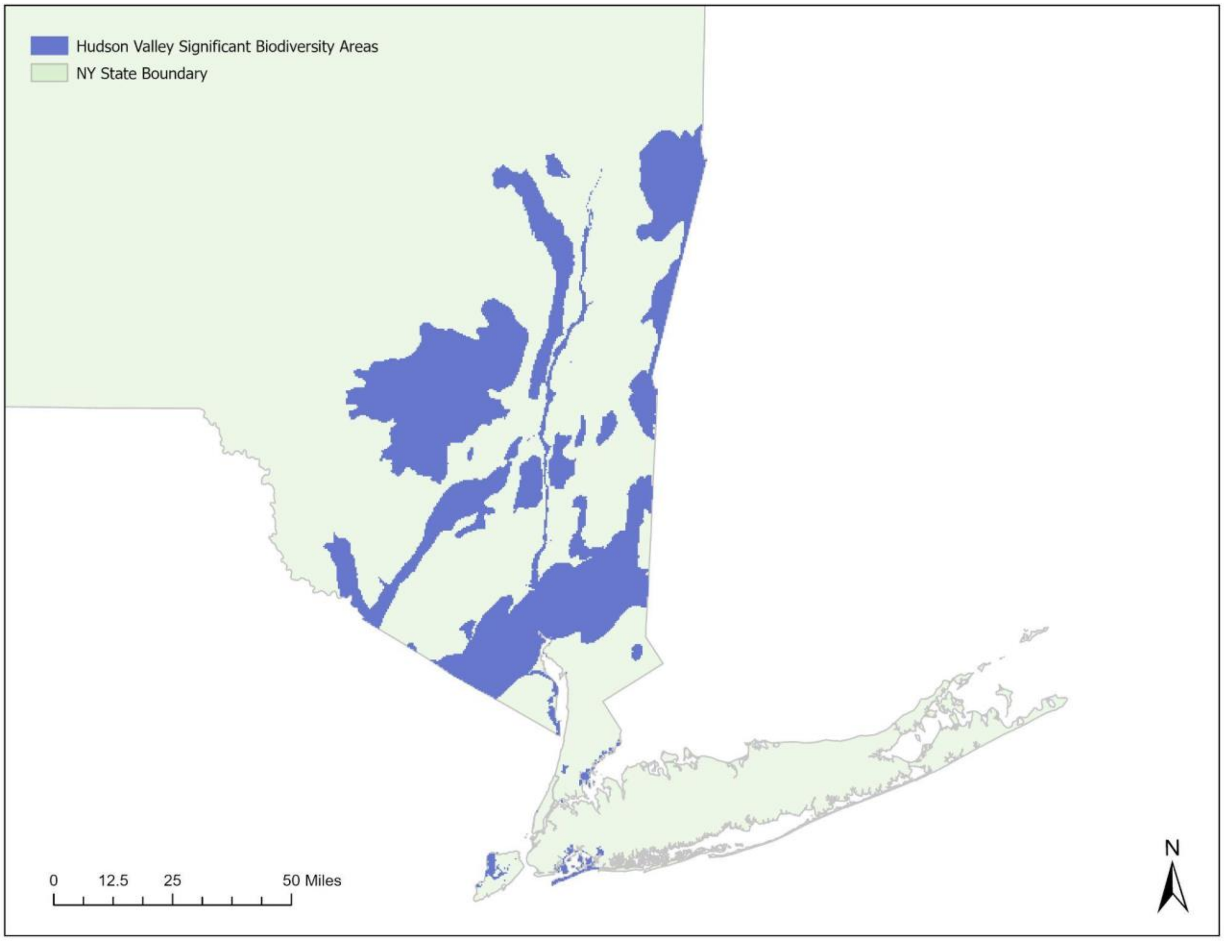

Figure 7. Hudson Valley SBAs.

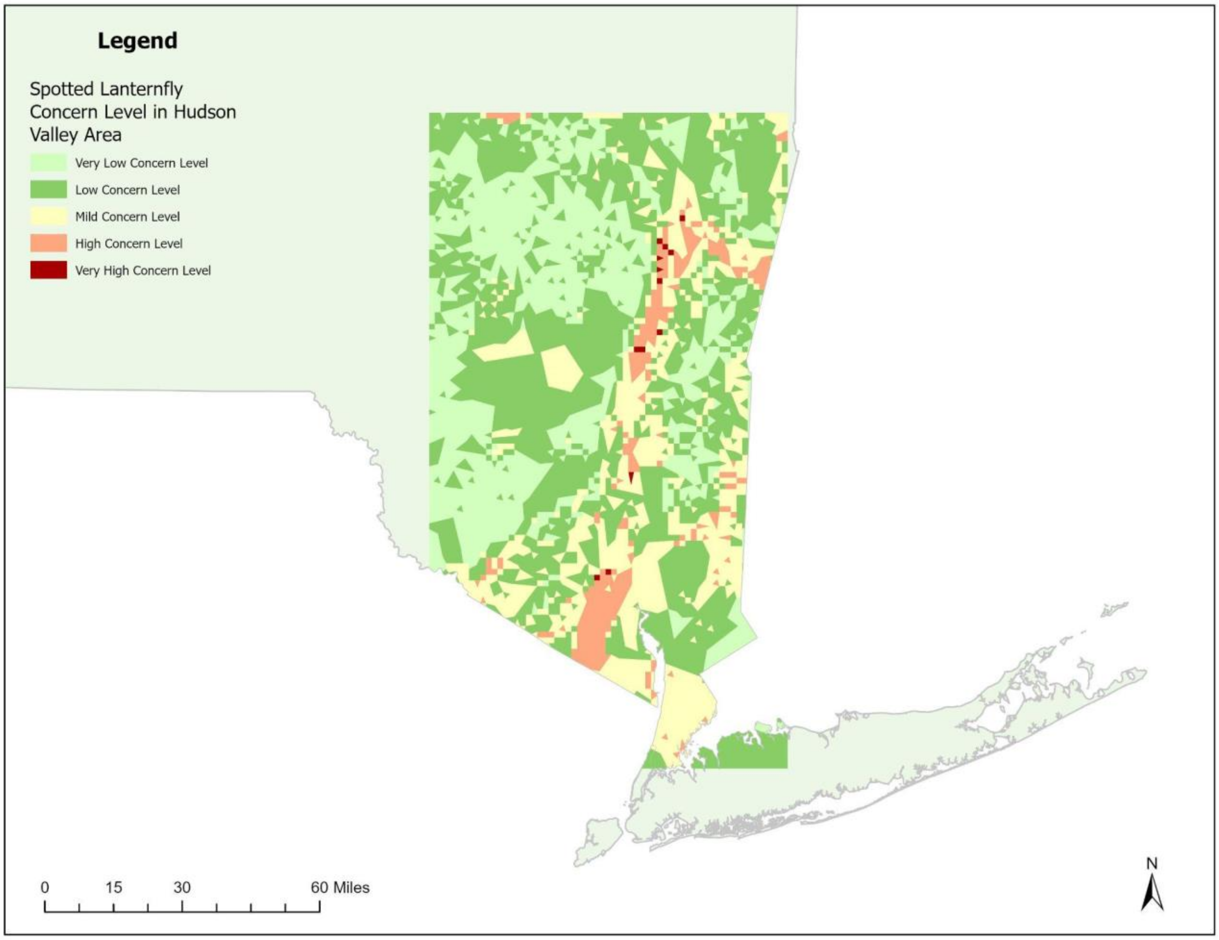

Figure 8. Geographic distribution of Hudson Valley SLF concern levels.

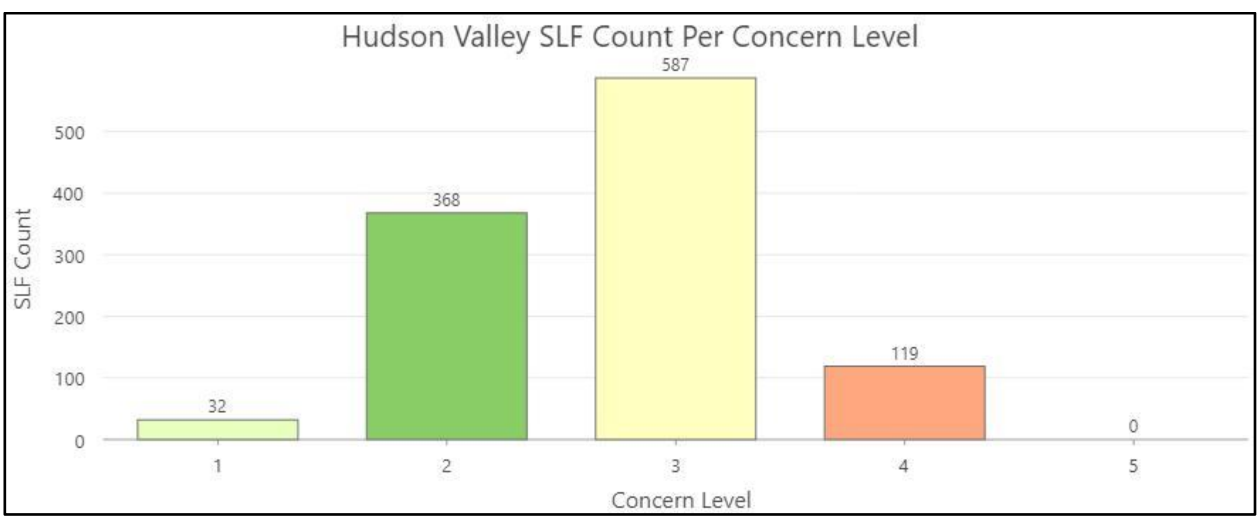

Figure 9. Hudson Valley SLF count per concern level.

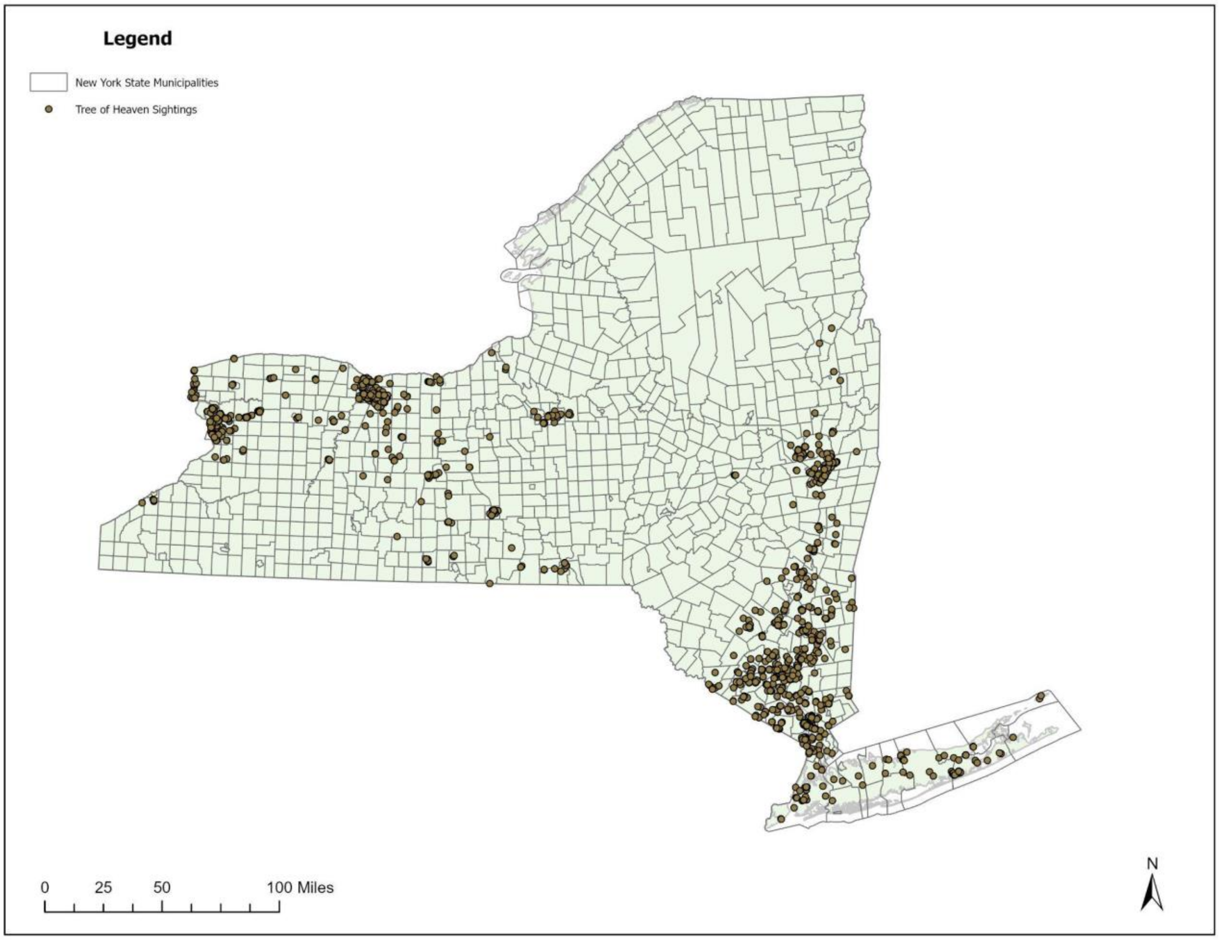

Figure 10a. TOH sightings.

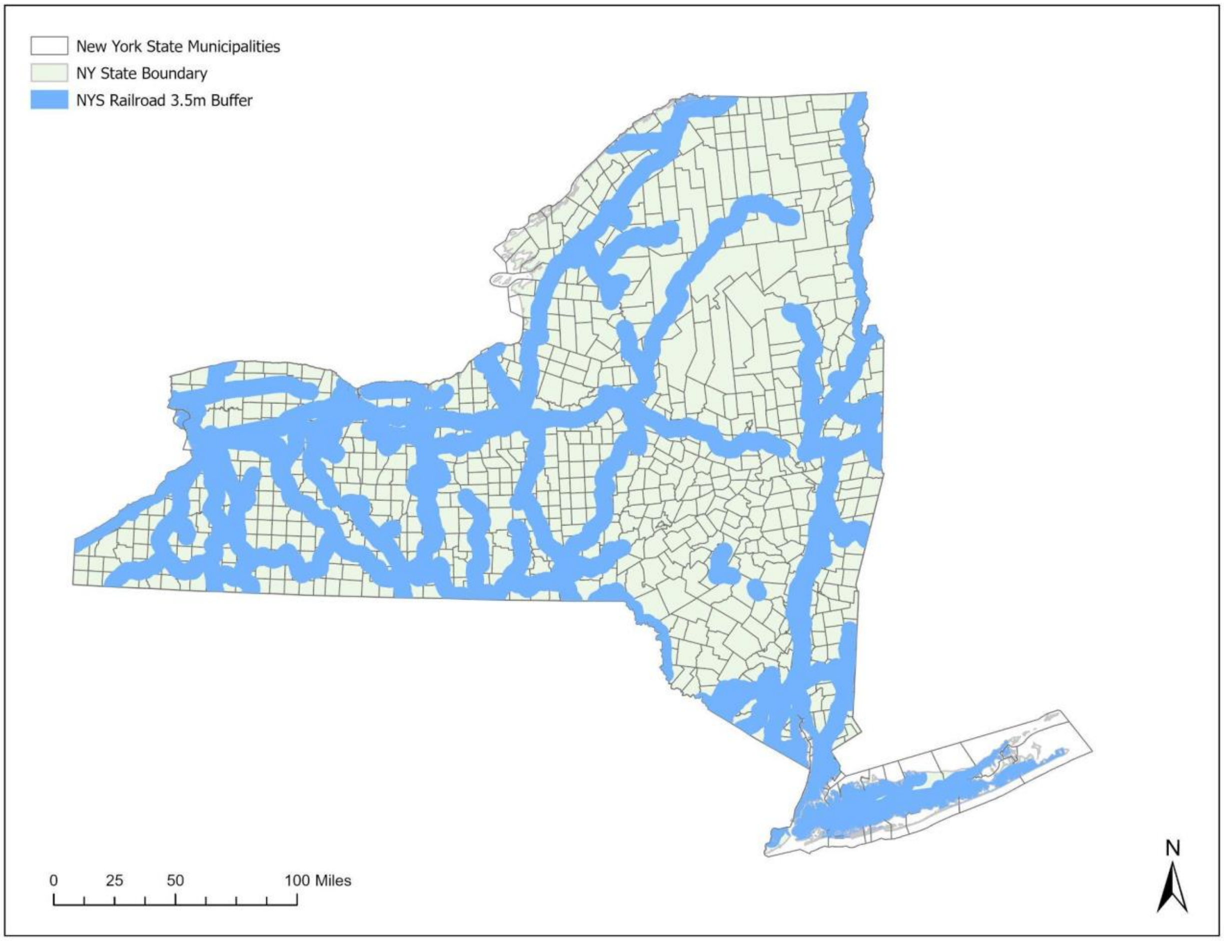

Figure 10b. NYS railroad 3.5m buffer.

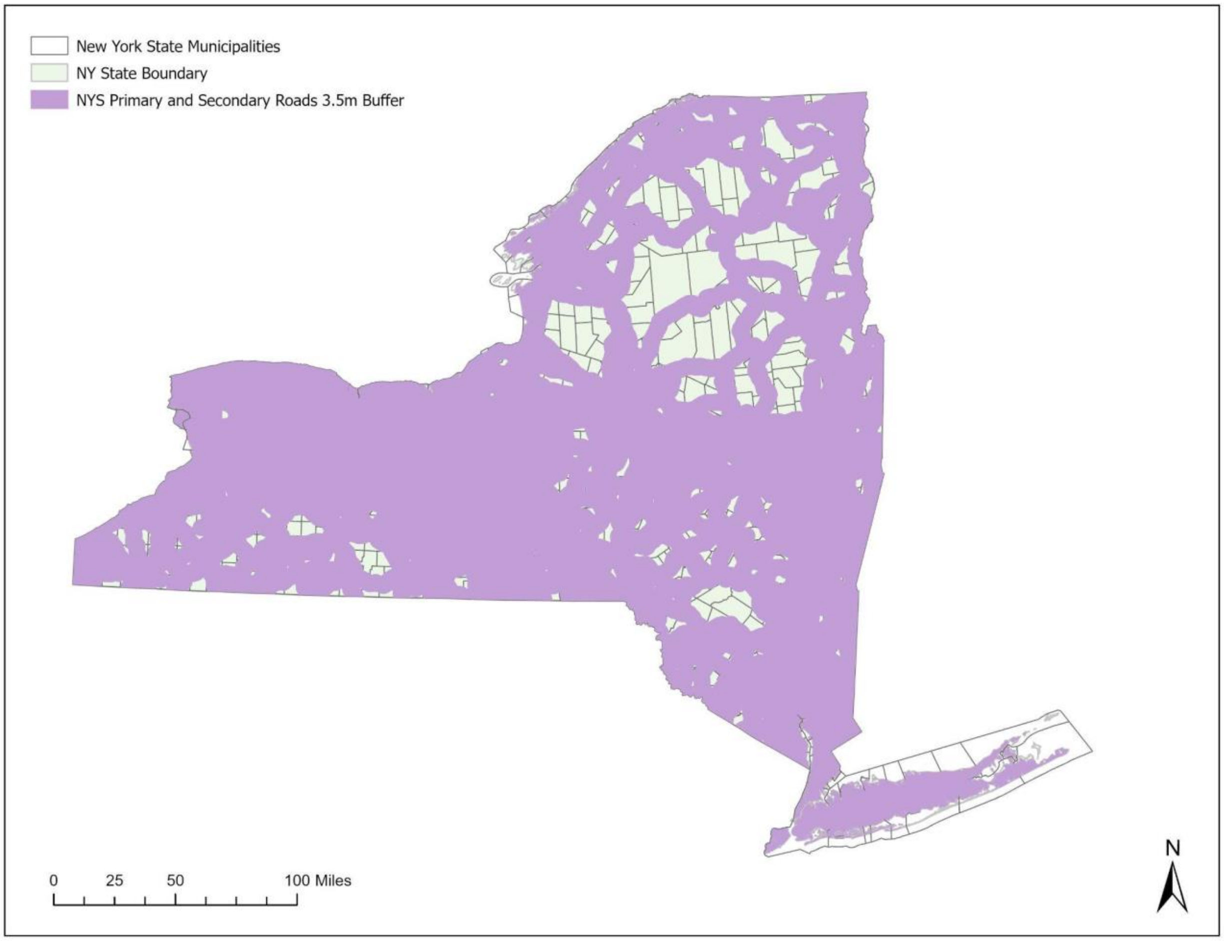

Figure 10c. NYS primary and secondary roads 3.5m buffer.

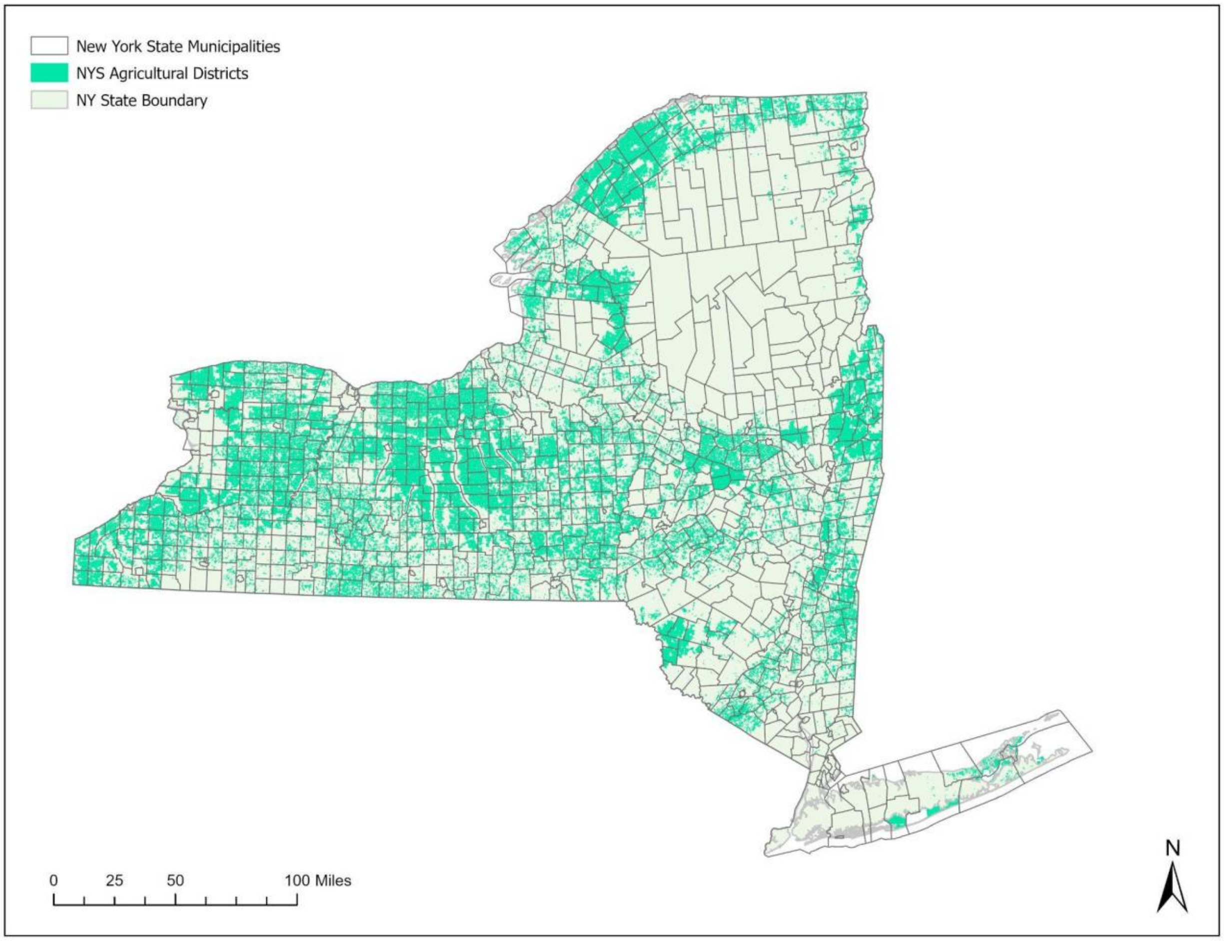

Figure 10d. NYS agricultural districts.

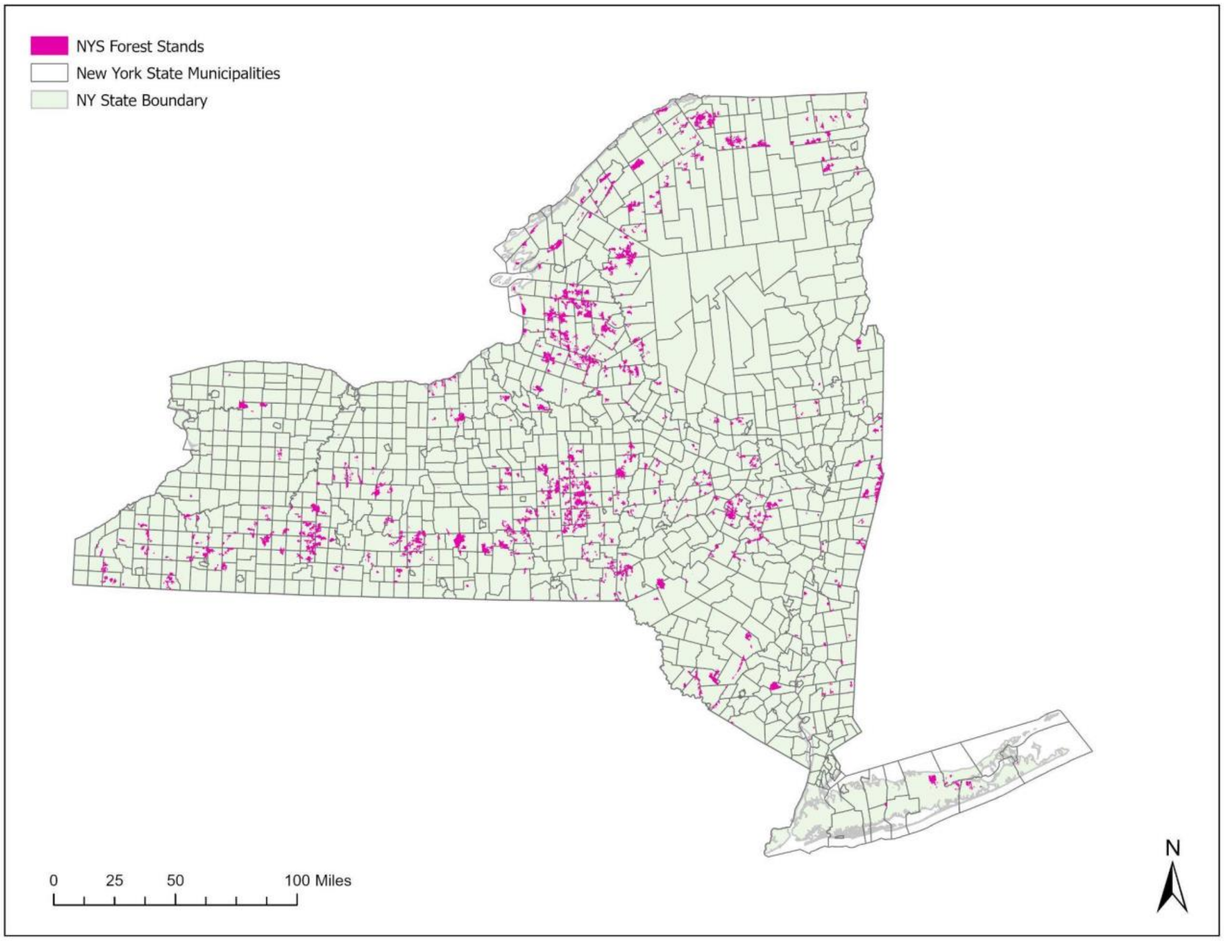

Figure 10e. NYS forest stands.

Variable	Est.	SE	t(Est/SE)	p-value
Intercept	-0.000	0.103	-0.000	1.000
TOH Count	**-0.306**	**0.107**	**-2.851**	**0.004**
Square Miles of Agriculture	0.155	0.110	1.411	0.158
Square Miles of Forested Land	0.028	0.112	0.251	0.802
Square Miles of Railroad Buffer	**0.615**	**0.213**	**2.888**	**0.004**
Square Miles of Road Buffer	**-0.746**	**0.209**	**-3.565**	**0.000**

Figure 11. Global regression results. Significant variables are in bold.

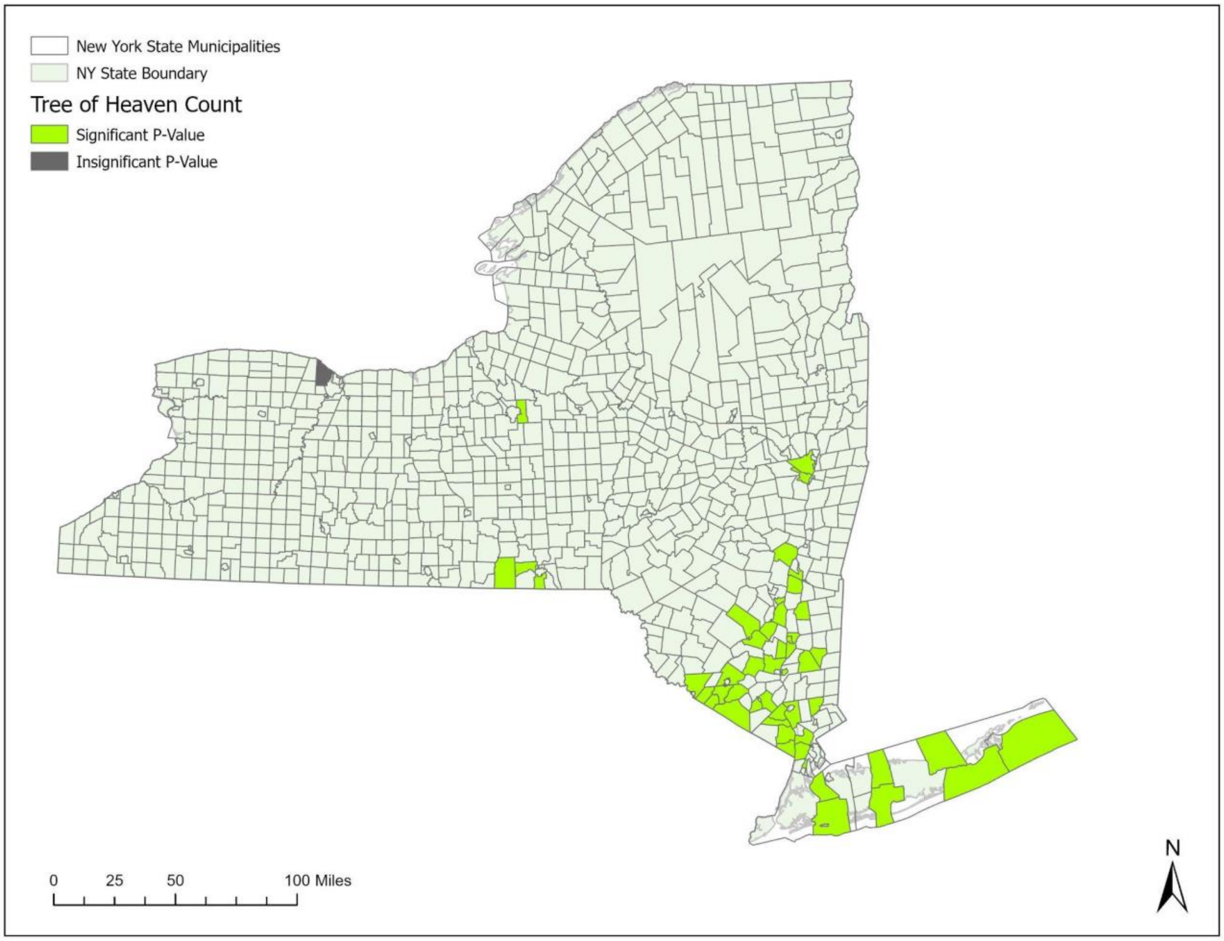

Figure 12a. TOH p-values by municipality.

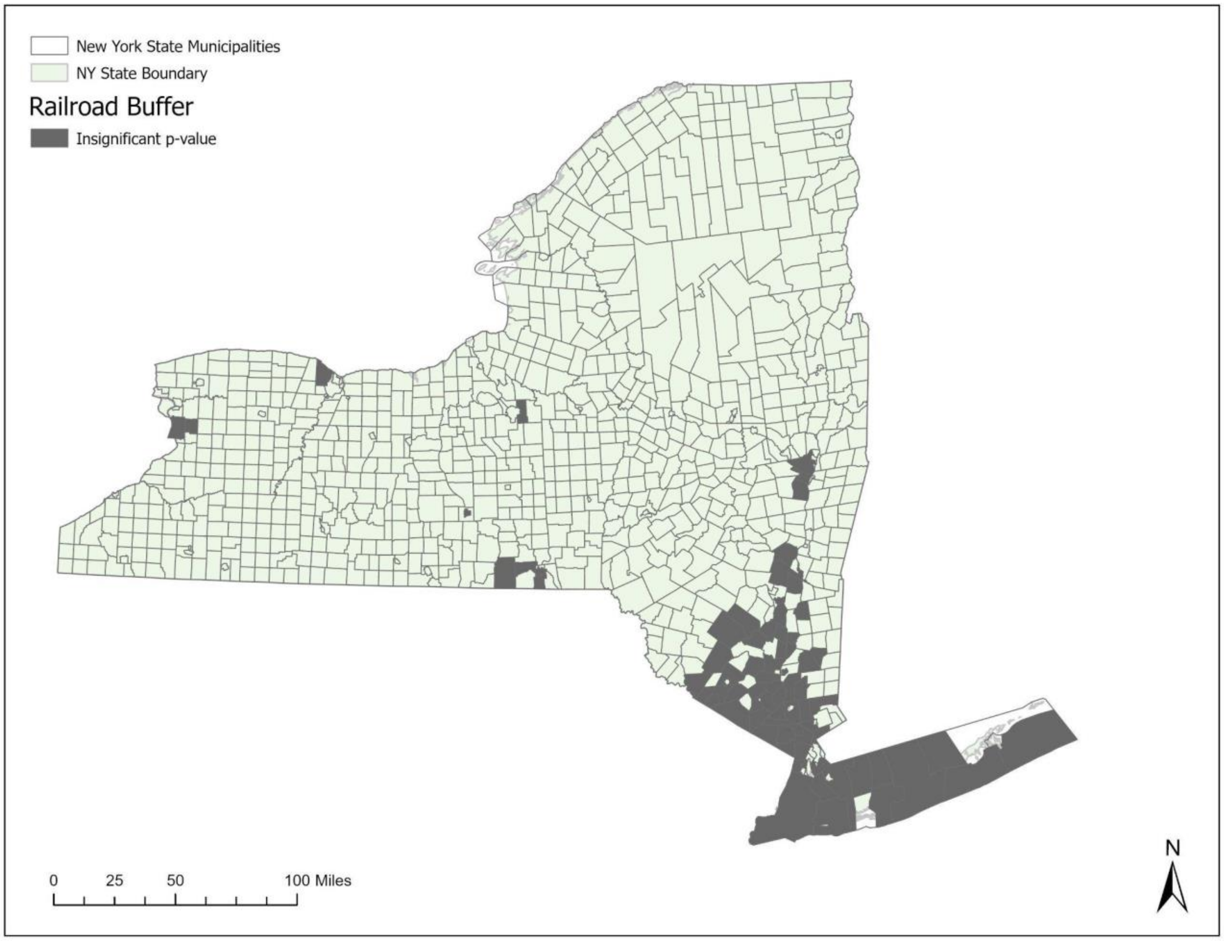

Figure 12b. Railroad buffer p-values by municipality.

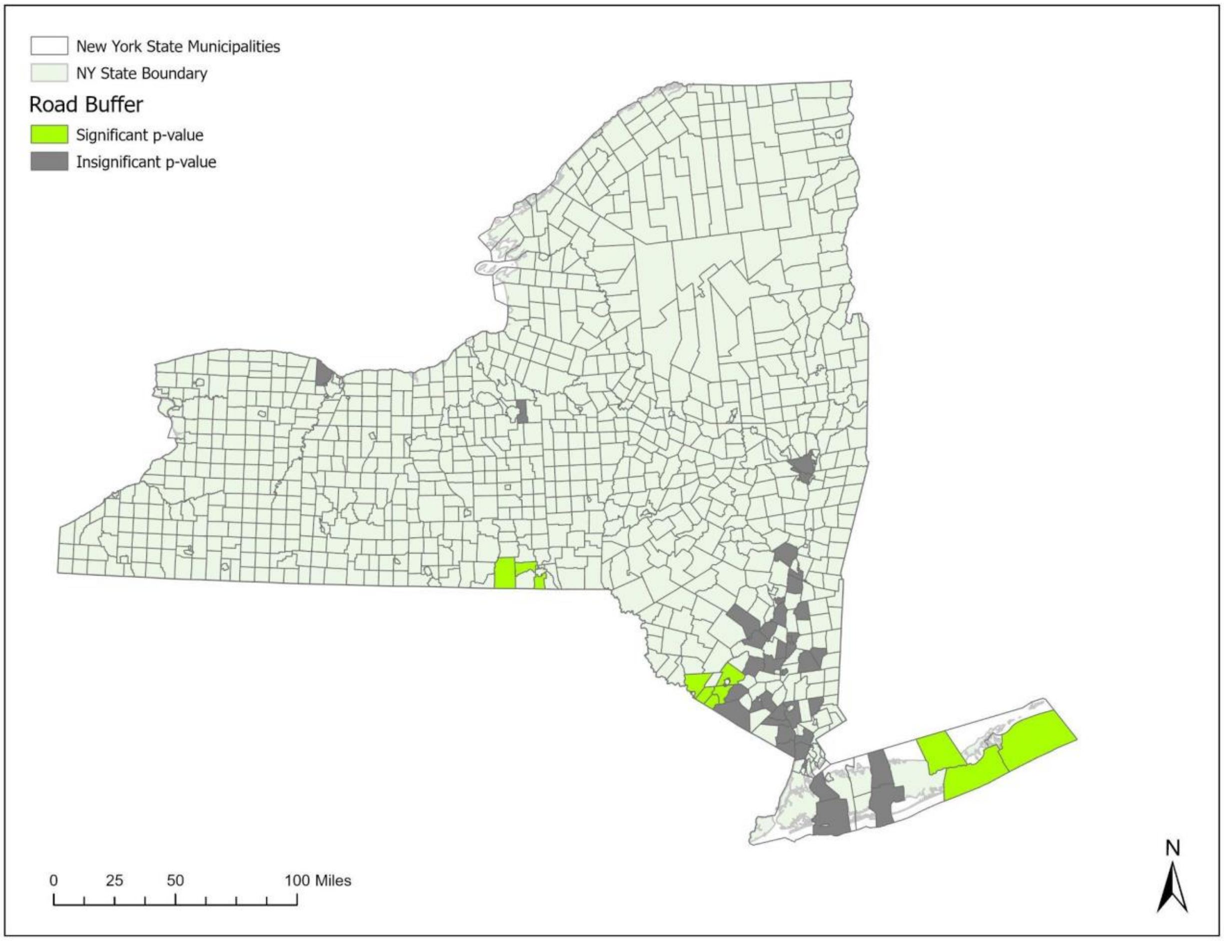

Figure 12c. Road buffer p-values by municipality.

Discussion

SLF distribution across NYS is highly clustered and more present in highly urbanized areas. Significant hotspots are located near NYC, indicating multiple adjacent municipalities exhibiting high numbers of SLF sightings. This is not surprising, as human mediated dispersal has been shown to be a primary factor in the spread of this pest. The results of the space-time cube visualization shows downward trends in SLF sightings near Staten Island. This indicates a trend toward SLF population stabilization and possible decrease in this area, which contained the first SLF sightings in NYS. The significant upwards trends scattered throughout the state indicate increasing populations going east, north, and northwest of Staten Island.

The identification of areas of high concern may be used to guide future SLF survey and management plans. Limited resources and budgets may require agencies to target specific locations instead of further wide-ranging surveys. Based on the previously discussed criteria, the areas of highest concern are in agricultural regions that overlap with transportation buffers, thus providing easy access for establishment on farmland. In the Hudson Valley, the added influence of SBAs helped to identify specific areas where overlaps occur between agricultural land, SBAs, and transportation buffers. These smaller, more targeted locations can allow for thorough survey and mitigation strategies to be enforced. Additionally, the presence of an upward space-time cube trend in the Hudson Valley further emphasizes the need for proactive management based on these known areas of high concern.

The global adjusted R-Squared value of 0.177 indicates that the model explains 17.7% of the adjusted SLF numbers per municipality can be explained by the significant independent variables (number of TOH, square miles of railroad buffer, and square miles of road buffer). The results of the global regression show that, on average across the entire study area, TOH presence, square miles of railroad buffer, and square miles of roads buffers have a statistically significant effect on SLF presence. The results of the local regression show that TOH presence had a strong influence in all but one municipality. The total square miles of railroad buffer showed no local significance, suggesting the relationship between SLF presence and railroad presence may be complex and not uniformly distributed. The total square miles of road buffer show local significance in eleven municipalities. These municipalities are located on eastern Long Island, near the Hudson Valley, and in Western NYS.

Recommendations

The strong influence of TOH presence in both the global and local regressions suggest that a strong focus must be placed on management and mitigation in areas with dense TOH populations. However, it should be noted that SLF may still feed only on hardwood trees even in the absence of TOH, although they may suffer decreased fitness (Uyi et al., 2021). The significance of both railroad and road buffers along with TOH presence in the global regression support the various findings that SLF spread is influenced by human transportation vectors. TOH have often been planted in urban settings due to their hardy nature, as they can tolerate dry soils and low pH values. Thus, TOH is widespread in poor soils adjacent to transportation vectors. They have a fast growth rate, are prolific seed producers, are persistent stump/root sprouters, and salt tolerant. TOH are also aggressive allelopathic competitors that create uniform, rather than mixed species, stands after invasion (Sadeghi et al., 2017). Management of SLF as they continue to spread across NYS will need to include the early detection of TOH establishments and numbers. A recent method of TOH detection involves the use of drones equipped with optical sensors. A 2023 study found that this method can be used to create a detailed infestation map to better understand its distribution and aid in the development of precise management strategies

(Naharki et al). Additionally, the use of different optical sensors can help locate TOH during various life stages. In areas identified as Very High Concern or High Concern levels for SLF establishment and areas with significant upward spatial-temporal trends, TOH detection and management is important for early SLF management.

Early cooperative efforts implemented by government, private, and academic entities in Pennsylvania included conducting surveys, implementing control tactics, implementing regulations to contain the insect, and prevent or minimize its potential movement, and providing scientific expertise (Urban et al., 2021). Similar actions have been taken in NYS, but it is essential to implement these efforts in areas near locations with significant upward spatial-temporal trends. These areas should receive high priority when implementing early management strategies since they are likely to be infested. Areas north of these locations also need early monitoring and management efforts because of climate change. Current invasive insect management techniques often include chemical pesticides, which can harm humans, ecosystems, and native pollinators. Safer management techniques include sterile male technique and RNA interference. If enough sterile males are released into a population, a reduction in population size will take place. RNA interference involves using exogenous double-stranded RNAs to target specific messenger RNAs for degradation, resulting in the silencing of the gene's expression. This method is species specific, reducing the possibility of affecting nontarget organisms (McLaughlin & Dearden, 2019). Additionally, the full-scale ecological threat posed by the SLF needs to be taken into further consideration. SLF possess both ecological and agricultural risks, while other invasive insects only pose agricultural or strictly ornamental plant risk. For example, box tree moth (*Cydalima perspectalis*) is an invasive insect that significantly defoliates boxwoods (*Buxus sp.)* in North America and Europe (Wiesner et al., 2021). Boxwoods are a popular ornamental landscape plant that are often non-native where they are sold. Box tree moth poses a serious economic threat for the boxwood industry, but unlike SLF, they are not known to be as high of a threat to ecosystem function and agriculture. Although this could change in the future, especially due to anthropogenic climate change, SLF currently poses a more wide-ranging threat. Thus, this should be considered when allocating funding and resources toward various invasive species management programs.

Further research that incorporates more independent variables into the MGWR is required to provide a stronger model that exhibits a higher R-Squared value. This study also made the many data gaps regarding the spatial distribution of SLF quite apparent. More sources of SLF presence data may aid in developing a more robust data set. This data may be acquired from other entities, such as the federal government and/or private agencies. Specific data related to each sighting, such as number of insects and plant type present, were not used in this study due to data collection inconsistencies. Invasive species studies are often done by government agencies, or those affiliated with government agencies, and thus seek to design management strategies. Additionally, many invasive species are reported to these agencies by the public through citizen science efforts or public outreach education. Therefore, the surveys and inspections being performed are normally nonrandom in nature since they target specific locations the species has been found. To engage in further research with a stronger data set, random, more standardized field studies need to be performed. Data collection should include multiple factors associated at all sites surveyed, such approximate insect count, host plants, temperature, and other organisms present. This random and consistent method of field surveying would result in data for both SLF-positive and SLF-negative sights, which can then be compared to each other for statistical differences. Further research that incorporates climate change models for SLF spread and establishment in NYS is also necessary moving forward. Increases in winter temperatures may reduce mortality of poikilothermic animals due to an increase of the temperature above their lower lethal temperature (Lee et al., 2011). Therefore, SLF may easily be able to expand its range further north as seasonal temperatures change and mean temperatures increase. It is crucial that climate change is incorporated into future management decisions regarding SLF and other invasive species.

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