

Research Article

Multivariate Climatic Drivers of Local Extirpation: Long-term Temperature, Snowfall, and Precipitation Dynamics in Michigan

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Abstract

This study applies a multivariate climatic framework to evaluate how interacting long-term changes in minimum temperature, snowfall, and precipitation contribute to species decline and local extirpation in Michigan. We integrate 129 years of minimum temperature data, 64 years of precipitation records, and multi-decadal snowfall measurements with species-occurrence histories to quantify climatic pressures driving documented losses. The analysis shows a pronounced post-2000 rise in winter minimum temperatures marked by the near disappearance of extreme cold events (e.g., February minimums rising from -30°F to -9°F). These warmer minimum temperatures disrupt key ecological pathways by reducing the duration and intensity of cold-dependent physiological cues, increasing overwinter metabolic stress, and expanding predator and pathogen survival windows. Concurrent declines in January–February snowpack and the virtual loss of April snowfall further compound risk by diminishing the insulating snow layer essential for thermal buffering, hibernation stability, and protection of subnivean microhabitats. Precipitation patterns reveal increasing seasonal imbalance, with reduced summer rainfall and elevated spring and autumn precipitation, altering hydrological stability, breeding-site persistence, and seasonal habitat quality. To evaluate species responses, we develop synthetic K-Nearest Neighbors (KNN) population models for several climate-sensitive taxa-including Blanchard's Cricket Frog, American Goshawk, Kirtland's Snake, and the Long-eared Owl-which represent a novel integration of long-term multi-variable climate anomalies with data-driven population modeling. These models show coherent seasonal and interannual population declines that align with observed climatic anomalies, highlighting the combined effects of winter warming, snowpack loss, and altered moisture regimes on demographic resilience. A broader historical comparison further indicates a shift in the dominant drivers of biodiversity loss: whereas early extirpations were primarily linked to habitat conversion, recent and ongoing declines increasingly stem from the interaction of climatic warming with persistent habitat degradation. The findings demonstrate that no single climatic factor explains extirpation patterns; instead, vulnerability emerges from interacting climatic stressors that reshape overwintering conditions, hydrological cycles, and habitat suitability. By merging long-term climate datasets with synthetic KNN population modeling, this study advances tools for assessing climate-driven extinction risk and provides actionable insight for conservation planning in the Great Lakes region.

Keywords

Climate Anomalies, Species Extirpation, K-Nearest Neighbors (KNN) Modeling, Biodiversity Decline, Temperature, Precipitation, Snowfall Trends, Multivariate Climate Analysis

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1. Literature Review

Understanding the relationship between climate dynamics and species decline has become a central focus in ecological research, particularly in regions experiencing rapid environmental change such as the Great Lakes. Numerous studies demonstrate that species responses to climate stressors are multi-faceted, involving the interplay of temperature, precipitation, snowfall, habitat fragmentation, and physiological sensitivity. This review synthesizes findings from 25 climate–biodiversity studies to contextualize the need for integrated, multivariate approaches when evaluating drivers of local extirpation.

Early landmark studies positioned temperature as the primary climatic driver of biodiversity change. Parmesan (2003) [1] documented widespread poleward and elevational range shifts, showing that rising minimum temperatures disrupt physiological thresholds and alter ecological interactions. Root et al. (2003) [2] similarly demonstrated that warming trends accelerate phenological mismatches, contributing to population declines across taxa.

Building on this foundation, regional studies identified winter warming as a particularly important stressor for cold-adapted species. Hobbs et al. (2016) [3] reported that warmer winters in North America reduce snowpack, increase freeze–thaw exposure, and undermine overwinter survival. Bukaita (2024) [30] further showed that global warming disproportionately intensifies minimum-temperature increases in northern temperate ecosystems, magnifying stress for cold-dependent taxa.

However, these temperature-centered studies often treat climate variables independently, leading to oversimplified explanations of population decline. This gap recognized by Van der Putten et al. (2010) [13] and Bellard et al. (2012) [14] motivates the present study, which emphasizes interacting climatic factors rather than temperature alone.

A growing body of research shows that precipitation regimes are equally important in determining species survival. Duffenbaugh and Field (2013) [4] demonstrated that variability in precipitation poses risks comparable to, or greater than, absolute warming. Swain (2021) [5] found that extreme rainfall events now increasingly common in the Midwest disrupt breeding cycles, reduce reproductive success, and destabilize habitat quality for amphibians and birds.

At broader ecological scales, Siepielski et al. (2017) [25] showed that precipitation variability shapes global patterns of natural selection, underscoring moisture as a driver of fitness and demographic stability. Regional analyses reinforce these findings: Guentchev et al. (2016) [8] identified increasing precipitation variability as a major stressor for forest and wetland communities in Michigan, while Larson (2014) [9] linked altered winter hydrology to prey declines affecting northern raptors such as *Accipiter gentilis*.

These studies highlight that precipitation cannot be considered in isolation from temperature; instead, their combined

influence shapes hydrological stability, habitat conditions, and species resilience.

Snowfall and snowpack are critical for overwinter survival in northern ecosystems, providing insulation, stabilizing subnivean habitats, and buffering species from extreme cold. Winkler et al. (2014) [6] documented long-term reductions in Great Lakes snow depth, while Notaro et al. (2014) [7] projected continued declines in regional snowfall with accelerated winter warming.

Snowpack loss affects ecological interactions as well: Sinclair et al. (2016) [17] demonstrated that changing minimum temperatures and snowfall conditions influence survival across vertebrate species. Peter et al. (2015) [18] and Thackeray et al. (2016) [19] found that reduced snowpack alters predator–prey dynamics, contributing to local species disappearance.

Together, these findings emphasize that snowfall patterns interact strongly with temperature trends yet few studies integrate these variables into combined models of extirpation risk.

Michigan represents a unique case study for multivariate climate–biodiversity interactions. Regional projections indicate substantial winter warming, reduced snowpack, and increased precipitation variability (Notaro et al., 2014 [7]; Guentchev et al., 2016 [8]). These shifts correspond with declining populations of climate-sensitive species, including amphibians and raptors.

Bukaita and Ghiurau (2025) [21] provided empirical evidence linking increases in minimum winter temperatures and altered precipitation to population declines across the northern United States. Complementary work by Bukaita, Anyaiwe, and Nelson (2024) [31] showed that winter minimum-temperature oscillations can serve as early indicators of climate-related stress, reinforcing the need for climate indices that integrate multiple variables rather than tracking temperature alone.

Local species occurrence records from Muskegon County [23] further demonstrate real-time losses in taxa such as *Acris blanchardi*, consistent with climate-driven declines documented in amphibian studies by McCaffery and Maxell (2010) [12].

Methodological advances play an essential role in detecting early warning signs of climate-driven decline. Van der Putten et al. (2010) [13] and Bellard et al. (2012) [14] explicitly called for multivariate models integrating climate variables with ecological interactions to avoid temperature-only predictions.

Machine learning techniques have begun to meet this need: Zhang et al. (2020) [15] applied KNN-based models to reconstruct population trajectories under climatic stressors, revealing nonlinear decline patterns preceding collapse. These approaches are strengthened by long-term datasets such as the Global Summary of the Month (GSOM) [22] and the Global

Daily Climate Dataset [24], which enable century-scale trend detection for minimum temperatures, precipitation, and snowfall.

The present study builds on this methodological foundation by integrating long-term, multi-variable climate anomalies with synthetic KNN population modeling, addressing the long-standing gap in assessing how combined climatic pathways accelerate extirpation risk.

Multiple studies emphasize that climate stress interacts with habitat degradation to drive species toward extirpation. Mantyka-Pringle et al. (2012) [16] showed that climate–habitat interactions elevate extinction risk in freshwater systems, while Chen et al. (2011) [20] linked failure to track shifting climatic niches with higher regional extirpation rates.

Urban (2015) [10] projected rising global extinction probabilities under combined climatic pressures, and Cahill et al. (2013) [11] found that climate change contributes to nearly half of documented declines worldwide. Bukaita and Ghiurau (2025) [21] further demonstrated that extreme climate anomalies preceding extirpation events significantly reduce reproduction and survival.

These findings underscore the necessity of analyzing climatic stressors as interacting pathways a framework that this research explicitly adopts.

2. Research Methodology

This study employs a multivariate climate-analysis framework to investigate how interacting climatic variables contribute to long-term population decline and local species extirpation, using Michigan as the focal case study. By integrating historical temperature, precipitation, and snowfall records with species-occurrence data, the methodology is designed to identify the principal climatic drivers associated with extirpation events and to quantify their influence on temporal population trajectories. Central to this approach is the combined use of long-term environmental records and synthetic population modeling, which together enable the examination of monthly climate anomalies and their correspondence with progressive species decline. This framework provides a rigorous basis for understanding how multiple climatic stressors—rather than temperature alone—shape species vulnerability in the Great Lakes region.

2.1. Data Collection

Climate data were compiled from multiple long-term monitoring sources. Monthly minimum, maximum, and average temperatures were obtained from the National Centers for Environmental Information (NCEI) Global Summary of the Month (GSOM) database. Temperature records from the Muskegon County Airport station, covering the period from June 1896 to January 2025, served as the primary dataset for analyzing long-term thermal trends. Precipitation and snowfall data were derived from the Global Daily Climate Dataset

curated by Guillem SD on Kaggle, which provides daily precipitation and snow-depth measurements for Lansing, Michigan from 1959 to 2023. These daily records were aggregated into monthly totals and averages using Python to ensure temporal consistency with the monthly temperature dataset.

Species data were collected from the Michigan Natural Features Inventory (MNFI), focusing specifically on endangered, threatened, and locally extirpated taxa within Muskegon County. The MNFI database provided scientific and common names, global and state conservation rankings, and the most recent year of confirmed occurrence for each species. Because long-term population counts were unavailable for most extirpated species, population trajectories were reconstructed using a K-Nearest Neighbors (KNN)–based synthetic modeling approach. This method generated realistic monthly population estimates leading up to observed extirpation years, enabling the identification of temporal decline patterns consistent with climatic anomalies.

2.2. Data Processing and Integration

All climate and species data were imported into R and converted into tibble objects to facilitate time-series analysis. Daily precipitation and snowfall values were aggregated into monthly totals, while minimum monthly temperatures (EMNT) were selected as the principal temperature metric given their importance for overwinter survival in northern ecosystems. Climate and population datasets were temporally aligned at the monthly scale, allowing direct comparison of seasonal climatic fluctuations with modeled patterns of species decline. This harmonization ensured that climatic anomalies—such as unusually warm winters or extreme precipitation events—could be accurately linked to changes in population trajectories.

2.3. Analytical Tools and Techniques

Analytical procedures consisted of both trend-based and statistical approaches. Long-term changes in minimum temperature, snowfall, and precipitation were examined using line plots, moving averages, and comparative analyses between pre-2000 and post-2000 periods to identify recent shifts in climatic regimes. The synthetic population time series generated through KNN modeling were used to evaluate both gradual and seasonal patterns of decline, with particular attention to breeding-season increases and overwinter survival reductions.

Quantitative relationships between climate variables and population changes were assessed using Pearson correlation coefficients to evaluate linear associations. Slope and trend analyses were additionally employed to quantify the directional magnitude of climatic shifts across the 130-year temperature record and the 65-year precipitation and snowfall datasets. Extreme weather anomalies were identified and examined for temporal proximity to downward shifts in pop-

ulation trajectories, highlighting potential ecological thresholds or stress periods.

Data visualization played an essential role in synthesizing results. Climate trends, anomaly patterns, and population trajectories were visualized using heatmaps, line charts, and seasonal plots constructed in R with the ggplot2 and tidyverse libraries. These visualizations enabled clear depiction of multivariate climate–population relationships and supported the interpretation of key patterns driving species extirpation in the region.

3. Metrics of Measurement

To rigorously assess the relationship between climatic variability and species decline, it is essential to employ well-defined and scientifically robust metrics that enable consistent comparison across temporal and ecological scales.

The metrics used in this study are selected to capture both the magnitude and the ecological relevance of temperature, precipitation, snowfall, and population change. Each metric aligns with established climatological standards and ecological modeling practices, ensuring that the analyses reflect meaningful environmental patterns rather than isolated or short-term fluctuations. Furthermore, by integrating synthetic population modeling with long-term climate records, these measurements provide a structured framework for identifying trends, detecting anomalies, and quantifying the degree to which climatic stressors correspond with observed or inferred declines in species abundance. The descriptions presented in Table 1 delineate the measurement strategies used to quantify climatic conditions, reconstruct population trajectories, and evaluate the strength of climate–population relationships within the study’s multivariate analytical framework.

Table 1. Measurement Methods and Climate–Population Interaction Metrics.

Variable	Metric	Measurement Approach
Minimum Temperature	°F	Monthly EMNT from GSOM dataset
Precipitation	mm	Monthly total from daily precipitation sums
Snow Depth	mm	Monthly total from daily snow depth sums
Species Population	Individuals (synthetic)	KNN-generated monthly population estimates based on last observed occurrences
Population Decline	% change per month	Derived from KNN-generated time series
Climate–Population Association	Pearson r	Correlation between population and climate variables
Extreme Event Identification	Threshold deviation	Monthly deviation from 30-year climatological mean

4. Software Tools

The analytical workflow for this study utilized a suite of computational tools designed to support data preprocessing, statistical modeling, time-series analysis, and visualization. Python served as the primary platform for data cleaning, aggregation, and preliminary processing of precipitation and snowfall records. These tasks are facilitated through established scientific libraries, including pandas, numpy, and pyarrow, which enabled efficient handling of large climate datasets and ensured data integrity prior to analysis.

R is employed for advanced time-series processing, implementation of the K-Nearest Neighbors (KNN) population modeling procedure, statistical evaluation, and generation of analytical visualizations. Key R packages included tsibble for structured temporal data handling, fable for forecasting and modeling workflows, and ggplot2 along with the broader tidyverse ecosystem for high-quality data visualization and reproducible analytical pipelines.

Geographic Information System (GIS) tools are used optionally to support spatial visualization of species occurrences within Muskegon County. These tools provided spatial context for interpreting ecological patterns and enhanced the capacity to illustrate climate–species interactions across relevant geographic scales.

5. Data Sources and Preparation

5.1. Temperature Data

Temperature records used in this study are sourced from the National Centers for Environmental Information (NCEI), a division of the National Oceanic and Atmospheric Administration (NOAA) [2]. Monthly temperature observations were obtained from the Muskegon County Airport weather station, covering the period from June 1896 to January 2025. This 129-year record provides a uniquely extensive temporal baseline for detecting long-term climatic changes relevant to ecological and conservation analyses.

The dataset contains five temperature variables as shown in [Table 2](#): minimum monthly temperature (EMNT), maximum monthly temperature (EMXT), mean temperature (TAVG), average monthly maximum temperature (TMAX), and average monthly minimum temperature (TMIN). For the purposes of this study, only EMNT is retained, as minimum tempera-

ture is most relevant to species overwintering survival, cold-stress sensitivity, and historical patterns of species extirpation. The long-term continuity of these data supports robust trend detection, seasonal comparison, and pre- vs. post-2000 climate regime analysis.

Table 2. Monthly Temperature Data for Muskegon County, Michigan.

Date	EMNT	EMXT	TAVG	TMAX	TMIN
1896 Jun	45	84	67.9	77.8	58
1896 Jul	50	86	69.4	77.9	60.7
1896 Aug	42.1	87.1	69.3	77.3	61.3
1896 Sep	30.9	82.9	58.5	65.8	51.1
1896 Oct	25	73.9	46.1	54.3	37.8
1896 Nov	12.9	62.1	37.4	43	31.9
1896 Dec	10	50	30.6	35.2	26
1897 Jan	-0.9	57	23.8	29.3	18.4
1897 Feb	6.1	37.9	26.4	31.4	21.5
1897 Mar	-11	64	30.4	37.4	23.4
...	...	...	...	...	...
2024 Mar	18.1	72	41.7	50.1	33.4
2024 Apr	32	77	51.4	60.7	42.2
2024 May	41	88	62.5	74.1	50.9
2024 Jun	42.1	93	70.2	79.5	60.9
2024 Jul	46	88	71.3	80.6	62
2024 Aug	50	91	71.9	81	62.7
2024 Sep	42.1	90	67	79.3	54.8
2024 Oct	29.1	77	55.2	66.6	43.8
2024 Nov	25.2	66.9	45.6	51.5	39.6
2024 Dec	12.2	53.1	33.9	39	28.9
2025 Jan	2.1	46	26	31.8	20.2

5.2. Species Extirpation and Conservation Status Data

Species occurrence and extirpation data are compiled from records provided by Michigan State University's natural heritage database presented in [Table 3](#). These data include scientific and common names, state-level conservation status, global conservation rank, state rank, the number of historical occurrences in Muskegon County, and the year of last observation. The dataset spans more than a century of biological

documentation and includes species classified as Special Concern (SC), Threatened (T), and globally rare taxa.

Each species' conservation rankings follow the NatureServe Global (G) and State (S) ranking systems, ranging from G1/S1 (critically imperiled) to G5/S5 (secure). These classifications provide essential ecological context regarding vulnerability to environmental change. Species with only a single historical occurrence or with no observations in over a century are classified as locally extirpated, while species last observed between 2000 and 2024 were retained as recently declining or at-risk taxa.

This structured compilation supports analysis of biodiversity loss in relation to climatic variables, particularly by

linking last-observed dates with long-term climate trends.

Table 3. Extirpations in Muskegon County [3].

Scientific Name	Common Name	State Status	Global Rank	State Rank	Occurrences in County	Last Observed in County
Rorippa aquatica	Lake cress	SC	G4*	S2	1	1898
Lithospermum latifolium	Broad-leaved puccoon	SC	G4	S2	1	1899
Triphora trianthophora	Nodding pogonia or three birds orchid	T	G4*	S1	1	1899
Euphorbia commutata	Tinted spurge	T	G5	S1	1	1901
...	...	...	...	...	...	...
Glyptemys insculpta	Wood turtle	T	G2G3	S2	11	2024
Lithobates palustris	Pickerel frog	SC	G5	S3S4	3	2024
Pantherophis spiloides	Gray rat snake	SC	G4G5	S2S3	4	2024
Plebejus samuelis	Karner blue	T	G1G2	S2	37	2024
Terrapene carolina carolina	Eastern box turtle	T	G5T5	S2S3	26	2024

Global Rank

- G1 Critically imperiled globally because of extreme rarity (5 or fewer occurrences range-wide or very few remaining individuals) or because of some factor(s) making it especially vulnerable to extinction.
- G2 Imperiled globally because of rarity (6 to 20 occurrences or few remaining individuals or acres) or because of some factor(s) making it very vulnerable to extinction throughout its range.
- G3 Either very rare and local throughout its range or found locally in a restricted range (e.g. a single western state, a physiographic region in the East) or because of other factor(s) making it vulnerable to extinction throughout its range; in terms of occurrences, in the range of 21 to 100.
- G4 Apparently secure globally, though it may be quite rare in parts of its range, especially at the periphery.
- G5 Demonstrably secure globally, though it may be quite rare in parts of its range.

State Rank

- S1 Critically imperiled in the state because of extreme rarity (5 or fewer occurrences or very few remaining individuals) or because of some factor(s) making it especially vulnerable to extirpation in the state.
- S2 Imperiled in state because of rarity (6 to 20 occurrences or few remaining individuals or acres) or because of some factor(s) making it very vulnerable to extirpation from the state.
- S3 Rare or uncommon in state (on the order of 21 to 100 occurrences).
- S4 Apparently secure in state, with many occurrences.
- ___* Data is insufficient, outdated, or incomplete.

5.3. Precipitation and Snowfall Data

Daily precipitation and snowfall records are obtained from *The Weather Dataset* by Guillem SD, which aggregates

global climate data through the Meteostat API and was accessed via Kaggle [4]. The full dataset contains more than 2.7 million daily climate records in Apache Parquet format, ensuring high-resolution temporal coverage.

For this study, the data are filtered to isolate weather ob-

servations from Lansing, Michigan, due to the absence of a complete long-term Muskegon precipitation dataset. Although Lansing lies approximately 100 miles east of Muskegon, the climatic patterns of the two regions are sufficiently similar to justify the substitution for regional-scale analysis. After filtering, the daily records are aggregated into monthly

precipitation totals and monthly snow-depth totals, enabling direct comparison with monthly minimum temperature trends.

The Lansing dataset spans May 1959 to August 2023 as shown in Table 4, providing 64 years of precipitation and snowfall information suitable for evaluating hydrological and winter-severity changes over the modern climatic era.

Table 4. Monthly Weather Data for Lansing Michigan.

Month	Precipitation mm	Snow Depth mm
1959 May	56.5	0
1959 Jun	29.3	0
1959 Jul	129.1	0
1959 Aug	98.1	0
1959 Sep	64.7	0
1959 Oct	126.8	0
1959 Nov	75.5	202
1959 Dec	56.7	228
1960 Jan	73.2	1601
1960 Feb	67.5	3636
...	...	...
2022 Oct	46.8	0
2022 Nov	27.1	440
2022 Dec	32	1230
2023 Jan	49.3	840
2023 Feb	79.7	790
2023 Mar	114.7	670
2023 Apr	98.8	0
2023 May	24.5	0
2023 Jun	22.7	0
2023 Jul	158.5	0
2023 Aug	105.2	0

5.4. Data Analysis Procedures

All data are imported into R and converted into time-series tables (tsibble format) to facilitate temporal alignment, visualization, and modeling. Analysis proceeded in multiple stages:

Minimum Temperature Trend Analysis

Long-term monthly EMNT values are examined to identify century-scale trends and to determine the coldest months of the year. Minimum temperatures before and after the year

2000 were compared to evaluate whether warming has accelerated in recent decades.

Snowfall and Precipitation Trends

Monthly snow-depth totals and precipitation amounts were assessed for shifts in maximum, minimum, and average values across the same pre-2000 and post-2000 intervals.

Visualization and Comparative Analysis

Graphical analyses including monthly distribution plots, mean trend overlays, and pre/post-2000 comparisons are used to detect abrupt or directional changes in winter severity and associated hydrological patterns as shown in Figure 1.

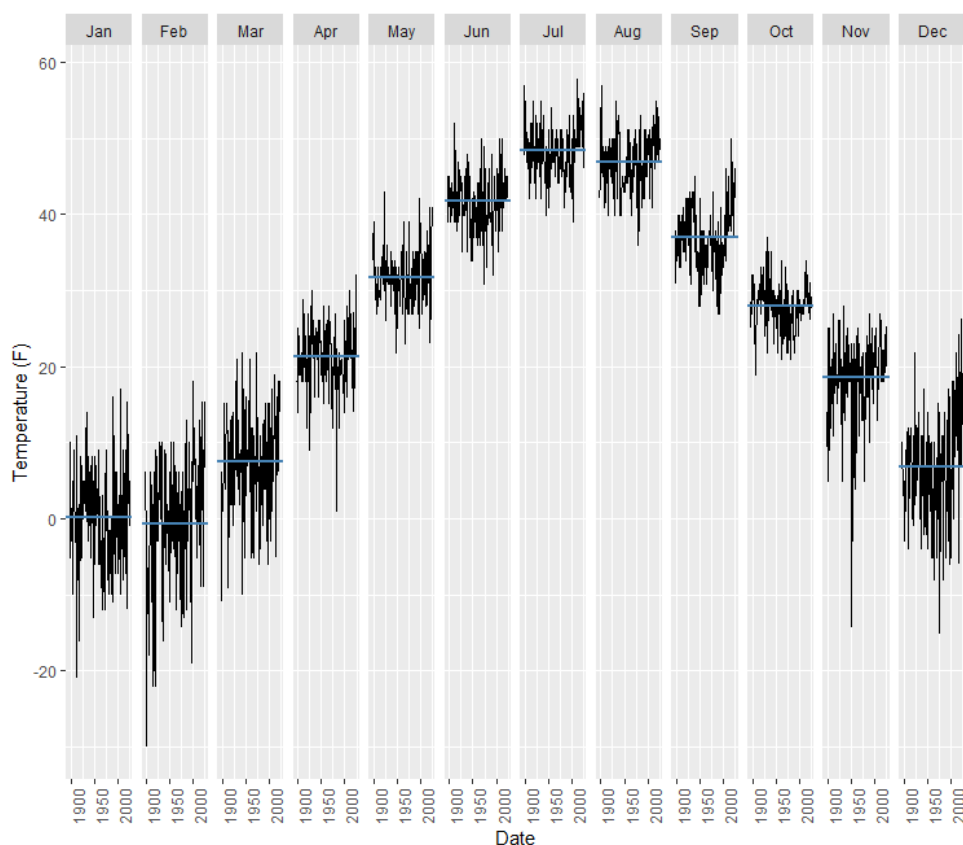


Figure 1. Minimum Monthly Temperature and the Mean.

As shown in Figure 1, long-term monthly patterns in minimum temperature become clearly observable across the 130-year record, with the mean monthly temperature depicted by the blue line. Among all months, February exhibits the most pronounced long-term trend and is consistently the coldest month of the year, followed by January and then December.

5.5. Synthetic Population Time Series for Selected Species

Because long-term population data for rare and extirpated species are seldom available, synthetic monthly population trajectories are generated using a K-Nearest Neighbors (KNN)-based modeling approach applied to the species' last observed dates. For each focal species, the final documented year of observation was used as an anchor point for building realistic decline curves capturing seasonal breeding pulses and gradual reductions in abundance.

Four species are selected due to their ecological sensitivity to winter severity and climatic stress:

Blanchard's Cricket Frog (*Acris blanchardi*) – sensitive to warmer winters and overwinter mortality

American Goshawk (*Astur atricapillus*) – affected by heat stress and prey availability

Kirtland's Snake (*Clonophis kirtlandii*) – dependent on

cold, moist prairie conditions

Long-eared Owl (*Asio otus*) – reliant on coniferous cover associated with cooler climates

Synthetic population heatmaps and seasonal curves were generated to visualize decline patterns and relate them to climatic variables.

6. Results

6.1. Long-term Trends in Minimum Temperature

Analysis of the 130-year minimum temperature record from Muskegon County reveals distinct seasonal and long-term patterns in winter temperature dynamics. As shown in Figures 2 and 3, minimum temperatures follow clear month-specific trajectories, with February consistently representing the coldest period of the year, followed by January and December. These patterns underscore the vulnerability of winter-dependent species to even modest increases in minimum temperature baselines.

To more clearly assess long-term shifts, the dataset was divided into two periods: pre-2000 and post-2000. This separation enables a focused comparison of historical cold-weather conditions with more recent warming trends.

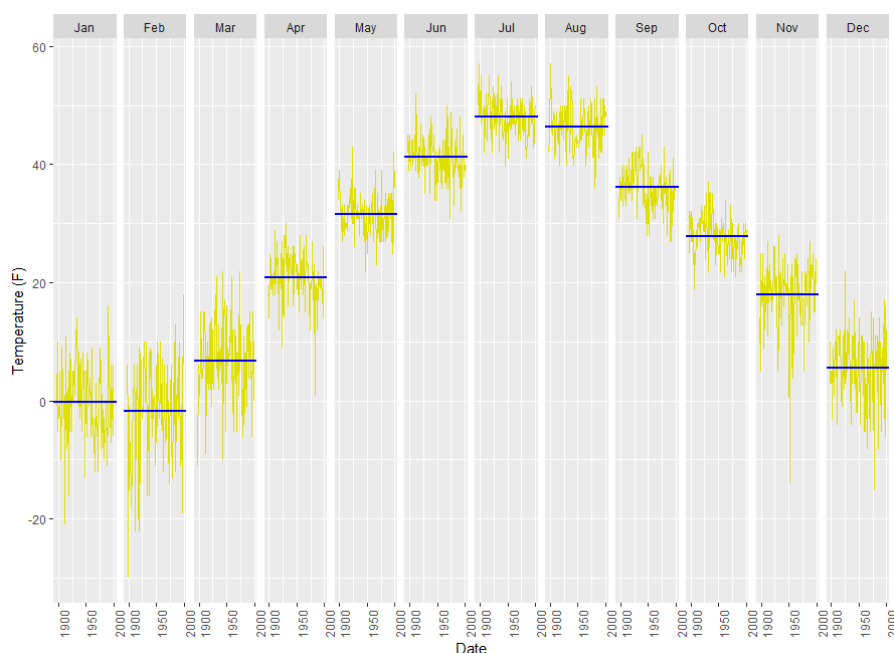


Figure 2. Minimum Monthly Temperature and Pre-2000 Mean Baseline.

As shown in Figure 2, the coldest month is February with a mean of -2 degrees Fahrenheit with January and December following with a mean of 0- and 5-degrees Fahrenheit respectively.

After the year 2000, the winter temperature profile shifted noticeably toward warmer conditions. January remained the

coldest month, with an average minimum of about 2 °F, but February and March experienced increases of more than 5 °F compared with their pre-2000 averages. December showed an even larger shift, with its mean minimum temperature rising by approximately 9 °F as shown in Figure 3.

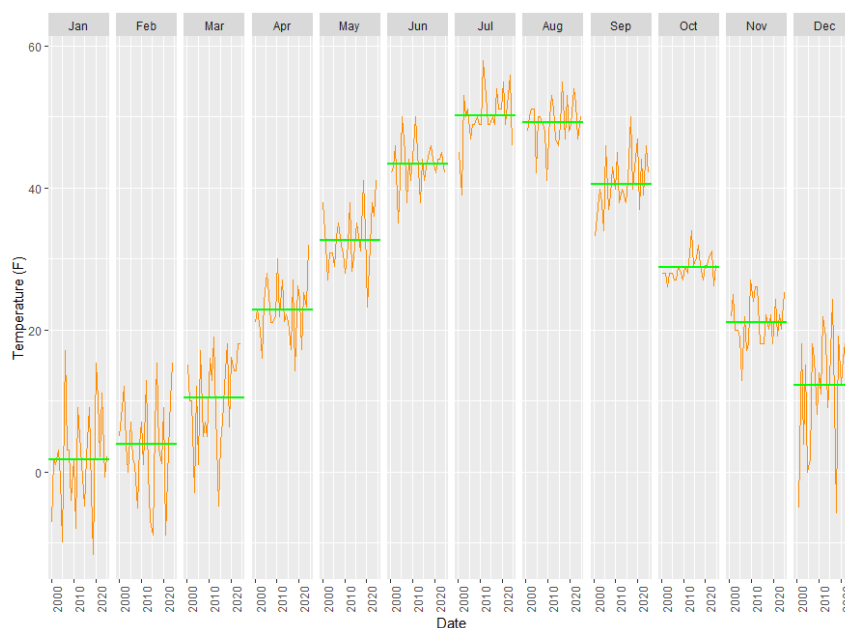


Figure 3. Minimum Monthly Temperature and Post-2000 Mean Baseline.

As shown in Figure 3, January records the coldest average minimum temperature at approximately 2 °F. February and

March follow with mean minimum temperatures of about 4 °F and 11 °F, respectively. December is slightly warmer, with an

average minimum of around 14 °F.

Figures 4 present two radar charts depicting the average minimum temperature for each month during the pre-2000 and post-2000 periods. A visual comparison of the two charts reveals a distinct and consistent warming pattern throughout the year. The post-2000 radar plot occupies a larger radial area, with its boundary extending farther outward from the center, indicating higher average minimum temperatures across all months relative to the earlier period. The most substantial increases occur during the coldest months December, January,

and February as well as during the transitional spring and autumn seasons. These patterns show that nighttime temperatures, which typically represent the coldest conditions of the day, have risen more sharply than those in warmer seasons. The observed expansion of the radar plot during the post-2000 period reflects the acceleration of warming associated with human-driven climate change. When interpreted together, the two charts provide clear local-scale evidence of a significant upward shift in monthly minimum temperatures across the full annual cycle.

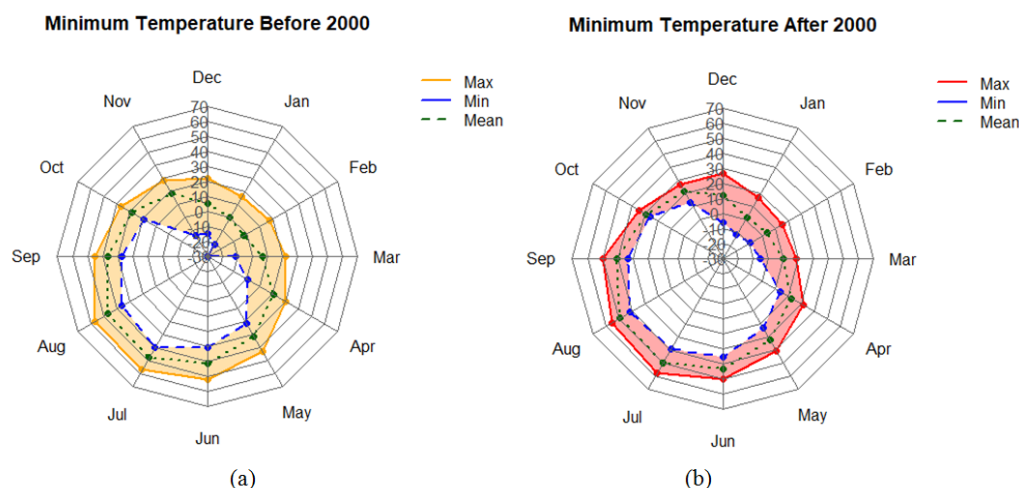


Figure 4. Comparison of Minimum Temperatures pre-2000 and post-2000.

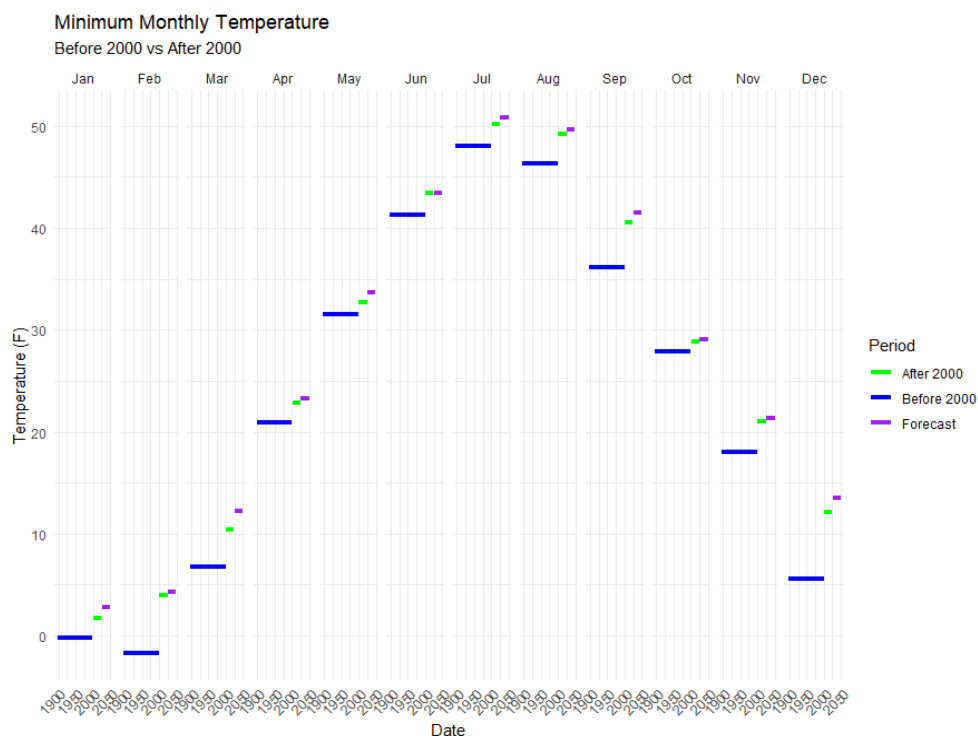


Figure 5. Observed and Forecasted Mean Monthly Minimum Temperatures: Pre-2000, Post-2000, and 2025–2050.

Figure 5 presents a comparison of mean monthly minimum temperatures across three periods: pre-2000, post-2000, and the projected 2025–2050 period using ARIMA forecasting model. The graph demonstrates a clear upward shift in monthly minimum temperatures throughout the year, with the most pronounced increases occurring during the winter and transitional months. Historical data indicate a warming trend in nighttime temperatures, while projections suggest that this trend will continue and potentially accelerate, with forecasted minimum temperatures exceeding both pre- and post-2000 values for nearly all months. The projected rise is particularly significant during the coldest months, implying a substantial reduction in extreme cold events, including frost days. These changes have critical implications for regional ecology and agriculture, including longer growing seasons and earlier plant dormancy break, while also introducing new risks associated with altered seasonal cycles.

6.2. Snowfall Variability Before and After 2000

Monthly snowfall depth comparisons shown in Figure 6 reveal heterogeneous but meaningful shifts in winter conditions. December displayed an isolated extreme outlier, nearly 3 meters above typical snowfall levels, but mean snowfall remained relatively stable. January exhibited a significant decline in maximum snowfall by roughly 2 meters, accompanied by an approximately 0.5-meter decrease in mean snowfall depth. February showed mixed behavior, with maximum snowfall reduced by about 1.5 meters, while average snowfall increased slightly. Snowfall in April virtually disappeared after 2000, whereas earlier decades recorded accumulation approaching 2 meters. These findings suggest that warming trends are contributing to both reduced snow-pack duration and altered seasonal snowfall distribution.

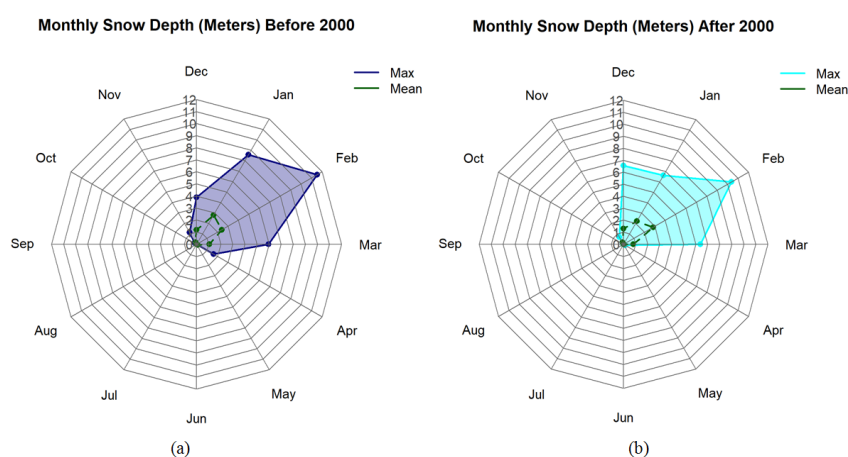


Figure 6. Comparison of Monthly Snow Depth pre-2000 and post-2000.

6.3. Precipitation Changes Across the Study Period

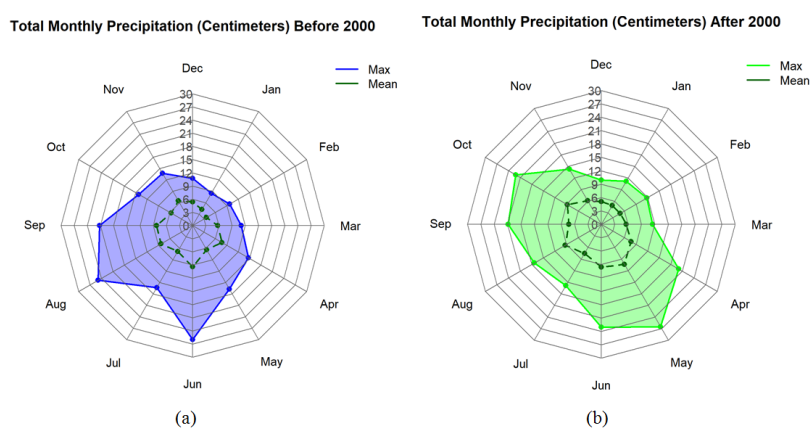


Figure 7. Comparison of Monthly Precipitation pre-2000 and post-2000.

Monthly precipitation patterns also demonstrated notable shifts over the 64-year Lansing dataset. As shown in Figure 7, August recorded one of the most substantial reductions in total precipitation, decreasing by approximately 6 centimeters after 2000. June experienced a decline of roughly 3 centimeters in maximum precipitation, while July remained relatively constant. Conversely, May and October exhibited increases in maximum precipitation of approximately 9 centimeters. Average precipitation similarly rose in these two months by around 3 centimeters. These results indicate that precipitation variability is becoming increasingly month-specific, with potential implications for habitat moisture regimes and breeding conditions for sensitive species.

6.4. Synthetic Population Trajectories for Select Species

Given the limited availability of systematic population counts, K-Nearest Neighbors (KNN) modeling is employed to generate synthetic monthly population trajectories for four climate-sensitive species with documented extirpation risk. These modeled trends allow comparison of population behavior relative to observed climate anomalies.

Blanchard's Cricket Frog (*Acris blanchardi*):

The Blanchard's Cricket Frog, *Acris blanchardi*, shown in Figure 8, exhibits population peaks during the spring breeding months, as illustrated in Figure 9, followed by a gradual decline. The continued reductions observed in later years correspond with documented effects of warmer winters, which reduce overwinter survival and contribute to long-term population decline in this species.



Figure 8. Blanchard's Cricket Frog (*Acris blanchardi*) [26].

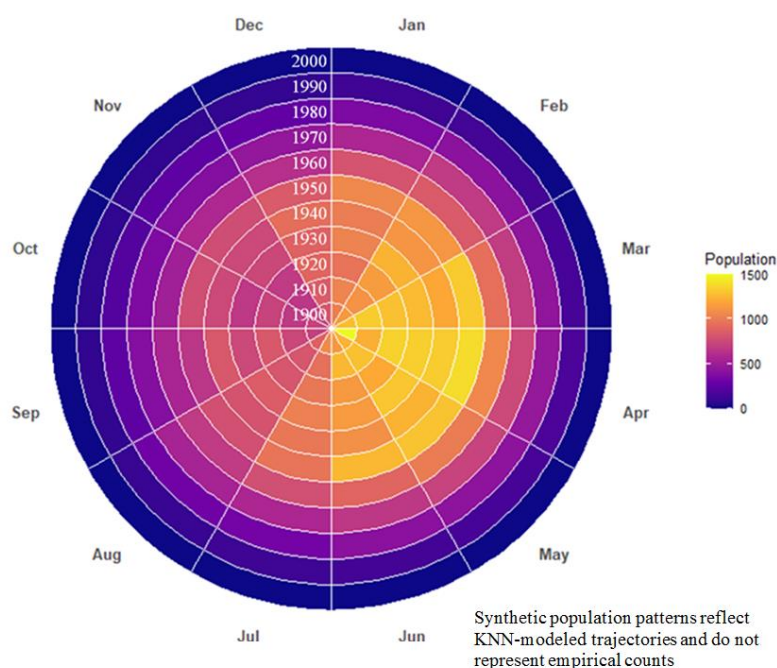


Figure 9. Population Heatmap of Blanchard's Cricket Frog.

American Goshawk (*Accipiter gentilis*):

The American Goshawk, *Accipiter gentilis*, depicted in Figure 10, exhibits pronounced seasonal peaks in population during the spring breeding months. Over time, these populations experience marked declines as shown in Figure 11

highlighting the progressive contraction of individuals outside of the peak season. These patterns align with ecological evidence indicating that elevated temperatures reduce hunting efficiency and that ongoing habitat degradation further contributes to long-term population decreases.



Figure 10. American Goshawk [27].

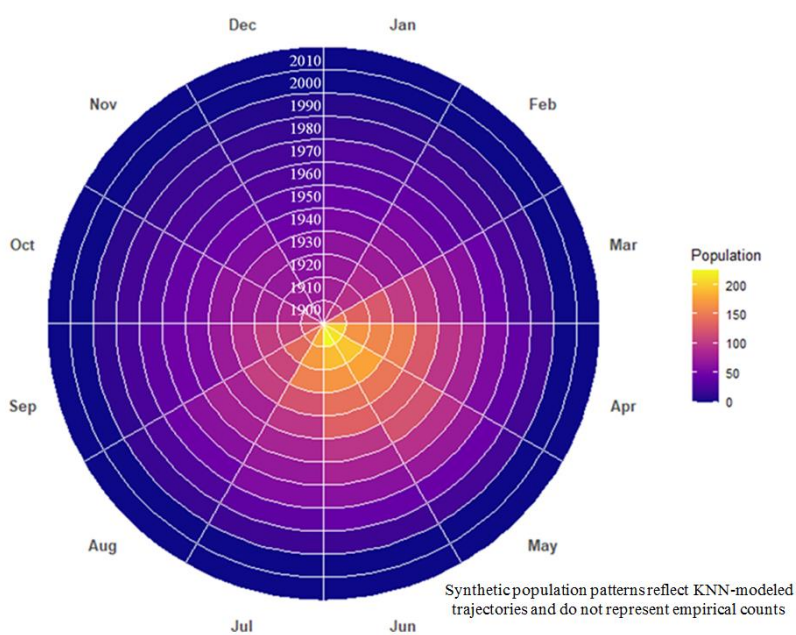


Figure 11. American Goshawk Population.

Kirtland's Snake (Clonophis kirtlandii):

The Kirtland's Snake, *Clonophis kirtlandii*, depicted in Figure 12, exhibits population dynamics shown in Figure 13, with peak abundance occurring from May through July. Populations gradually contract into the late season and winter

months. This pattern reflects the species' sensitivity to thermal stress and the impact of reduced winter snow insulation, consistent with the declines observed in the synthetic population series.



Figure 12. Kirtland's Snake [28].

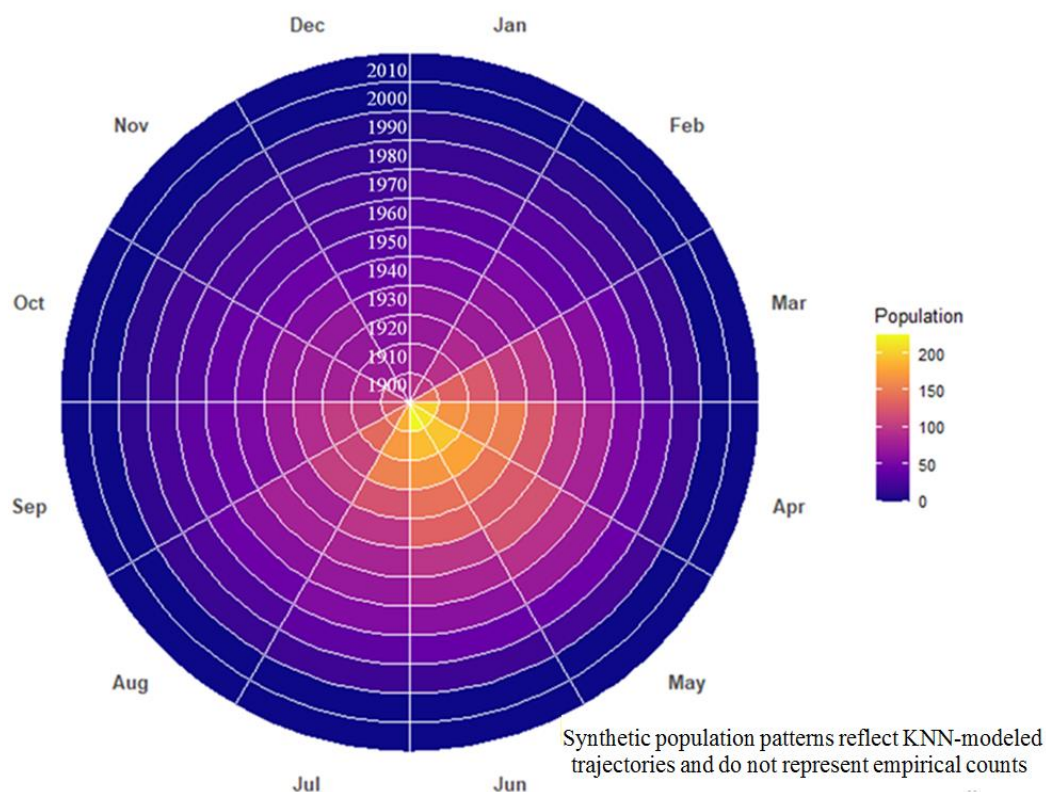


Figure 13. Kirtland's Snake Population.

Long-eared Owl (Asio otus):

The Long-eared Owl, *Asio otus*, illustrated in Figure 14 with corresponding population dynamics presented in Figure 15, demonstrates maximal abundance during June and July, coinciding with the species' breeding period. Thereafter,

population levels exhibit a progressive decline, culminating in local extirpation by 2005. This contraction is likely attributable to the reduction of dense coniferous habitats, driven by increased temperatures and altered snow regimes, which have adversely affected both survival and reproductive success.



Figure 14. Long-eared Owl [29].

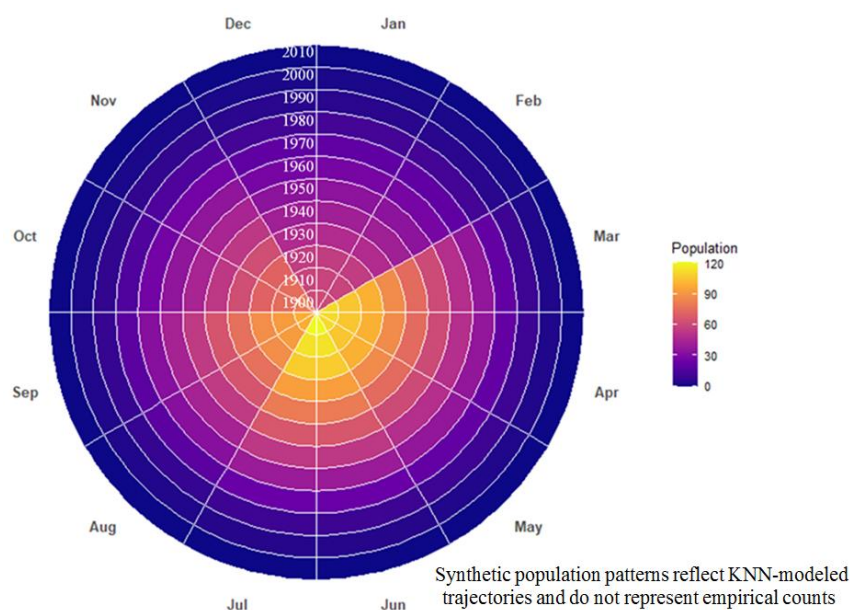


Figure 15. Long-eared Owl Population.

7. Other Extinct and Locally Extirpated Species in Michigan

Michigan's ecosystems have historically supported a remarkable diversity of plant and animal species, from forests and wetlands to prairies and rivers. Table 4 highlights additional species that have become locally extirpated or extinct in Michigan, illustrating the continuing impacts of climate change and habitat alteration.

The species listed in Table 5 demonstrate a broad range of ecological sensitivities. Aquatic species, such as Lake sturgeon (last observed 2015) and Wild rice (2016), are particularly vulnerable to warmer winter temperatures, which disrupt spawning and growth, while hydrological changes exacerbate habitat stress. Migratory and wetland birds, including the Cerulean warbler (2013) and Prothonotary warbler (2005), experience shifts in breeding timing and food availability due to altered winter temperatures and wetland hydrology. Forest birds, such as the Red-shouldered hawk (2014) and Hooded warbler (2003), are also affected by temperature-driven changes in prey dynamics and nesting success.

Plants have similarly faced substantial pressures. Wetland and prairie species, including Lake cress (1898), Tall nut rush

(1987), and Pitcher's thistle (2013), are sensitive to warmer winters that accelerate drying, alter soil freeze-thaw cycles, and compromise seed dormancy and early growth. Forest understory plants, such as Ginseng (2010) and Virginia blue-bells (2011), have experienced increased stress from both temperatures shifts and herbivory.

Freshwater mussels and snails, including Slippershell (1936), Round lake floater (1930), and Campeloma spire snail (1932), have been severely impacted by the combination of warming winters, habitat loss, and water quality degradation, reflecting the vulnerability of aquatic invertebrates to even small environmental changes. Prairie insects, such as the Great Plains spittlebug (2014) and Dune cutworm (1989), have declines closely linked to minimum winter temperatures affecting survival.

The chronological span of these extirpations illustrates a historical transition in Michigan's biodiversity losses: earlier extirpations were largely driven by direct habitat destruction, while more recent declines increasingly reflect the compounded effects of climate warming interacting with ongoing habitat degradation. This underscores the urgency of implementing integrated conservation strategies that address both habitat preservation and climate adaptation to prevent further losses.

Table 5. Extinct and Locally Extirpated Species in Michigan: Primary Drivers and Observed Years.

Common Name	Last Observed	Notes
Lake sturgeon	2015	Cold-water fish; warmer winters reduce suitable spawning conditions and alter river thermal regimes; also impacted by damming & overfishing

Common Name	Last Observed	Notes
Wild rice	2016	Aquatic plant; sensitive to warmer water temperatures during winter and early spring; hydrological changes exacerbate stress
Cerulean warbler	2013	Migratory bird; warmer winters shift insect emergence and breeding timing, affecting food availability
Prothonotary warbler	2005	Wetland-dependent; warmer winters modify wetland hydrology and breeding habitat quality
Black tern	2005	Wetland bird; altered winter temperatures impact prey populations and wetland conditions
Red-shouldered hawk	2014	Forest raptor; warmer winters affect prey dynamics and nesting success
Hooded warbler	2003	Forest bird; sensitive to winter temperature shifts impacting early-season foraging
Prairie warbler	1998	Breeding success linked to warmer winters, which affect insect abundance and habitat quality
Lake cress	1898	Wetland plant; warmer winters accelerate water loss and drying of wetlands, contributing to habitat degradation
Broad-leaved puccoon	1899	Forest understory plant; warmer winters reduce dormancy survival and increase stress from habitat loss
Nodding pogonia / three birds orchid	1899	Forest plant; warmer winters may disrupt flowering cycles and seedling survival
Tinted spurge	1901	Prairie/forest species; warmer winters alter soil freeze-thaw cycles, affecting survival
Black and gold bumble bee	1930	Pollinator; warmer winters can reduce overwintering survival and disrupt seasonal activity
Round lake floater	1930	Freshwater mussel; warmer winters accelerate metabolic rates, increasing stress in altered wetlands
Campeloma spire snail	1932	Aquatic snail; warmer winter waters amplify impacts of pollution and habitat loss
Slippershell	1936	Freshwater mussel; reduced winter chilling affects reproduction and stream survival
Rainbow	1936	Mussel species; warmer winter temperatures degrade habitat and increase predation risk
Pink heelsplitter	1936	Freshwater mussel; warming winters reduce cold-water refugia in streams and wetlands
Fawnsfoot	1936	Freshwater mussel; affected by both warmer winters and habitat destruction
Bigmouth shiner	1940	Stream fish; warmer winters alter seasonal flows and reduce suitable cold-water habitats
Furrowed flax	1949	Prairie/grassland plant; warmer winters may reduce seed survival and dormancy success
Missouri rock-cress	1950	Prairie/rocky habitat plant; winter warming alters microhabitat conditions
Spotted gar	1956	Wetland and river fish; warmer winters affect spawning cues and water temperatures
Woodland goosefoot	1961	Forest/woodland plant; warmer winters increase stress and susceptibility to habitat change
Trailing wild bean	1961	Forest understory plant; warmer winters disrupt dormancy and early growth
Scirpus-like rush	1983	Wetland species; warmer winters reduce ice cover, affecting water levels and survival
Purple spike rush	1987	Wetlands; warmer winters accelerate drying and habitat degradation
Tall nut rush	1987	Wetlands; survival and reproduction impacted by warmer winter conditions
Meadow beauty	1988	Prairie/wetland plant; altered winter conditions change soil moisture and nutrient availability
Hall's bulrush	1988	Wetlands; warmer winters impact water levels and plant survival
Few-flowered nut rush	1988	Wetlands; temperature-sensitive survival affected by milder winters
Dune cutworm	1989	Sand dune insect; warmer winters reduce larval overwintering success
Sprague's pygarcia	1990	Prairie moth; warmer winters disrupt pupal survival

Common Name	Last Observed	Notes
Pine katydid	1991	Pine forest specialist; winter warming affects egg survival and seasonal cycles
Virginia water-horehound	1994	Wetland plant; warmer winters accelerate desiccation and habitat loss
Blanchard's cricket frog	1996	Amphibian; warmer winters can increase winter mortality and disrupt breeding timing
Kirtland's snake	1996	Prairie wetlands; warmer winters reduce hibernation survival and habitat suitability
American goshawk	2000	Forest predator; winter warming indirectly affects prey populations
Henslow's sparrow	2002	Prairie bird; survival influenced by milder winters altering cover and food availability
Northern prostrate club-moss	2003	Wetlands & forest understory plant; sensitive to temperature shifts in winter
Deertoe	2004	River mussel; warmer winter water stress compounds habitat loss and poor water quality
Paper pondshell	2004	Freshwater mussel; survival impacted by milder winters in combination with habitat destruction
Tall green milkweed	2005	Prairies converted; warmer winters may affect seed dormancy and establishment
Long-eared owl	2005	Forest predator; warmer winters affect prey abundance and hunting success
Northern harrier	2005	Grassland & wetland bird; winter warming changes prey distribution and cover
Black redbhorse	2005	Riverine fish; warmer winter water temperatures affect growth and reproduction
Eastern massasauga	2005	Wetland-dependent; warmer winters impact hibernation and wetland hydrology
Umbrella-grass	2006	Wetland plant; milder winters reduce survival and water availability
Cross-leaved milkwort	2006	Prairie/wetland plant; warmer winters alter soil moisture and dormancy
Whorled mountain mint	2006	Grassland plant; winter warming may reduce seedling survival
Grasshopper sparrow	2007	Prairie bird; winter warming affects cover and overwinter survival
Tall meadowrue	2007	Wetland & prairie plant; survival impacted by milder winter stress
Ginseng	2010	Forest understory; warmer winters reduce dormancy success and increase herbivory stress
Downy sunflower	2011	Grassland plant; winter warming alters soil freezing cycles and seed survival
Dwarf-bulrush	2011	Wetland plant; warmer winters affect water levels and plant persistence
Northern appressed clubmoss	2011	Forest/wetland plant; milder winters reduce cold-dependent dormancy survival
Virginia bluebells	2011	Forest wetlands; winter warming impacts timing of flowering and growth
Queen snake	2011	Streamside/wetland snake; warmer winters affect hibernation and prey availability
Bald-rush	2011	Wetlands; warmer winters exacerbate drying and survival stress
Pitcher's thistle	2013	Dune plant; warmer winters reduce cold dormancy success and seedling survival
Atlantic blue-eyed-grass	2013	Coastal wetlands; warmer winters alter water levels and cold stress
Hill's thistle	2014	Prairie plant; winter warming affects dormancy and early growth
Great Plains spittlebug	2014	Prairie insect; winter survival depends on minimum temperatures
Climbing hempweed	2014	Wetland/prairie plant; warmer winters reduce cold survival and water-dependent habitats

8. Conclusion

This study demonstrates that long-term climatic shifts, particularly in minimum temperatures, snowfall depth, and

precipitation variability, are primary drivers of species vulnerability and local extirpation, as illustrated in the Michigan case study. Analysis of a 129-year minimum temperature record revealed pronounced month-specific warming trends, with February, January, and December historically being the

coldest months. Post-2000 conditions show a substantial reduction in extreme cold events, with winter minimum temperatures rising by 5 °F to 20 °F across critical months, fundamentally altering overwintering environments for cold-adapted and winter-dependent species. Projected warming for 2025–2050 suggests that these trends will continue, with nighttime temperatures expected to rise further, particularly during the coldest months, extending the growing season while introducing new ecological risks such as earlier dormancy break in plants.

Snowfall patterns further reflect this climatic transition. Comparisons of pre- and post-2000 snowfall reveal significant declines in January and February snowpack and the near disappearance of April snow, reducing both the duration and insulating capacity of snow cover. These changes disrupt thermoregulation, dormancy, and reproductive success for numerous species.

Precipitation trends highlight increasing variability, with post-2000 reductions in summer rainfall—such as a 6-cm decline in August contrasting with increases of up to 9 cm in May and October. These shifts alter soil moisture regimes, flood cycles, and habitat suitability, particularly affecting amphibians, wetland plants, grassland birds, and aquatic organisms dependent on predictable seasonal water availability.

Collectively, these results demonstrate that species decline in Michigan arises from the interaction of multiple climatic stressors rather than temperature changes alone. Warmer winters, reduced and redistributed snowfall, and increasingly variable precipitation create a compound climate environment that undermines survival, reproduction, and population stability. When combined with habitat degradation, these factors accelerate biodiversity loss, as evidenced by the documented chronology of extinctions and local extirpations.

By integrating long-term climatic data with ecological interpretation, this research highlights the importance of multivariate frameworks for assessing species risk under rapid environmental change. The findings provide actionable insights for conservation planning in the Great Lakes region and underscore that ongoing and projected warming, particularly of minimum temperatures, will continue to reshape ecological conditions, amplifying challenges for cold-adapted species.

Abbreviations

EMNT	Minimum Temperature
EMXT	Maximum Temperature
TAVG	Average Temperature
TMIN	Minimum Average Daily Temperature
TMAX	Maximum Average Daily Temperature

Conflicts of Interest

The authors declare no conflicts of interest.

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