Exploring the Associations Between Mercury Releases, Temperature, and Bank Swallow Abundances in Southern Ontario

by

Anushri Mahadeo

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Abstract

Bank swallow (*Riparia riparia*) populations in North America have experienced significant long-term declines since the 1970s. A potential limiting factor may be reduced flying insect prey availability associated with complex factors like climate change and pollutants, including pesticides and heavy metals. However, the impacts of heavy metals like mercury and changing temperature regimes on bank swallow declines remain unknown. This study aimed to 1) identify temporal changes in anthropogenic mercury releases, temperature, and bank swallow abundances from Period A (2001-2005) to B (2018-2022) and 2) examine the associations between the predictors (mercury and temperature) and bank swallow abundances in Southern Ontario. All datasets were obtained from publicly available sources. Bank swallow abundances were estimated through ordinary Kriging, and mean predicted abundances, temperatures, and mercury releases were summarized by defined regions within Southern Ontario using ArcGIS Pro. Multiple regression analysis was performed to study the relationships between the variables. Results revealed declines in bank swallow populations (-9.9%) alongside increasing temperatures (+5.3%), with a significant negative association between the two. Mercury exhibited no significant changes between the periods of interest and was not a substantial predictor of bank swallow abundances. However, the inclusion of both predictors strengthened the overall model, and regional inconsistencies suggest an interplay between these threats and additional factors. While mercury pollution was insignificant in the current model, its bioaccumulation in aquatic environments is complex, so several contributors were likely unaccounted for. Overall, these findings stress the need for a multifaceted approach in bank swallow conservation efforts, considering the interactions between numerous environmental threats.

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List of Abbreviations

Abbreviation	Definition
AHCCD	Adjusted and Homogenized Canadian Climate Data
ECCC	Environment and Climate Change Canada
GIS	Geographic Information Systems
Hg(0)	Elemental mercury
Hg(II)	Inorganic divalent mercury
MeHg	Methylmercury
NABBS	North American Breeding Bird Survey
NPRI	National Pollutant Release Inventory
OBBA	Ontario Breeding Bird Atlas
PSE	Prediction standard error
RMSE	Root-mean-square error

1.0 INTRODUCTION

1.1 The State of Bank Swallows in Ontario

1.1.1 Bank Swallow Ecology

Bank swallows (*Riparia riparia*) are small, migratory songbirds with an extensive distribution in Canada, with populations located in all provinces and two territories.[1] In Ontario, populations are predominantly located in the southern portion, near the northern shores of Lakes Erie and Ontario.[2] They are found in lowland habitats and open areas, typically near water bodies that provide a source of erosion to create their nesting burrows in sandy vertical banks.[1] Colonies may also be situated in anthropogenic habitats, including sand and gravel pits.[1] During the breeding season (May to July), bank swallows forage over open aquatic and terrestrial habitats, approximately 200-500 meters from their colony, with distances up to 1 kilometre travelled occasionally due to prey availability and climate.[1] Since these swallows are aerial insectivores, they almost exclusively feed on flying insects such as flies, bees, wasps, and beetles, with occasional terrestrial/aquatic prey.[1] Thus, they are often tied to the water due to the abundance of significant food sources like emergent aerial insects.[2] Based on their feeding behaviours, bank swallows are important for controlling insect populations.[3] Due to their specific habitat requirements, they are also important indicators of the health and diversity of nearby aquatic environments, which are crucial to numerous other biota.[4]

1.1.2 Bank Swallow Population Status

1.1.2a) Methods of Gathering Bird Population Trend Data

Trends in the distribution and abundance of birds, including bank swallows, have been assessed using data from large-scale citizen science projects that record breeding evidence of birds during May to July.[1] These projects include the Ontario Breeding Bird Atlas (OBBA) and North American Breeding Bird Survey (NABBS).[1] The OBBA has an extensive coverage of populations in several bank swallow habitats, however, many colonies may have been under-reported.[2] Occurring over a larger geographic scale, the NABBS is a standardized roadside bird survey.[1] While the NABBS encompasses most of the Canadian bank swallow range, there may be sampling biases that lead to inaccuracies in estimated abundances.[1,2] As it occurs at roadside stops, there may be overestimates at human-made habitats compared to natural habitats.[1,2] Additionally, spatial sampling gaps may exist in northern regions, resulting in underestimates.[1] Nevertheless, the OBBS and NABBS could provide insights into the spatiotemporal trends in bank swallow abundances and distributions.

1.1.2b) Bank Swallow Population Declines

North American aerial insectivore populations have been experiencing considerable long-term declines since the 1970s, with the steepest reductions seen in bank swallows.[5] In Canada, losses of about 98% were seen since the 1970s.[5] Based on NABBS data, annual population declines of about 10% were found in the 1990s, but have since reduced to approximately 5%.[5] Ontario is one of the provinces with some of the greatest long-term declines of 9.5% annually.[5] Despite increases in volunteers participating in the second OBBS, there were fewer atlas squares with confirmed bank swallow breeding evidence.[1,5] Population estimates in specific regions have also reflected these declines, as populations in the Lake Erie shorelines reached a low in 2020.[5] Due to these declines, bank swallows have been listed as “threatened” in Ontario’s 2014 *Endangered Species Act*, and the 2017 federal *Species at Risk Act*.[5] Therefore, it is imperative to analyze the threats that impact bank swallow survival and reproduction to devise strategies to reduce further declines.

1.2 Threats to Bank Swallows

The specific reasons for bank swallow population declines remain unclear, with numerous threats potentially having contributions.[5] A major proposed driver is the reduction in the abundance of their insect prey, which are likely sensitive to natural habitat losses, climate change, and pollutants, including pesticides and heavy metals.[5,6] It is unlikely that any of these factors alone contribute to the declines; instead, they likely result from complex interactions among multiple factors.[6] Particularly, the impacts of heavy metals like mercury, as well as changes in temperature and precipitation regimes, remain unknown, and are cited as approaches to recovery in both the Canada and Ontario Recovery Plans.[2,5]

1.2.1 Mercury Pollution

Mercury is a neurotoxin capable of inducing harmful neurological effects in living organisms when accumulated in increasing concentrations over time.[7] Historically, mercury pollution is a global issue, with the majority of anthropogenic inputs to the atmosphere, land, and water stemming from urban and industrial areas.[7] Generally, mercury contamination is higher at point sources, areas with extensive water management, coastal locations, and environments with greater industrial activity.[8] Mercury is released and/or converted to various forms in the environment that include gaseous elemental mercury (Hg(0)), inorganic mercury, and organic mercury compounds such as methylmercury.[9] The gaseous form of mercury persists in the atmosphere for 6-18 months, allowing it to also deposit in both local and distant areas from point sources.[7,9]

1.2.1a) Quantifying Mercury Releases in Ontario

The releases, disposals, and transfers of pollutants from various Canadian facilities are tracked through the publicly available National Pollutant Release Inventory (NPRI).[10] Mercury is one of the contaminants whose releases to the air, water, and land are tracked.[10]

In Canada, mercury releases have reduced since the 1980s due to increased restrictions, the closure of industrial operations, and phasing out its usage in various products.[10] In Ontario, emissions have been reduced by 90 percent since the 1990s, however, releases are still prevalent.[10,11] As of 2019, Ontario contained the highest quantities of mercury released to the atmosphere and water of all the provinces.[10] Specifically, waste and wastewater systems contribute to the majority of aquatic mercury releases, while atmospheric releases stem from the waste treatment and disposal sector, electrical facilities, and iron and steel industries.[10] Despite reductions in mercury loads through the years, it remains persistent in environments and continues to affect biota.[12,13]

1.2.1b) How Mercury Enters Food Webs

Mercury undergoes complex biogeochemical cycling when it enters the environment. Atmospheric Hg(0) can be oxidized to inorganic divalent mercury (Hg(II)), which can enter aquatic and terrestrial systems through wet and dry deposition (Fig. 1).[12] Wet deposition occurs when it enters ecosystems through precipitation, while dry deposition refers to its direct settling on the surface (Fig. 1).[12] High levels of wet deposition typically result from local gaseous emission sources.[14] In terrestrial ecosystems, the mercury that does not recycle into the atmosphere can be incorporated into the soil and deposited onto aboveground vegetation.[12] However, most mercury concerns revolve around its contamination in aquatic ecosystems.[12] Anaerobic sulfate- and iron-reducing bacteria facilitate the methylation of small portions of Hg(II) in wetlands, lakes, and reservoirs, thus converting it to highly toxic methylmercury (MeHg) (Fig. 1).[12] This form is the most bioavailable and harmful, as it readily assimilates into aquatic biota and biomagnifies up the food chain.[12] Biomagnification occurs when higher trophic level predators consume contaminated prey, and the concentrations of MeHg increase, or bioaccumulate, in their tissues.[12] For instance, studies have demonstrated rapid changes in MeHg concentrations in aquatic biota in response to atmospheric emissions and wet deposition from local sources.[14]

1.2.1c) The Impacts of Mercury on Bank Swallows

The predators vulnerable to MeHg exposure are not solely limited to those inhabiting aquatic systems, but also terrestrial species, such as swallows.[7] In the spring, MeHg production is the highest due to anoxic water column conditions.[15] This coincides with the breeding seasons of many migratory birds, potentially putting them at risk.[15] As emergent insects are important prey sources for bank swallows, their consumption may expose these birds to large concentrations of aquatic contaminants like mercury (Fig. 1).[8]

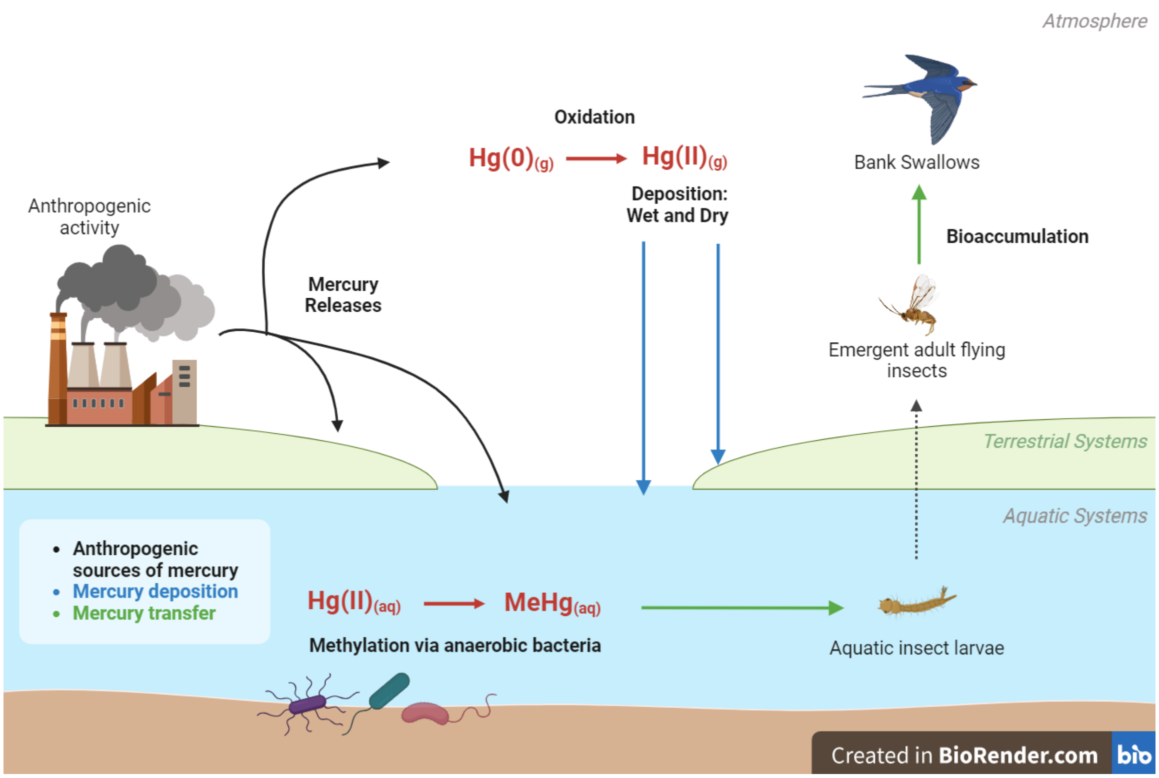


Figure 1. The transfer of mercury to bank swallows. Mercury can be released to the environment through anthropogenic activities. It is converted to various forms, assimilates into aquatic larval insects, and transfers to bank swallows through consumption of emergent adult insect prey. Figure generated using BioRender.

Adult bank swallows were found to have some of the highest feather mercury concentrations in Saskatchewan, Ontario, and Yukon, suggesting a link between feeding habits and mercury exposure.[8] Various studies have highlighted a range of negative biological impacts of mercury on similar swallow species. Field studies of tree swallows residing near heavily contaminated rivers demonstrated that smaller eggs and fewer fledglings were produced compared to reference locations.[16–18] In these cases, their insect prey had significantly higher mercury levels, providing evidence for the biomagnification of mercury and its negative effects on reproductive outputs.[16,17] Changes in tree swallow parental nesting behaviours have also been found, as females with greater concentrations of mercury spent approximately 12% less time incubating their eggs, potentially slowing embryonic development.[19] Additionally, compromised immune function has been found in mercury-exposed tree swallows, particularly weaker inflammatory responses.[20] Overall, research has provided evidence for biological changes in swallows post-mercury contamination that may ultimately impact their reproductive output and survivorship. However, the potential links between mercury exposure and their population declines remain unknown.[8]

1.2.2 Changes in Temperature Regimes

Climate change has resulted in broad-scale changes and variability in temperatures with expected negative impacts on wildlife, including bank swallows.[5] ECCC has identified changes in temperature regimes as a potentially pervasive, continuing threat to bank swallows, but the impacts remain unknown.[5] The abundance of their insect prey depends on the weather, as the timing of insect emergence, development, and activity is impacted by temperature.[21] Insect emergence occurs earlier in warmer spring temperatures, and their activity is lower in temperatures below 18.5 ºC.[21] Since bank swallows have highly specialized foraging niches by feeding almost exclusively on flying insect prey, they may experience severe food shortages and difficulties when foraging during unfavourable climate conditions.[21] Studies on tree swallows have demonstrated associations between increasingly worse weather conditions during the early stages of nestling development, and their survival.[18,21] Driven by changes in weather, there may also be temporal mismatches in prey availability and their energy needs upon arrival in North America during the breeding season.[22] Specifically, spring temperatures in Canada have been increasing, resulting in the earlier emergence of insect prey.[5] This can thus affect bank swallows, as significantly lower breeding performance was found in Maritime populations following temperature increases.[22] This may be associated with their failure to shift their clutch initiation dates to adapt to earlier insect emergence.[22]

Furthermore, some studies have proposed potential combined effects of mercury exposure and inclement weather conditions.[16,17] In general, periods of extremely low temperatures and intense heat may increase or conceal the effects of contaminants on avian reproduction.[18] Unusually high temperatures during the nesting period were also associated with reduced nestling success in mercury-contaminated tree swallows.[17] Warmer temperatures may result in increased foraging activity and thus greater mercury uptake.[23] The availability of methylmercury may also increase in higher temperatures.[16,23] However, research on the interaction of these threats is limited, particularly concerning bank swallows, indicating a need for future study.

1.3 Determining Spatiotemporal Associations Between Bank Swallow Populations, Mercury, and Temperature

1.3.1 Spatial Analytical Methods

Various spatial analytical methods can be applied to model the relationships between bank swallow population threats and their abundances. Firstly, geographic information systems (GIS) is software that integrates, analyzes, maps, and measures various spatial data and is a crucial tool for biodiversity assessment and monitoring.[24] GIS incorporates spatial datasets of species, contaminants, surrounding landforms, climate, and more, which can be mapped to visualize their distributions and associated temporal changes.[24]

Complex predictive analyses, such as spatial interpolation, that estimate population distributions and abundances based on observed occurrences can also be performed with GIS.[24] This can be useful in estimating abundances and distributions across a larger landscape with only bird point count data.[25] Kriging is a common spatial interpolation model that can be applied in species mapping.[25]

1.3.2 Statistical Methods: Multiple Linear Regression

Multiple linear regression analysis evaluates the strength and direction of associations between multiple independent predictors and a single continuous dependent variable.[26] This helps to evaluate the individual impacts of each variable, while controlling for the others.[26]

1.3.3 Goals of the Current Study

Most previous studies have explored the direct biological impacts of mercury and climate change threats to bank swallows, with few, if any, spatiotemporal explorations of their combined effects and possible connections to the species' long-term population declines in Ontario. Therefore, the general goal of this study was to analyze the relationships between point source mercury releases and mean temperature and bank swallows in Southern Ontario. Specifically, the objectives of this study were to: (1) compare bank swallow abundances, mean spring temperature, and mercury release quantities from 2001-2005 (Period A) and 2018-2022 (Period B), both in Southern Ontario as a whole and within smaller regions, and (2) assess the potential associations between bank swallow abundance and temperature and quantities of mercury released using regression analysis. Based on literature findings, it was hypothesized that associations between the predictors and bank swallow abundances would be found. Specifically, it was anticipated that areas with higher levels of mercury release and greater temperature rises would correspond to larger declines in bank swallow populations. Overall, this project was important to enhance our understanding of the threats to bank swallow populations and better devise mitigation strategies that support their conservation.

2.0 METHODS

2.1 Study Area

As Southern Ontario (78.2-82.6 ºW and 42.2-45.2 ºN) contains the majority of bank swallow populations in the province, it was selected as the study site for this thesis.[2] It is located within the Great Lakes watershed, bounded by Lakes Ontario, Erie, and Huron in the southernmost regions. It is highly populated, with over 85% of residents in urban cities, mostly near the Great Lakes shores.[27] Economic activities are key features, with major industries including mining, oil, gas, and agriculture.[27] To conduct regional comparisons and statistical analyses, Southern Ontario was divided into its 26 ecodistricts for this study, with the feature layer dataset obtained from the Ontario GeoHub.[28] These ecodistricts differ in physiographic characteristics and environmental conditions, thus influencing species composition and distributions.[29]

2.2 Data Sources and Software

Publicly available bank swallow, mercury release, and temperature data spanning 2001-2005 and 2018-2022 were used in analyses. Geospatial analyses were conducted with ArcGIS Pro (version 3.2.1), and statistical analyses were completed through R (version 4.3.2).

2.2.1 Ontario Breeding Bird Atlas (OBBA)

Each OBBA occurs within a 5-year period, during which volunteers record visual and auditory breeding evidence of birds in 10-kilometre by 10-kilometre squares.[1] In each square, 5-minute point counts are conducted in a single roadside or off-road location, for a total of 20 hours over the 5-year atlas duration.[30] Observers record point counts at distance intervals ranging from 0-100 metres to over 100 metres.[30] For the current study, only OBBA data from May to July 2001-2005 and 2021-2022 were available, which included total point counts at both distance intervals and coordinates of point count locations.

2.2.2 North American Breeding Bird Survey (NABBS)

Occurring annually, data collection for the NABBS situates volunteers at a single 39.2 kilometre route, taking 3-minute point counts over 50 stops along that route.[1] At each stop, point counts are taken within a distance of 400 metres.[31] The sum of point counts taken from May to July 2001-2005 and 2018-2022 for each route and route coordinates were used in this study.

2.2.3 National Pollutant Release Inventory (NPRI)

Pure elemental mercury and the weight of mercury in compounds, alloys, or mixtures are reported to the NPRI annually.[32] As of 2000, facilities are required to calculate and report releases if the quantities manufactured, processed, or used exceed a 5-kilogram threshold.[32] For this study, this dataset was the source of the locations and quantities of mercury releases to the air and water in Southern Ontario between 2001-2005 (n = 443) and 2018-2022 (n = 305).

2.2.4 Environment and Climate Change Canada (ECCC) – Temperature Data

ECCC has various climate stations situated in Canada, which collect hourly records of various climatic variables, including temperatures, precipitation, wind, and more.[33] Daily data are derived from these hourly observations by calculating the means, maximums, minimums, and sums of these variables.[33] For usage in research, ECCC has also adjusted climate station datasets by removing discrepancies arising from non-climatic factors, such as instrumentation changes and observation procedures.[34] The resulting datasets are known as Adjusted and Homogenized Canadian Climate Data (AHCCD). Monthly mean temperatures from May-July 2001-2005 (n = 727) and 2018-2020 in Southern Ontario were obtained from the AHCDD climate data extraction tool. As monthly data were unavailable for 2021-2022, daily temperature AHCCD means were obtained by manually downloading data from stations within the study area, and mean monthly temperatures were calculated. The total number of 2018-2022 monthly and daily temperature data points used in the study was 5390.

2.3 Spatial Interpolation of Bank Swallow Abundances by Ordinary Kriging

Kriging methods use available point counts to predict abundances at locations lacking that data, giving more importance to nearby points compared to distant ones.[25] Ordinary Kriging is a common form of this that creates a predictive map capable of estimating population size at a particular site based on normalized continuous data.[25] Bank swallow point counts for each period of interest were initially plotted over Southern Ontario ecodistricts using ArcGIS Pro. Points external to the ecodistricts of interest in Southern Ontario and locations without counts were removed. Since the bank swallow point counts were recorded at discrete locations, the entire study area was not covered evenly. Thus, ordinary

Kriging was applied using ArcGIS Pro to develop a continuous prediction surface to estimate bank swallow abundances across the study area. Owing to a larger quantity of point counts in Period A, a subset (n = 404) was created by filtering for those located < 1 km from the Period B counts (n = 396). This was done to ensure an equitable comparison between the periods of interest. Both point count datasets were ln transformed prior to interpolation. Ordinary Kriging was performed to generate a predictive surface map for each dataset using the Geostatistical Wizard. The settings were configured to ensure that mean counts were taken if multiple points shared the same location.

A semivariogram was created by configuring the model type and parameters that best fit the data (Table 1). Semivariograms are graphs that show how similar or different known points are with increasing separation distances.[35] The semivariance, which is half of the average variance between paired points, is plotted on the y-axis, and separation distance is plotted on the x-axis, providing an idea of how measurements change over space.[35] A model needs to be developed to fit the distribution pattern of the values observed on the semivariogram.[35] This fitting process involves manually altering specific parameters, such as the distance between pairs of points (lag size), the number of distance intervals (lags), the y-intercept of the semivariogram (nugget), the distance at which the semivariogram flattens (range), and the sill value at the range minus the nugget (partial sill).[35]

Once the model was fit, the maximum and minimum numbers of observed neighbouring points used in estimating the abundance at a location were specified. For Period A, the minimum was 2, and the maximum was 7; for Period B, the minimum was 3, and the maximum was 10. The resulting prediction surface maps were exported as rasters and clipped to align with the Southern Ontario outline. The mean abundances and associated standard deviations within each ecodistrict polygon were computed using the Zonal Statistics tool. Means were summarized in a new map layer to permit comparisons by ecodistrict and usage in statistical analyses. With the Geostatistical Wizard, prediction standard error (PSE) surface maps were also generated.

Table 1. Semivariogram models and parameters used in ordinary Kriging of bank swallow point counts. The model and parameters selected were based on values that resulted in a fitted model line close to the average crosses on the semivariogram graph.

Period	Model	Lag size	Lags	Nugget	Range	Partial Sill
A	Gaussian	0.0124	8	0.89	0.0995	1.07
B	Exponential	0.0099	9	0.22	0.012	0.82

2.4 Summarizing Mean Mercury Releases and Temperatures by Ecodistrict

To initially visualize the data for each period, the locations of mercury releases and temperature stations were plotted over the Southern Ontario ecodistrict polygon layer using ArcGIS Pro. Points external to the ecodistricts of interest were deleted. Using the Summarize Within tool, the mean quantities and standard deviations of mercury releases and temperatures were computed for each ecodistrict and visualized in new polygon feature layers.

2.5 Statistical Analyses

Specific ecodistricts of interest were utilized in the statistical analyses. Those excluded from the analysis met one or both of the following criteria: 1) absence of actual point counts taken in those regions, suggesting bank swallow absences that were not accounted for in the interpolation, and 2) missing temperature data for any of the periods of interest.

2.5.1 Temporal Comparison of Mercury, Temperature, and Abundances

Paired statistical analyses were employed to compare the mercury releases, temperatures, and predicted bank swallow abundances across the broader spatial scale of Southern Ontario between Periods A and B. The differences between each variable within each ecodistrict were computed and tested for normality using a Shapiro-Wilk test. For the datasets exhibiting normal distribution, a paired samples t-test was utilized. This method compared the means of each variable taken from the same ecodistrict and generally evaluated whether statistically significant differences across Southern Ontario existed. A paired samples Wilcoxon signed rank test was conducted for the non-normally distributed datasets. This test operates on principles similar to the t-test but is tailored to analyze non-normally distributed data. Boxplots with connected paired points were generated to visualize the comparisons for each variable.

2.5.2 Regression Analysis

Using the region-specific means from both time periods, multiple linear regression analysis was performed to analyze the associations between mean bank swallow abundances and the predictor variables 1) mean mercury release quantities, 2) mean temperatures, and 3) the interaction between mean mercury releases and temperatures within the entirety of Southern Ontario. This model was formulated as follows:

*Mean bank swallow abundance (ln(individuals per unit area)) ~ mean temperature (ºC) + mean mercury release quantities (kg) + mean temperature (ºC)*mean mercury release quantities (kg)* (1)

Individual linear regression analyses were performed to assess the relationships between the temporal differences in temperatures, mercury releases, and swallow abundances among individual ecodistricts. This approach aimed to determine the consistency of these relationships among ecodistricts.

3.0 RESULTS

3.1 Predicted Bank Swallow Abundances by Ordinary Kriging

The resulting prediction surface maps of bank swallow abundances generated through ordinary Kriging are depicted in Figures 2A and C. These maps suggested a greater number of individuals per unit area in Period A compared to Period B (Fig. 2A, C). Since the distances at which point counts were taken varied by the data source used, "per unit area" refers to areas between 100-400 m^2.[30,31] In Period A, the distribution of bank swallows was more concentrated in the southernmost and northeastern regions of the province (Fig. 2A). The swallows were generally more evenly and sparsely distributed in Period B (Fig. 2C).

The PSE outputs are depicted in Figures 2B and D. In Period A, lower PSEs were found precisely at point count locations, whereas in Period B, these lower errors broadly covered the areas encompassing the point counts (Fig. 2B, D). Period B generally exhibited a lower PSE than Period A (Table 2). The mean error and root-mean-square error (RMSE), other measures of the prediction accuracy, were also generated (Table 2). Period A exhibited a negative mean error, indicating that the mean predicted values were slightly lower than the observed values, while Period B's value reflected the opposite trend (Table 2). For both periods, the RMS values were close to 1 (Table 2).

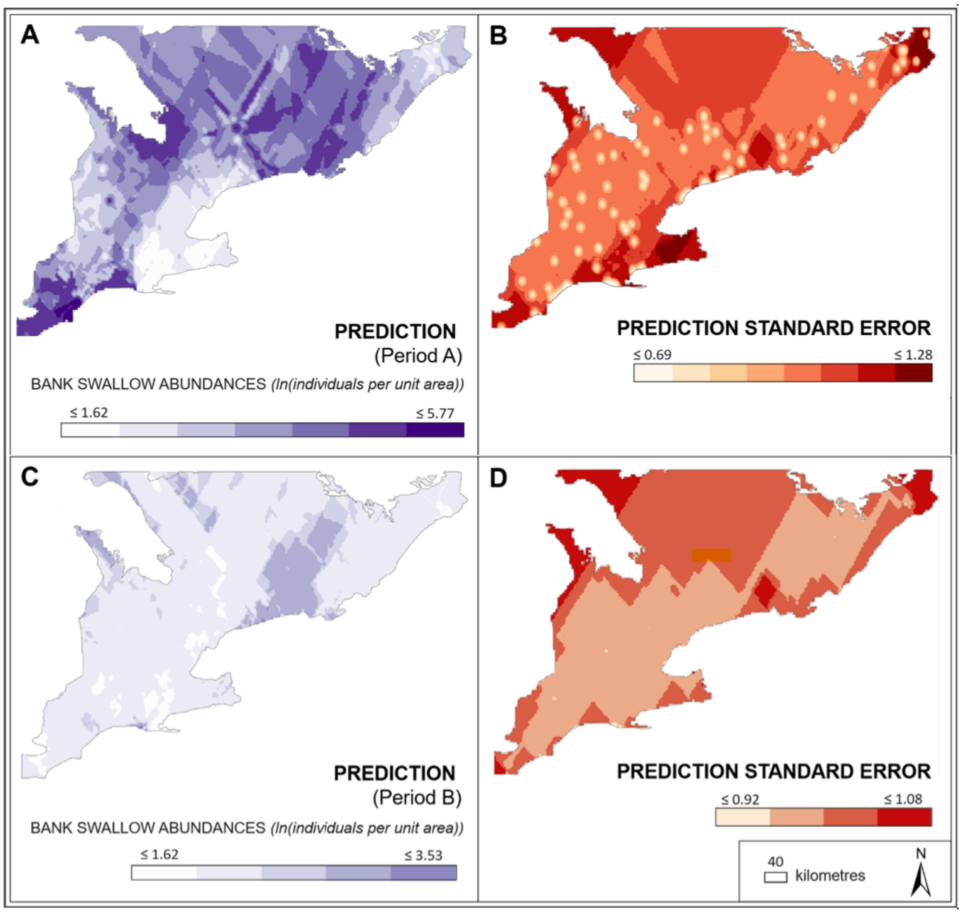


Figure 2. Ordinary Kriging output maps of predicted bank swallow abundances and standard errors for Periods A (2001-2005) and B (2018-2022). Prediction surface maps for Period A (A) and Period B (C), and prediction standard error maps for Period A (B) and Period B (D) were generated through ordinary Kriging in ArcGIS Pro.

Table 2. Ordinary Kriging model performance metrics for Periods A (2001-2005) and B (2018-2022). Generated from the ordinary Kriging model outputs in ArcGIS Pro, the metrics below reflect different aspects of prediction accuracy. Mean error represents the average difference between predicted and observed values, RMSE reflects the variability of the prediction errors around the mean error, and average standard error indicates the average uncertainty associated with the predictions.

Period	Mean Error	Root-Mean-Square Error	Average Standard Error
A	-0.0174	1.04	± 1.24
B	0.0156	0.956	± 1.05

3.2 Temporal Comparisons in Southern Ontario

A total of 11 ecodistricts were excluded from the statistical analyses because of missing data or the presence of outliers. Due to missing temperature data in either period, Charleston Lake, Pembrooke, Havelock, Algonquin, and Oak Ridges were omitted. Brent, Parry Sound, Bancroft, Tobermory, and Huntsville were removed due to the absence of observed bank swallow point counts in those regions. Additionally, Essex was identified as an outlier due to unusually high bank swallow observation counts recorded in Period A. For the remaining ecodistricts, statistically significant differences in each variable between the two periods were assessed, with the findings summarized in Table 3.

Table 3. Paired statistical test outputs assessing the temporal changes in abundances, mercury releases, and temperatures. Across the larger spatial scale of Southern Ontario, paired t-tests were conducted for mean bank swallow abundances and temperatures, while a paired Wilcoxon signed rank test was done for mean mercury releases. (*) indicates $p < 0.05$, (***) indicates $p < 0.001$.

	Mean Bank Swallow Abundance	Mean Mercury Release Quantities	Mean Temperature
P-value	0.00882 *	0.153	5.92×10^{-6} ***
Percent change (%)	-9.9	N/A	5.3

3.2.1 Comparison of Bank Swallow Abundances

The predicted mean bank swallow abundances per region are depicted in Figure 3. The ecodistricts of Picton (#6), Meaford (#14) and Barrie (#9) had the greatest abundances in Period A, while Grimsby (#4), Niagara (#7), and Toronto (#13) had the fewest (Fig. 3A; Table A1). In Period B, Toronto (#13), London (#11), Kemptville (#1), Stratford (#3), St. Thomas (#5) and Barrie (#9) had the lowest abundances (Fig. 3B; Table A2).

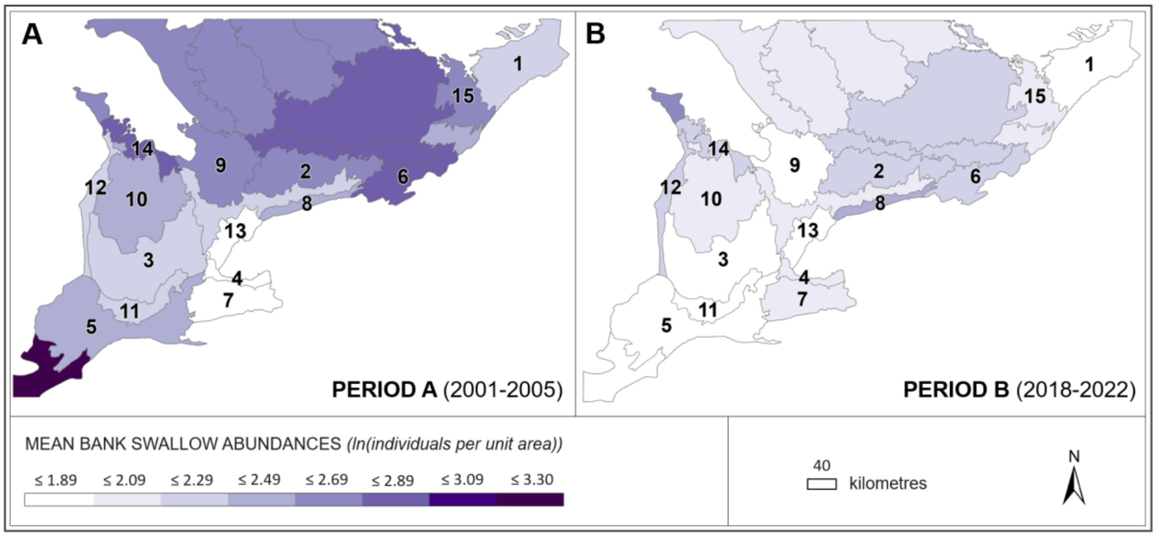


Figure 3. Mean predicted bank swallow abundances per ecodistrict. (A) Average abundance for Period A. (B) Average abundance for Period B. Ecodistricts of interest were numbered (see Table 4 for the corresponding ecodistrict names). Figure generated with ArcGIS Pro.

Figure 4 illustrates the temporal comparison of mean abundances both across Southern Ontario as a whole and within individual regions, as depicted by the boxplot. The mean abundance in Southern Ontario in Period A was 2.28 ± 0.37 ln(individuals per unit area), while it was 2.00 ± 0.20 in Period B (Fig. 4). As the data followed a normal distribution according to the Shapiro-Wilk test for normality ($p = 0.069$), a paired t-test was conducted to compare the means between both periods. The difference was statistically significant, as indicated by $p < 0.05$ at a 95% confidence interval (Table 3). This reflected a 9.9% decrease in the mean number of bank swallows per unit area from Period A to Period B

(Table 3). As shown by the varying slopes of the paired lines, there was regional variability in predicted abundances, which will be discussed in 3.3.1 (Fig. 4).

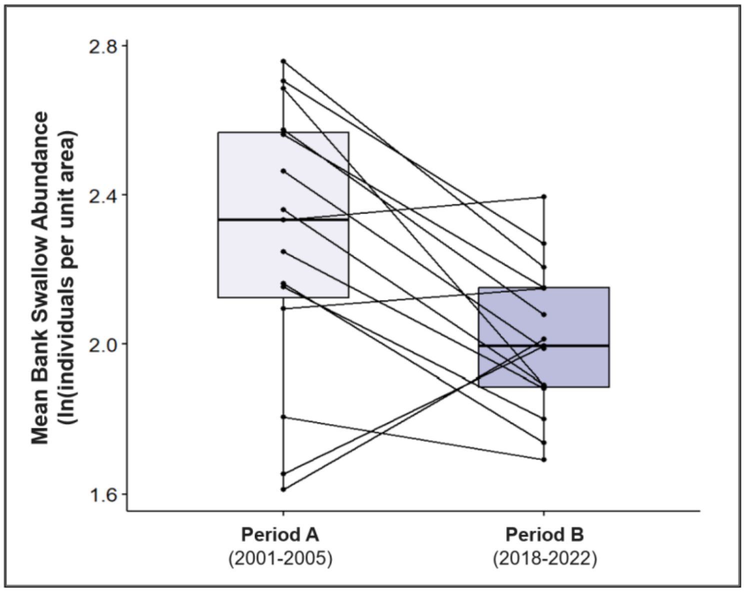


Figure 4. Overall and region-specific temporal comparison of predicted bank swallow abundances. The mean abundance in Southern Ontario is depicted by the boxes in Periods A and B. Each point represents the mean abundance for each region and is linked by paired lines. Figure generated through R.

3.2.2 Comparison of Mercury Release Quantities

The mean amounts of mercury released into the air and water per ecodistrict are displayed in Figure 5. For both periods, the ecodistricts with the greatest release quantities were predominantly situated closest to Lake Ontario (Fig. 5). In Period A, facilities in Kemptville (#1), Grimsby (#4), St. Thomas (#5), Picton (#6), Niagara (#7), Oshawa-Coburg (#8), and Toronto (#13) released the most mercury, with mean quantities ranging from 10-30 kg (Fig. 5A; Table A1). Stratford (#3), Grimsby (#4), Picton (#6) and Oshawa-Coburg (#8) had the greatest releases in Period B (Fig. 5B; Table A2).

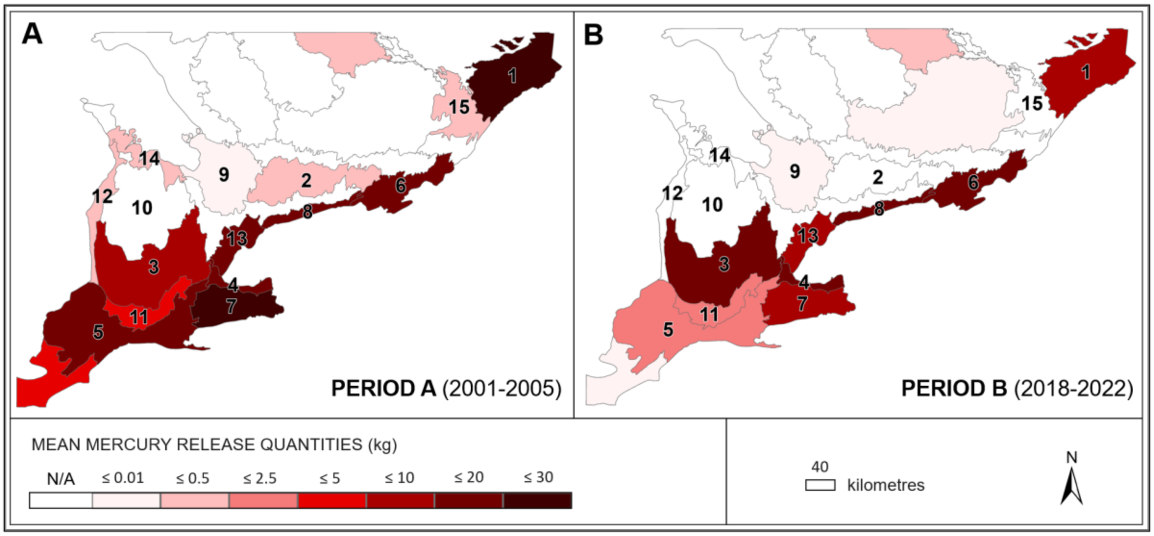


Figure 5. Mean mercury release quantities by ecodistrict. (A) Average mercury released in Period A. (B) Average mercury released in Period B. Ecodistricts of interest were numbered (see Table 4 for the corresponding ecodistrict names). Figure generated with ArcGIS Pro.

Generally, mercury releases were greater in Period A, with an average of 9.0 ± 9.3 kg released per ecodistrict, compared to a mean of 5.8 ± 7.0 kg released in Period B (Fig. 6). The Shapiro-Wilk test for normality revealed non-normality in the dataset ($p = 0.0358$), so a paired Wilcoxon signed rank test was conducted. This revealed a non-significant difference in mercury release amounts between the periods, as indicated by $p > 0.05$ at a 95% confidence interval (Table 3). Regions exhibited variability in mercury emissions, with some experiencing increases or decreases between the periods (Fig. 6).

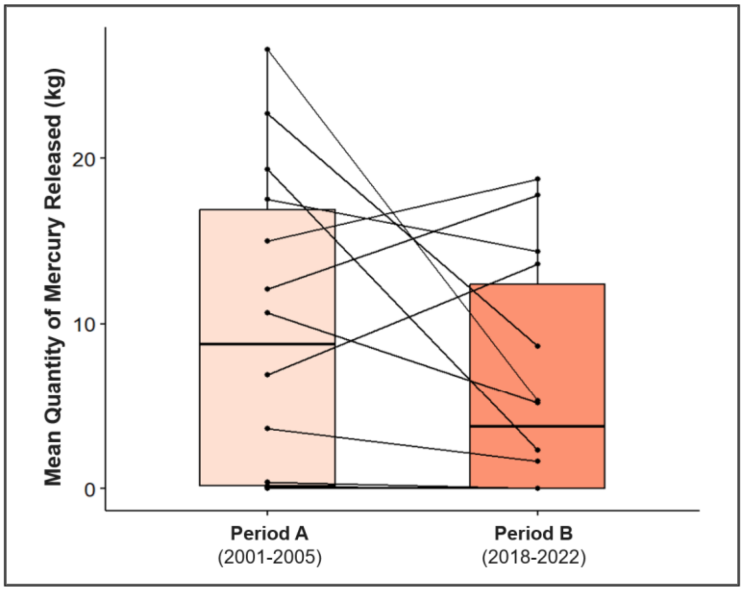


Figure 6. Overall and region-specific temporal comparison of mercury releases. The mean quantity of mercury released in Southern Ontario is depicted by the boxes in Periods A and B. Each point represents the mean release amount for each region and is linked by paired lines. Figure generated through R.

3.2.3 <u>Comparison of Temperatures</u>

The average temperatures per ecodistrict are displayed in Figure 7. Period B was marked by a greater number of ecodistricts exhibiting mean temperatures ranging from 18-20 ºC, including Kemptville (#1), Grimsby (#4), Thomas (#5), Niagara (#7), London (#11), and Toronto (#13) (Fig. 7B; Table A2). No ecodistricts were within this range in Period A, with most temperatures between 16-18 ºC (Fig. 7A; Table A1). In both periods, the warmest regions were typically situated along the Great Lakes (Fig. 7).

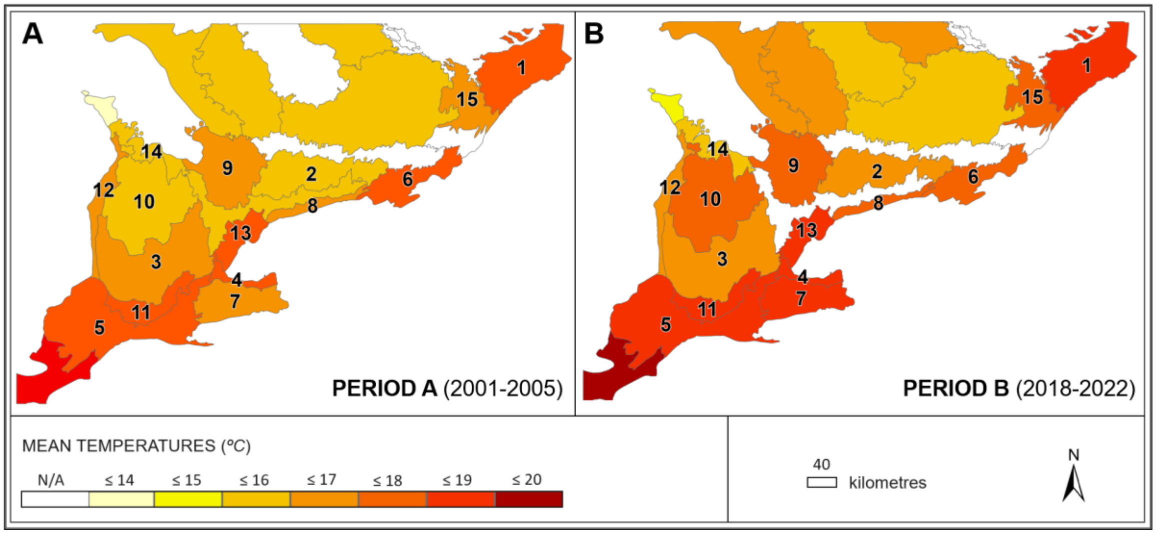


Figure 7. Mean temperatures by ecodistrict. (A) Average temperature for Period A. (B) Average temperature for Period B. Ecodistricts of interest were numbered (see Table 4 for the corresponding ecodistrict names). Figure generated with ArcGIS Pro.

From Period A to B, the mean temperature in Southern Ontario increased from 16.7 ± 0.75 ºC to 17.6 ± 0.85 ºC (Fig. 8). This temperature increase was assessed through a paired t-test, which was conducted due to the normal distribution of the data ($p = 0.708$). A statistically significant increase by 5.3% was found ($p < 0.001$) at a confidence interval of 95% (Table 3). Limited regional variability was observed regarding the direction of temperature change between the two periods, as evidenced by the predominance of increasing slopes in the paired lines depicted in Figure 8.

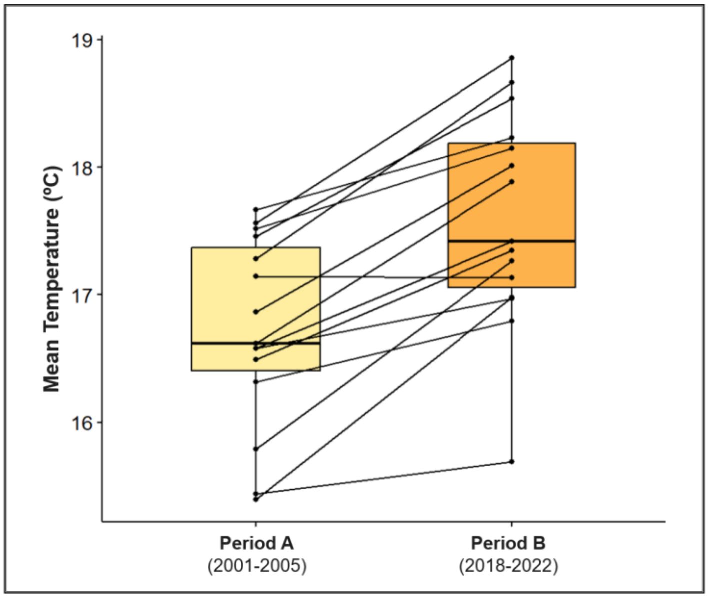


Figure 8. Overall and region-specific temporal comparison of temperatures. The mean temperature in Southern Ontario is depicted by the boxes in Periods A and B. Each point represents the mean temperature for each region and is linked by paired lines. Figure generated through R.

3.3 Assessing the Relationships Between Predictors and Bank Swallow Abundances

3.3.1 Multiple Linear Regression Analysis

The multiple linear regression analysis utilized a total of 30 observations, excluding ecodistricts with no mercury releases. Overall, the model had an adjusted R^2 of 0.406. The p-value of 8.30×10^{-4}, calculated on 3 and 26 degrees of freedom (DF) for the numerator and denominator, respectively, suggested that the complete model was statistically significant.

Of all three predictors, there was an overall statistically significant relationship between mean bank swallow abundances and mean temperatures (Table 4). The $p < 0.001$ at a 95% confidence interval and the negative t-value indicated a strong, statistically significant negative relationship between mean temperature and mean bank swallow abundance (Table 4). Conversely, the relationships between mean mercury released, the interaction term, and bank swallow abundances were not statistically significant as their p-values were slightly beyond the threshold of 0.05 (Table 4). As suggested by the t-values, there may be a marginally significant negative association between mercury releases and abundances, as well as the interaction between mean temperature and mean mercury releases interaction term and abundances (Table 4).

The fitted residuals plot demonstrated greater variance close to the middle, suggesting that outliers skewed the data, such as observations 4 and 6 (Fig. A1A). Most values on the Q-Q plot fit the prediction line closely, particularly in the middle, while a few values near the ends deviated significantly (Fig. A1B). This suggested that the model was relatively normally distributed overall, but outliers may have been present.

The overall relationship between bank swallow abundance and their predictors based on this model was determined to be:

*Mean bank swallow abundance (ln(individuals per unit area)) = -0.295 (mean temperature ºC) -0.311 (mean mercury released kg) -0.0181 (mean temperature (ºC)*mean mercury release quantities (kg))* (2)

Table 4. Multiple linear regression results for predictors of bank swallow abundances. Note that (***) indicates $p < 0.001$. Sample size ($n = 30$).

Predictor	Estimate	Standard Error	t-value	p-value
(Intercept)	7.17	1.09	6.56	5.91×10^{-7} ***
Mean Temp	-0.295	0.0648	-4.56	1.09×10^{-4} ***
Mean Mercury	-0.311	0.157	-1.98	0.0585
Interaction (Temp*Mercury)	-0.0181	0.00911	1.99	0.0577

Individual linear regression models were generated to assess each predictor individually in the context of both periods, as well as separately. In terms of mercury releases, there was a very weak negative association with abundances when both periods were incorporated, with an adjusted R^2 of -0.000706 (Fig. 9A). When comparing both periods, this relationship was negative within Period A, while it was slightly positive in Period B (Fig. 9B).

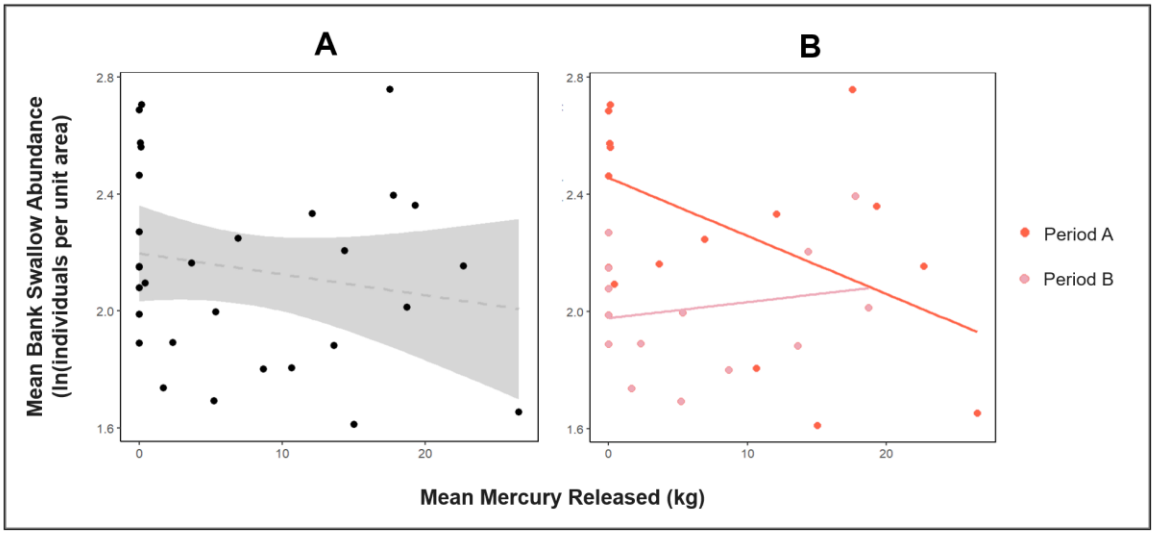


Figure 9. Linear regression model of mean mercury releases and bank swallow abundances. Each point represents the associated mercury release quantity and abundance for an ecodistrict. (A) Data for both periods were incorporated. (B) Individual slopes were generated to differentiate the relationship for each period. Plots were generated in R.

For the temperature analysis, there was a stronger negative relationship between mean temperature and bank swallow abundances in the context of both periods, with an adjusted R^2 of 0.364 (Fig. 10A). This negative relationship persisted upon analyzing each period individually (Fig. 10B).

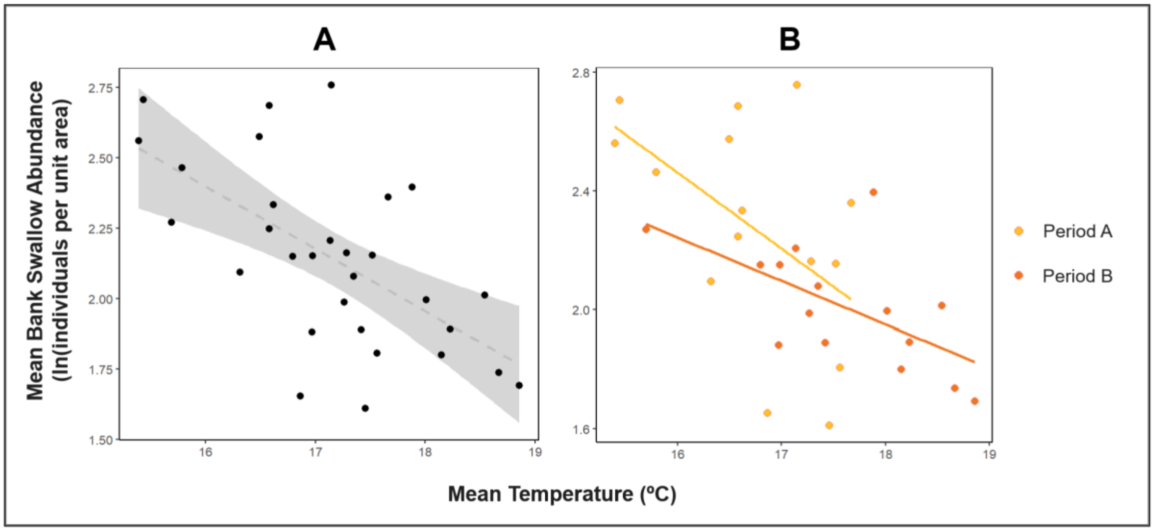


Figure 10. Linear regression model of mean temperatures and bank swallow abundances. Each point represents the associated temperature and abundance for an ecodistrict. (A) Data for both periods were incorporated. (B) Individual slopes were generated to differentiate the relationship for each period. Plots were generated in R.

3.3.2 Assessing Temporal Differences in Each Variable by Ecodistrict

For each region, the differences in the mean value of each variable were taken between Periods A and B and are displayed in Table 5. In terms of the changes in regional bank swallow abundances, 4/15 regions exhibited increases. The greatest occurred in Grimsby (#4) and Niagara (#7). The most substantial declines were observed in Barrie (#9), Picton (#6), and Smiths Falls (#15). Regarding mercury release quantities, 11/15 ecodistricts declined by Period B, with the greatest in Niagara (#7), St. Thomas (#5), and Kemptville (#1). Stratford (#3), Grimsby (#4), and Oshawa-Coburg (#8) experienced increases. In terms of temperature changes, 14/15 experienced increases, with the greatest observed in Peterborough (#2), Mount Forest (#10), and London (#11). Picton (#6) had a negligible decrease by 0.01 ºC. Mount Forest (#10) was a unique case as it was the sole ecodistrict without mercury releases in either period. It experienced one of the highest temperature increases, and was still marked by bank swallow declines.

Table 5. Region-specific differences in mean abundances, mercury released, and temperatures from Period A to B. The difference was calculated by subtracting the mean value for Period A from that of Period B. Dark grey shading represents the greatest declines, defined by the following magnitudes: Abundance ≥ -0.50; Mercury ≥ -5. Light grey shading represents the greatest increases, defined by the following: Abundance ≥ 0.30; Mercury: ≥ 5; Temperature: ≥ 1.

No.	Ecodistrict	**Mean Abundance** *(ln(individuals per unit area))*	**Mean Mercury Release Quantities** *(kg)*	**Mean Temperature** *(ºC)*
1	Kemptville	-0.35	-14.0	0.63
2	Peterborough	-0.41	-0.11	1.59
3	Stratford	-0.37	6.70	0.39
4	Grimsby	0.40	3.71	1.08
5	St. Thomas	-0.47	-17.0	0.56
6	Picton	-0.55	-3.18	-0.01
7	Niagara	0.34	-21.2	1.15
8	Oshawa-Coburg	0.06	5.66	1.27
9	Barrie	-0.80	-1.04×10^{-4}	0.84
10	Mount Forest	-0.48	0	1.47
11	London	-0.43	-1.98	1.38
12	Kincardine	0.06	-0.41	0.48
13	Toronto	-0.11	-5.44	1.30
14	Meaford	-0.45	-0.13	0.25
15	Smiths Falls	-0.50	-0.06	0.86

It was expected that ecodistricts with greater mercury releases and temperatures would have experienced more pronounced bank swallow declines. These relationships were analyzed through linear regression models (Fig. 11). Contrary to expectations, it was found that the four regions with increases in abundances still experienced rising temperatures (Fig. 11A; Table 5). Additionally, the regions with the most significant declines in abundances did not coincide with those experiencing the greatest temperature increases (Fig. 11A; Table 5). The overall relationship was found to be weak and statistically insignificant, as evidenced by a low adjusted R^2 of -0.0106 and a p-value of 0.372.

In terms of the relationships between differences in mercury release amounts and bank swallow abundances, inconsistent results were also found. One region (Niagara) had the most drastic decrease in mercury released, but also had the second-greatest rise in swallow abundance (Fig. 11B; Table 5). However, among the other three ecodistricts in which swallow populations increased, there were marginal decreases in mercury emissions, or they were among the few with increased releases (Fig. 11B; Table 5). Furthermore, among regions exhibiting the most significant swallow declines, there were variations in the magnitudes of mercury release reductions (Fig. 11B; Table 5). Overall, the relationship was weak and not statistically significant, marked by a low adjusted R^2 of -0.0632 and a p-value of 0.689.

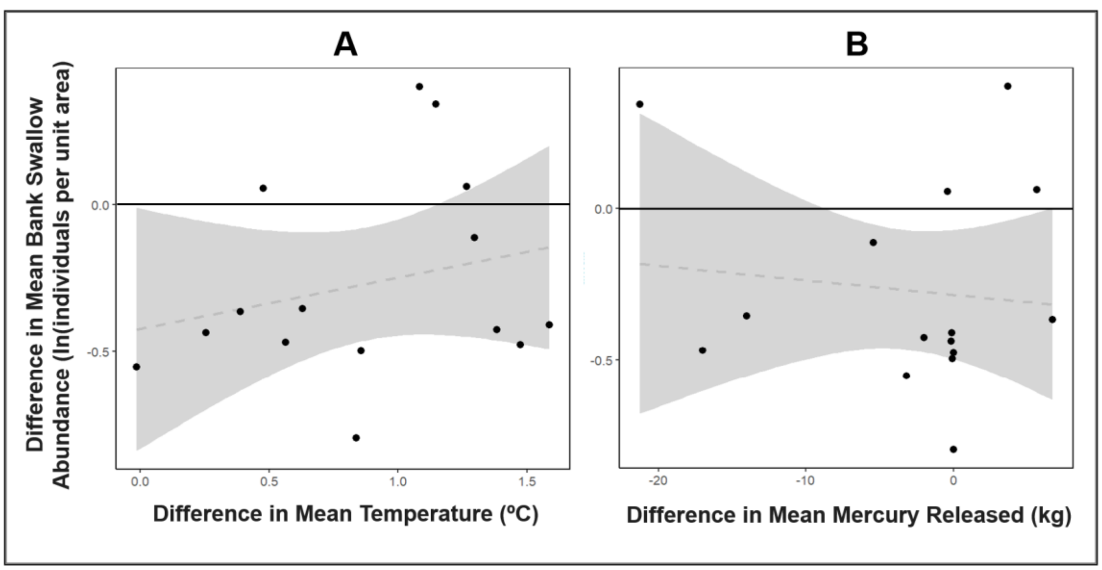


Figure 11. Linear regression models of the relationship between differences in predictors and bank swallow abundances. Each point represents the difference in the respective predictor variable and abundance for

a specific ecodistrict from Period A to B. (A) Differences in mean temperature. (B) Differences in mean mercury released. Plots were generated in R.

4.0 DISCUSSION

4.1 The Significance of Mercury and Temperature in Predicting Bank Swallow Abundances

The statistical significance of the multiple linear regression model indicated that the collective influence of mercury release quantities, temperature, and the interaction between mercury and temperature accounted for a substantial proportion (40.6%) of the variability observed in mean bank swallow abundance during Periods A and B. While no other similar models assessing these factors on bank swallow populations have been conducted, this general finding is consistent with studies indicating the role of multiple factors in aerial insectivore declines.[6] Although the complete model had moderate explanatory power, the individual impacts of each predictor varied.

4.1.1 Temperature May be a Significant Factor in Bank Swallow Declines

There was an overall significant 5.3% increase in temperature in Southern Ontario from Period A to B (Fig. 7, 8). This warming trend aligned with the predicted increases of 3-8 ºC over the next century in Ontario.[36] Since it was the most influential predictor in the model (Table 4), temperature was the most significant potential contributor among those studied. There was a negative relationship between the variables, suggesting that for every 1 ºC increase in the mean temperature, there was a corresponding decrease in mean abundances by 0.295 ln(individuals per unit area) (Table 4). This relationship was maintained even in the absence of the other two predictors, highlighting its strength (Fig. 10A). Furthermore, the finding that the relationship was consistent among both periods suggested that temperature may have short-term associations (across 5-year periods) with bank swallow abundances as well (Fig. 10B).

These findings may have reflected changes in temperature-sensitive contributors that had impacted the reproductive success of bank swallows. Increasing spring temperatures may have led to shifts in the timing of insect emergence, altering the availability of food resources for bank swallows.[21,22] Insects may have emerged earlier than the arrival of swallows at their breeding grounds, which may have consequently experienced food shortages.[21,22] This could have resulted in decreased breeding performances, as previous research observed that bank swallows struggled to adjust their clutch initiation dates to adapt to these phenological mismatches.[22] Past studies highlighted the importance of adjusting laying dates in achieving higher reproductive outputs in response to rising spring temperatures.[37] These consequences have been proposed to drive long-term population declines in other migratory aerial insectivores.[38] In contrast, a 2011-2012 study on tree swallows found no significant relationship between increasing temperatures and fledgling successes.[18] However, this study was conducted over a shorter time period, potentially not capturing the longer term impacts. Overall, the current study provides evidence for temperature's potential role in driving declines through such mechanisms, yet further investigation is required to understand the underlying causes.

When considering the contribution of temperature increases to the declines in abundances from Period A to B, there was high interregional variability (Table 5; Fig.11A). It was unclear whether higher temperatures impacted some regions more than others, which warrants further study. The resulting weak association may be indicative of a stronger negative relationship between temperature and swallow abundances on a larger spatial scale (within Southern Ontario) as opposed to smaller regions. For instance, a prior study analyzing the impacts of temperature on aerial insectivore population declines was conducted on country-wide scale.[38] Additionally, the regional variability highlights the need to explore additional drivers of population declines within these individual ecodistricts. Overall, the negative associations between temperature increases and swallow declines on a larger spatial scale were as anticipated, but the region-specific patterns did not always follow the overall trend.

4.1.2 Mercury Pollution May Not Be a Significant Predictor

The slight reduction in mercury release quantities from Period A to B, although statistically insignificant, did align with the timing of closing certain mercury emission sources. These include the ban on coal-fired electricity generation in 2015, which likely attributed to the reduced emissions in St. Thomas (#5), Niagara (#7), and Toronto (#13) (Fig. 5; Table 5).[39] Moreover, main point release sources were often situated in urban centers near the Great Lakes, suggesting a role of urbanization on the quantities of mercury released (Fig. 5).[27] Considering the overall statistically insignificant difference between both periods, and the fact that a few ecodistricts did exhibit increases, Ontario may need to implement further measures to continue reducing emissions.

Given that the majority of significant point atmospheric and aquatic sources of mercury were situated near water bodies, persistent localized biological mercury hotspots may have formed within those aquatic environments (Fig. 5).[8,14] Literature findings have suggested that the presence of these aquatic hotspots may contaminate the food supply of bank swallows, permitting the transfer of this toxic metal to bank swallows during the breeding season.[8,12,15] Previous studies have found negative consequences on egg production, fledgling successes, and parental incubation behaviours in those situated near mercury-contaminated water bodies.[16–19] Thus, it was hypothesized that these mechanisms may have contributed to driving long-term population declines in bank swallows, so associations between the quantities of environmental mercury outputs and the abundances of bank swallows would have been found. However, this expectation was not strongly supported by the results of this study. The inclusion of mercury releases in the statistically significant multiple regression model of bank swallow abundances indicated its overall importance when controlling for the effects of other predictors (Table 4). The negative relationship with abundances could be indicative of the proposed mechanisms and consequences of mercury-polluted swallow habitats on their reproductive outputs, but further study is required (Table 4).

Despite this, numerous other points of evidence, such as the marginal significance of mercury releases in the multiple regression model, inconsistencies in the direction of the relationship among both periods, and interregional variability in the magnitude of differences from Period A to B suggest that mercury releases may not be the strongest contributor to the swallows' declines in Southern Ontario (Table 4; Fig. 9; Fig. 11B). While studies have shown that wet deposition from atmospheric emissions can lead to local aquatic mercury hotspots, some of those gaseous emissions can also travel away from point sources.[7,9,14] In addition, wet mercury deposition can originate from non-local sources, such as the global atmospheric pool.[40] Therefore, one explanation could be that local emission sources did not significantly contribute to aquatic mercury pollution and were not effective predictors of bank swallow populations.

4.1.3 Multiple Factors May Influence Mercury Bioaccumulation

Another reason for the insignificant association between mercury pollution and abundances could involve the complex nature of mercury bioaccumulation, as local mercury concentrations are just one of several drivers.[41] Previous work has also demonstrated regional variability in aquatic mercury concentrations, attributing to differences in watershed characteristics.[40] In addition, aspects of lake water chemistry, such as dissolved organic carbon, sulfates, pH, dissolved oxygen, and salinity impact the methylation of mercury into the easily accumulated MeHg.[23,40–42] The biology of the organisms of interest, climate, and landscape conditions are also determinants of mercury bioaccumulation and its exposure to aerial insectivores.[8,40,41,43] Thus, aquatic mercury levels are highly dependent on region-specific characteristics, many of which were not assessed in the current study. The need to examine these drivers was evidenced, as the inclusion of the interaction between temperature and mercury release quantities in the multiple regression model enhanced its explanatory power and significance (Table 4). This may align with previous research suggesting consequences such as reduced nestling success and increased methylmercury bioavailability from this interaction.[17,18,23] Since this interaction term was marginally significant alone, it was not a strong predictor, reinforcing the need to explore further drivers (Table 4).

4.2 Future Work and Study Limitations

4.2.1 Exploring Additional Factors Impacting Mercury Levels and Bank Swallow Abundances

Due to ongoing MeHg production, the presence of legacy mercury, and the potential for decade-long delays in improvements following emission reduction measures, mercury is still a relevant issue in aquatic ecosystems.[12,13] Based on the evidence of its potential impacts on bank swallow reproductive outputs, future research is required to better assess its impacts on population declines.[16–19] These studies can instead examine direct measures of aquatic and invertebrate MeHg concentrations and their relationship with bank swallow abundances. Additional factors influencing mercury bioaccumulation can be explored in future models as well.

Furthermore, it is crucial to consider several unexamined factors since the overall model explained only 40.6% of the variation in bank swallow abundances, outliers in the model residual plots were present, and there was interregional variability in the magnitude of temporal differences in the predictors and abundances. Other proposed drivers include neonicotinoid insecticides, accumulated through aquatic-terrestrial transfers which have been linked to steep declines of aerial insectivores.[6,44,45] Habitat loss, other agricultural practices, changes in precipitation regimes, and air-borne pollutants may also be important contributors.[5] Future models can incorporate these factors to gain a more holistic understanding of the birds' declines. Lastly, as bank swallows migrate to certain regions of North America for the breeding season, there may be threats to their survival in their non-breeding grounds as well. Thus, research can also expand to identify and evaluate alternate threats in those regions.

4.2.2 Statistical Improvements

As the abundances reported in this study were predictions based on point count data, several limitations should be considered. Ideally, the RMSE should be close to 0 to indicate a predictive model closely aligning with measured values.[25] However, the resulting values for both interpolations were closer to 1, suggesting discrepancies in the models' accuracy (Table 2). This may be attributed to the outliers in the dataset, differences in the distances from which observers quantified counts in each bird survey, and sampling biases associated with the point count datasets.[1,2] Therefore, there is a need for further model refinement, the removal of outliers in the datasets, and controlling for data collection discrepancies in future work.

In addition, more complex modelling techniques could be employed, as the simple linear regression models applied may have generalized the complexity of the studied relationships. For instance, mixed effects modelling can control for the variation associated with each region.[46] This could provide a clearer understanding of the independent predictors of bank swallow abundances.[46] Also, given the current study's focus on two time periods, future research can conduct year-by-year analyses over a longer duration. This can capture trends over a broader temporal scale and provide more insight into the relationships between the predictors and abundances.

4.2.3 Alternative Approaches to Understanding Population Declines

As applied in the current study, correlative approaches are important for understanding the relationships between species population trends and threats.[47] However, the mechanisms through which mercury and temperature may influence bank swallow abundances remain undetermined, as the study method applied cannot assume causality.[47] To investigate these effects, studies that assess the impacts of threats on demographic processes that drive population trends, such as breeding successes and juvenile survival, can be performed in the future.[47] Experimental studies can also be conducted to directly observe the effects of mercury and temperature changes on the health and reproduction of bank swallows. In conjunction with statistical modeling, these could be useful in clarifying causative relationships between population trends and limiting factors.

5.0 CONCLUSIONS

This study applied ordinary Kriging to assess changes in bank swallow abundances from Period A (2001-2005) to B (2018-2022) in Southern Ontario using OBBA and NABBS point count data. Through geospatial visualizations and paired statistical analyses, it was found that their declines continued over these 13 years. Past studies and recovery strategies have attributed reductions in their insect prey to their historical losses, driven by a combination of factors, including habitat loss, climate change, and pollution.[5,6] However, the influences of changing temperatures and mercury on their population declines have remained unclear.[2,5] Building on previous research that investigated the effects of mercury pollution and increasing temperatures on reproductive successes, the current study utilized statistical techniques to analyze them in the context of bank swallow abundances in Southern Ontario.[16–19,21,22,37,38] Temperatures significantly increased, while mercury pollution did not significantly change from Period A to B. The multiple linear regression model demonstrated the significance of considering mercury release quantities, temperature, and their interaction in understanding the population declines of bank swallows in Southern Ontario. The significant negative relationship between temperatures and predicted abundances indicated that climate change may be an important threat to the species. Mercury pollution emerged as a marginally significant predictor, suggesting that indirect indicators of aquatic mercury concentrations may not capture the complexity of mercury methylation and bioaccumulation. Thus, the associations of mercury with bank swallow abundances remain unclear. Future research should focus on modelling direct measures of aquatic mercury as a predictor. Lastly, the relationships differed among larger and smaller spatial scales, highlighting the need to control for regional differences in future models and account for additional drivers, such as habitat loss, pesticides, and more.

In conclusion, this study uncovered spatiotemporal dynamics between threats and population declines in bank swallows. It highlighted the need to consider multiple drivers in their continuing declines, revealing increasing temperatures as a critical factor. Applying spatial interpolation by ordinary Kriging and multiple regression models can identify priority threats for conservation measures by analyzing their relationships with population trends. Continued research will enrich our understanding of the interactions between various threats and inform targeted conservation actions to support bank swallow populations.

6.0 APPENDIX A

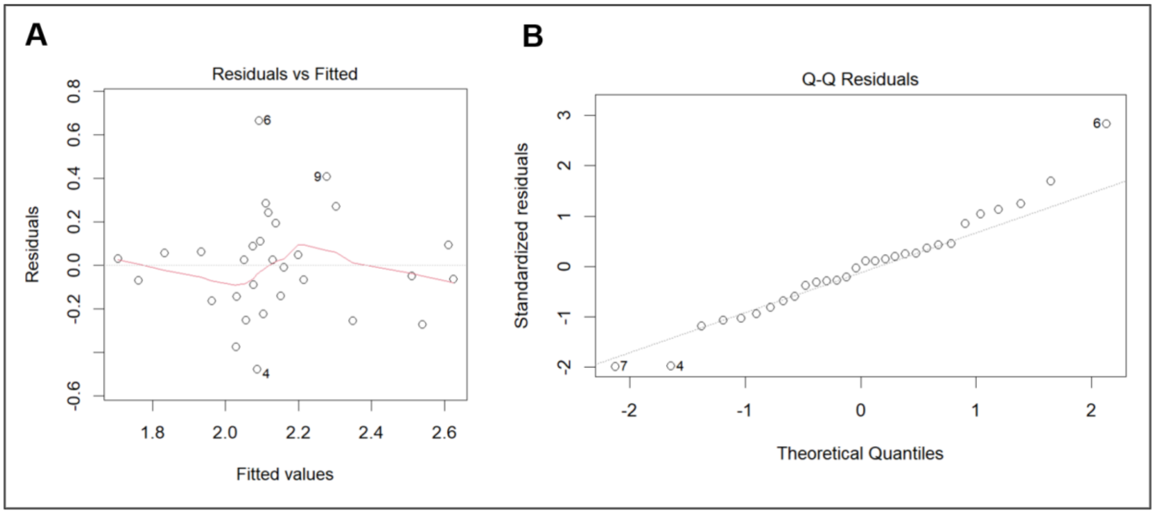
Table A1. Summary of all mean variables per ecodistrict in Period A (2001-2005). The mean abundance, mercury releases and temperatures, along with their standard deviations, were computed for each ecodistrict in ArcGIS Pro.

No.	**Ecodistrict**	**Mean Abundance** *(ln(individuals per unit area))*	**Mean Mercury Release Quantities** *(kg)*	**Mean Temperature** *(ºC)*
1	Kemptville	2.15 ± 0.24	22.7 ± 58.8	17.5 ± 3.4
2	Peterborough	2.56 ± 0.24	0.106 ± 0.21	15.4 ± 3.5
3	Stratford	2.25 ± 0.30	6.92 ± 11.0	16.6 ± 3.7
4	Grimsby	1.61 ± 0.18	15.0 ± 26.7	17.5 ± 3.9
5	St. Thomas	2.36 ± 0.64	19.3 ± 46.8	17.7 ± 3.7
6	Picton	2.76 ± 0.31	17.5 ± 26.9	17.1 ± 3.6
7	Niagara	1.65 ± 0.25	26.6 ± 64.4	16.9 ± 3.7
8	Oshawa-Coburg	2.33 ± 0.50	12.1 ± 28.8	16.6 ± 3.8
9	Barrie	2.69 ± 0.29	$5.71 \times 10^{-4} \pm 7.9 \times 10^{-4}$	16.6 ± 3.8
10	Mount Forest	2.46 ± 0.25	0	15.8 ± 3.6
11	London	2.16 ± 0.50	3.64 ± 5.8	17.3 ± 3.8
12	Kincardine	2.09 ± 0.15	0.412 ± 0.33	16.3 ± 3.6
13	Toronto	1.81 ± 0.19	10.6 ± 16.0	17.6 ± 3.9
14	Meaford	2.71 ± 0.31	0.134 ± 0.02	15.4 ± 3.8
15	Smiths Falls	2.58 ± 0.20	0.0580 ± 0.04	16.5 ± 3.6

Table A2. Summary of all mean variables per ecodistrict in Period B (2018-2022). The mean abundance, mercury releases and temperatures, along with their standard deviations, were computed for each ecodistrict in ArcGIS Pro.

No.	Ecodistrict	Mean Abundance *(ln(individuals per unit area))*	Mean Mercury Release Quantities *(kg)*	Mean Temperature *(ºC)*
1	Kemptville	1.80 ± 0.15	8.65 ± 4.5	18.1 ± 4.7
2	Peterborough	2.15 ± 0.34	0	17.0 ± 4.1
3	Stratford	1.88 ± 0.18	13.6 ± 19.7	17.0 ± 4.8
4	Grimsby	2.01 ± 0.20	18.7 ± 27.3	18.5 ± 5.1
5	St. Thomas	1.89 ± 0.27	2.32 ± 4.4	18.2 ± 5.1
6	Picton	2.21 ± 0.17	14.4 ± 5.4	17.1 ± 4.4
7	Niagara	2.00 ± 0.23	5.33 ± 8.6	18.0 ± 4.7
8	Oshawa-Coburg	2.40 ± 0.23	17.8 ± 40.1	17.9 ± 4.8
9	Barrie	1.89 ± 0.21	$4.67 \times 10^{-4} \pm 5.8 \times 10^{-5}$	17.4 ± 5.0
10	Mount Forest	1.99 ± 0.19	0	17.3 ± 4.9
11	London	1.74 ± 0.15	1.66 ± 2.4	18.7 ± 4.0
12	Kincardine	2.15 ± 0.18	0	16.8 ± 5.1
13	Toronto	1.69 ± 0.13	5.21 ± 7.1	18.9 ± 4.4
14	Meaford	2.27 ± 0.16	0	15.7 ± 4.8
15	Smiths Falls	2.08 ± 0.12	0	17.3 ± 4.6

Figure A1. Diagnostic plots of the multiple linear regression model for bank swallow abundances. (A) Fitted residuals plot demonstrating the variance of the residuals, which are the differences between the observed and predicted values, against the fitted (predicted) values. (B) Q-Q plot assessing how well the observed standardized residuals plot related to theoretical quantiles and the 1:1 line expected if the distribution were normal.



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