



# Living Planet Report Canada 2025

## Technical Supplement

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# Canadian Living Planet Index

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## Introduction

### What is the Living Planet Index

The Living Planet Index (LPI) is a biodiversity indicator used to measure the state of wildlife. Similar to the way a stock market index measures economic performance, the Living Planet Index measures ecological performance by tracking patterns in wildlife abundance over time.<sup>i</sup> The LPI is calculated by aggregating temporal trends in wildlife abundance from multiple datasets across geographic areas of interest. In Canada, the LPI method has been applied to calculate an overall index at a national scale, focusing specifically on native vertebrate species.

Globally, the indicator was first published in 1998 and has been updated biennially to track average population abundance of monitored vertebrate species over time. By contrast, the Canadian Living Planet Index (C-LPI) was first released by World Wildlife Fund Canada (WWF-Canada) in 2007,<sup>ii</sup> with updates published in both 2017<sup>iii</sup> and 2020.<sup>iv</sup> Notably, the C-LPI is a modified version of the global LPI. Importantly, the C-LPI should be viewed as the best possible snapshot of trends in Canadian wildlife populations at a given time and should not be directly compared to previous iterations of the index. The latest findings from the C-LPI are published in the Living Planet Report Canada (LPRC) 2025.

## Data

### Sources and coverage

Assessment and documentation of temporal population abundance is conducted across Canada for a variety of reasons. In some instances, monitoring is conducted before and after natural disturbances, anthropogenic pressures or conservation interventions to assess associated impacts on wildlife abundance. Other times, monitoring is carried out to determine sustainable harvest quotas. Irrespective of the circumstance, population monitoring over time can be used to determine whether populations are increasing, decreasing, or exhibiting stable trends of abundance, on average. Notably, new technologies help monitor population abundance in real time, and in remote locations, enhancing our knowledge base on the status of wildlife in Canada.

Numeric population data contributing to the C-LPI were compiled from a variety of sources, including peer-reviewed scientific literature, government monitoring (e.g., Parks Canada, Fisheries and Oceans Canada, and provincial entities), and citizen science (e.g., data contributing to the State of Canada’s Birds). While some of this data was compiled for previous iterations of the LPRC, WWF-Canada and the Zoological Society of London periodically work to update the database — both in terms of new records, and by extending the time span of current records. Approximately 1,300 new records (population time series) were obtained since 2020, including 27 new species. Moreover, roughly half the dataset (2,263 population time series) contained data from 2017 onward (the 2020 LPRC exhibited C-LPIs from 1970 to 2016). The 2025 LPRC contains C-LPIs that span from 1970 to 2022. In total, nearly 450 sources of data, contributing to 5,099 monitored populations of 910 species are included within the C-LPI.

The population time series data has broad spatial coverage (Figure 1). The national C-LPI includes data for monitored vertebrates, including birds, fish, mammals, amphibians and reptiles. The index weighs each species equally, so disaggregating the trend into taxonomic groups can help uncover patterns that may not be evident at the national level. Fish and birds are the primary taxonomic groups in the C-LPI, accounting for 43.3% and 41.1% of species in the analysis, respectively (Figure 2). The relative proportion of mammals (11.4%) and amphibians and reptiles (4.2%) is smaller. This is expected, given that there are comparatively fewer species in these taxonomic groups in Canada (Table 1).<sup>v</sup> Taxonomic biases also exist in the broader context of conservation research with fish, amphibians and reptiles often underrepresented relative to the number of species in these groups.<sup>vi</sup>

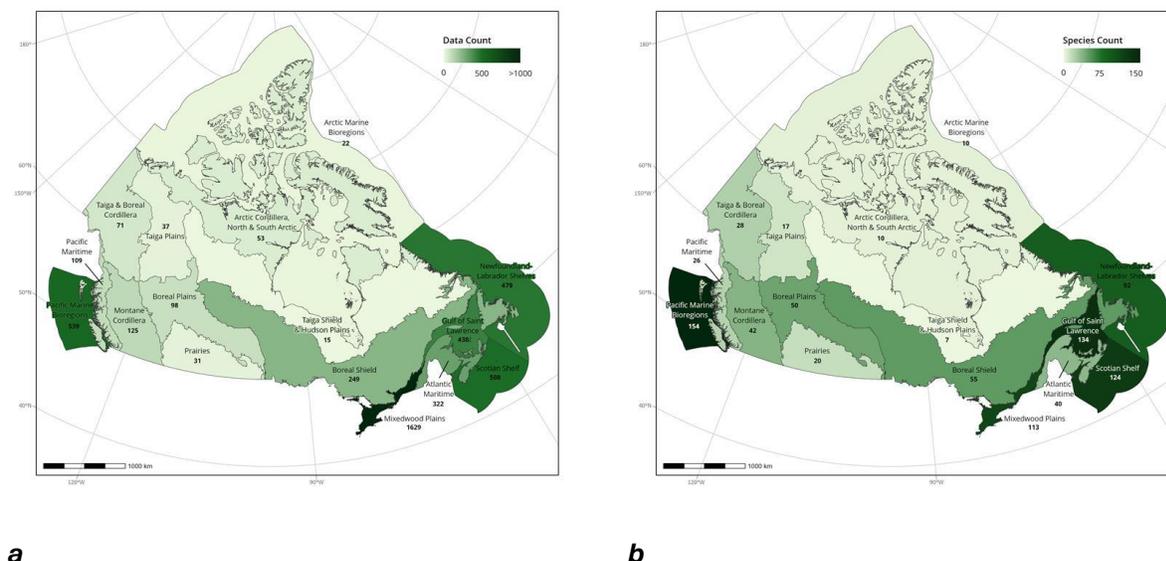


Figure 1. Spatial distribution of data contributing to the Canadian Living Planet Index by (a) population time series (i.e., monitored population) and (b) species, per terrestrial ecozone and marine bioregion.

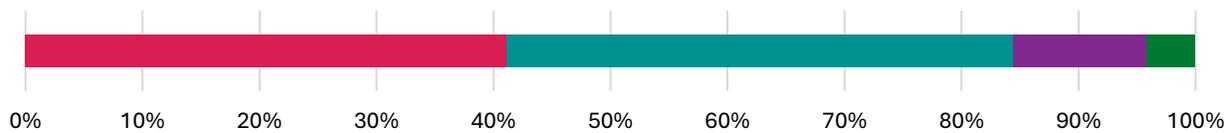


Figure 2. Relative proportion of birds (red), fish (teal), mammals (purple) and amphibians & reptiles (green).

Table 1. Representation of native vertebrate species considered of conservation interest according to Canada's Wild Species Report (exotic species, hybrids and accidental species are excluded) included in the analysis.

Taxonomic Group	Number in C-LPI	Percent Included
Birds	374	83%
Fish	394	38%
Mammals	104	53%
Amphibians & reptiles	38	44%
<b>Total</b>	<b>910</b>	<b>51%</b>

There is considerably more data contributing to the C-LPI since WWF-Canada's first publication in 2007 (Figure 3). Impressively, since 2007, the number of time series has quadrupled, and the number of species has more than doubled. Most of these data gains were realized in 2017. While subsequent data collection was endeavored, the dataset has achieved only incremental gains in new species since.

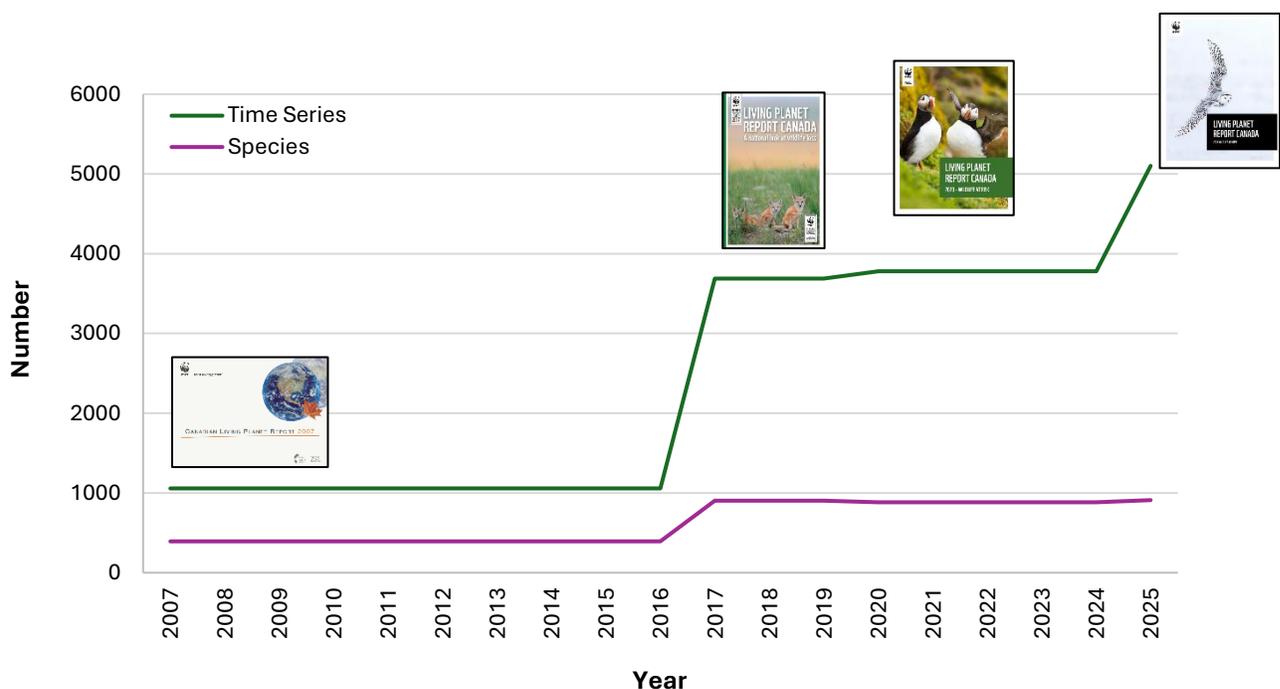


Figure 3. Number of population time series and species contributing to the Canadian Living Planet Index and associated Living Planet Report Canada published in 2007, 2017, 2020 and 2025.



## Inclusion/exclusion of data

Criteria for the inclusion of species population data in the index followed the approach of previous iterations of the Living Planet Index as developed by the Zoological Society of London,<sup>vii</sup> with slight modifications for Canada:<sup>viii ix</sup>

- Populations must have been consistently monitored in the same location, using the same method over time.
- Data must be numerical (i.e., a population count or another reliable population-size proxy, such as population estimates, spawning stock biomass, density, etc.).
- Species must be native to Canada and have applicable conservation status rank according to Canada's Wild Species Report<sup>x</sup> (i.e., exotic species, hybrids and accidental species under the NatureServe rank of "not applicable" were excluded).
- Population data must be available for at least three years between 1970 and 2022.

To align approaches between the C-LPI and the federal government's Canadian Species Index, 12 birds were also removed from the dataset and bird data were restricted to time series provided by ECCC. Nine birds were excluded as they only recently expanded their range into Canada: Wild Turkey, Anna's Hummingbird, Black-necked Stilt, Great Egret, Red-bellied Woodpecker, Bushtit, Carolina Wren, Blue-gray Gnatcatcher, and Blue-winged Warbler. Finally, three geese were excluded given their designation as nuisance species. These exclusions were necessary to align C-LPI and CSI indicators so that the only differences are additional data uploads within interim publication years.<sup>xix</sup>

## Investigation of the data

In collecting temporal trends in population abundance for use in the C-LPI, all data that fits the criteria for inclusion is incorporated. However, some temporal, spatial, taxonomic and species biases that underlie the data and can limit and influence population trends. Consequently, the underlying data included in the analysis of the C-LPI can impact the results that are obtained.

For instance, population trends for approximately half of the native, regularly occurring species in Canada have been included within the C-LPI. Conversely, the C-LPI is missing population trends in abundance for half of Canadian wildlife. If the data were available, inclusion of these species may alter the final trajectory and magnitude of the C-LPI. However, a lack of publicly available population trend data hinders our ability to accurately report on trends for all vertebrates in Canada. In addition, the collection of data is biased toward certain species (including those that are charismatic or of socioeconomic importance<sup>xii</sup>), taxonomic groups<sup>xiii</sup> and biotic traits.<sup>xiv</sup> Further, non-random site selection<sup>xv</sup> and geographical representation may also exaggerate or dampen aggregate indicators of relative abundance. Similarly, data may not be evenly distributed from a spatial and temporal perspective, and thus, some regions and time periods may contribute more prominently. The variation and inherent biases in the underlying data can subsequently impact the calculation of the geometric mean of relative abundance indices.



Of the species for which biotic trait data (body size, lifespan and trophic level) was available (Figure 4), there was considerable overlap for vertebrates within the C-LPI compared to those lacking C-LPI data. In the distribution of biotic variables (Figure 5), body size boasted an overlap of 78.5% while lifespan had an overlap of 80.3%, yet differences among distributions were apparent for all three variables ( $p < 0.001$ ). Discrepancies were particularly prevalent in the representation of fishes, where the C-LPI is biased towards larger-bodied and longer-lived species.

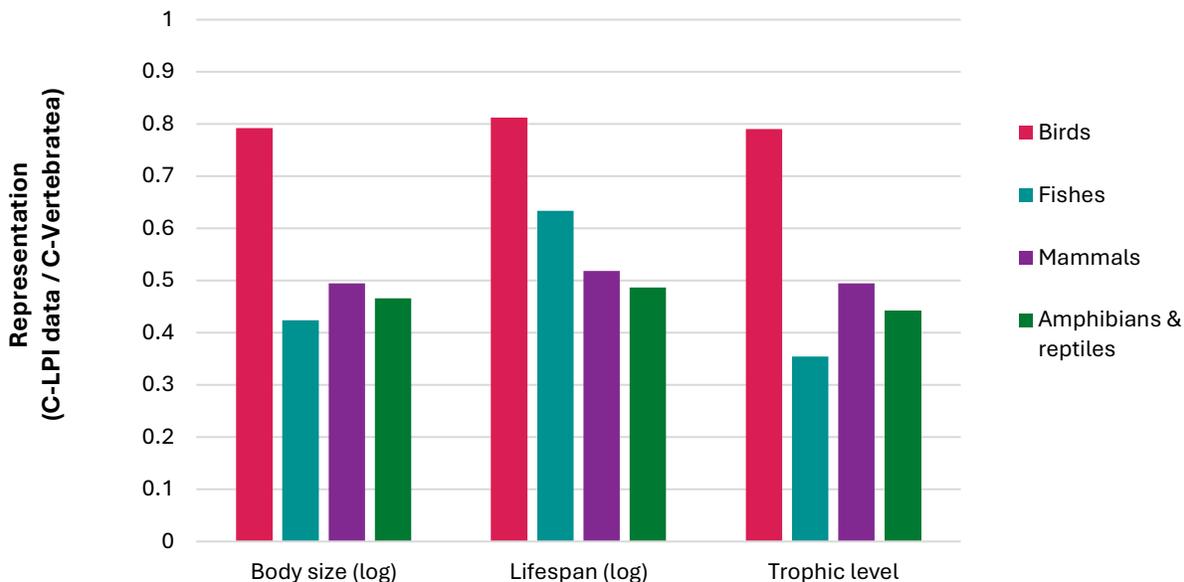


Figure 4. Data availability for assessing the distribution of species traits. Bars depict the representation of species with trait data in the Canadian Living Planet Index, relative to the number of species with trait data for the broader vertebrate subphylum in Canada (C-Vertebrates), following methods from Currie et al. 2022.

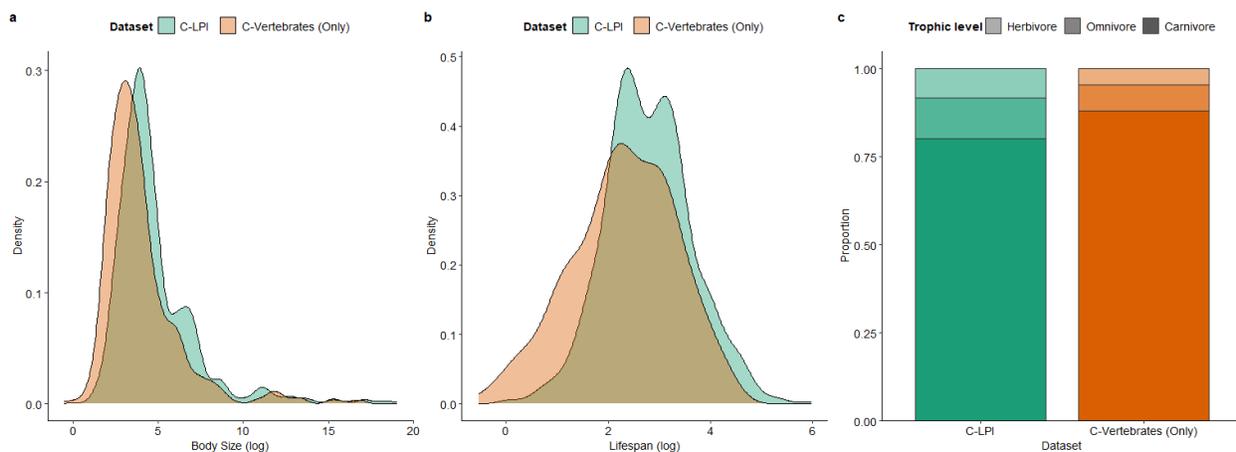


Figure 5. Comparing distributions of (a) body size, (b) lifespan, and (c) trophic level for species included within the Canadian Living Planet Index (C-LPI) Trait database, compared to other native Canadian vertebrate species lacking LPI data (C-Vertebrates Only), following methods from Currie et al. 2022.

Data availability also improves over time. For instance, there is more data contributing to the national C-LPI in the latter half of the time period examined (Figure 6). When examining either population time series or species, 1970 holds the lowest number of records and 2010 holds the highest. Consequently, the baseline year can affect the final calculation of the geometric mean. Importantly, the C-LPI is a relative measure, comparing trends to the baseline year of 1970. Therefore, any shift in the baseline year may result in differing overall average trends. Within the C-LPI dataset, the number of population time series triples from 1970 to 2010 and falls off thereafter. On average, 5.6 population time series contributed to a species, with variation among taxonomic groups (Figure 7). For instance, national-level time series were available for all birds through aggregated trends provided through ECCC, while some fish trends were disaggregated by departmental divisions.

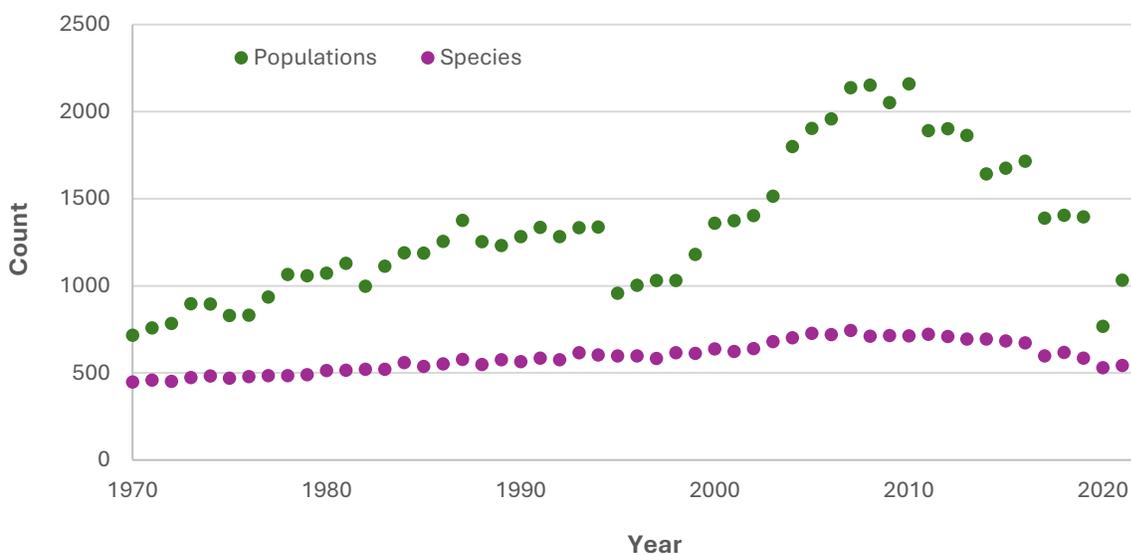


Figure 6. Number of population time series and species contributing to the Canadian Living Planet Index by year.

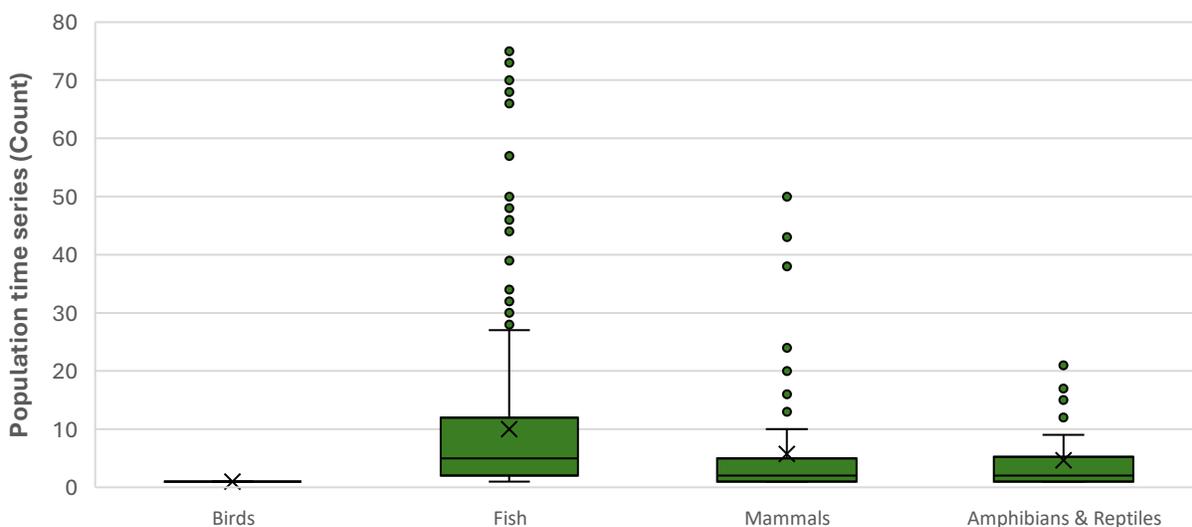


Figure 7. Boxplot representing the number of population time series contributing to a species in the Canadian Living Planet Index, by taxonomic group. The Xs represent the average number of population time series contribution to a specific species. The Y-axis is restricted to 80, and thus three fish species are not depicted to improve visualization.

## Methods

### Calculating the index

The *rlpi* package<sup>xvi</sup> was used to run the C-LPI, using selectable options for calculating a modified index for Canada. For consistency with the global LPI, index values were calculated with a baseline year of 1970. Consequently, any changes in wildlife populations that occurred prior to 1970 are not reflected in the results reported in the LPRC 2025, which showcases only recent changes in monitored population abundance. This is important to note, given that monitored population abundance in 1970 may differ from historical abundance.

#### Replicates

In cases where there was spatial and temporal overlap of population time series for a given species, only one of the overlapping populations was retained (to reduce geographic sampling bias). Priority for inclusion was given to higher quality data, which encompasses time series length, fullness, and credibility of the data source.

#### Zeros

Mathematically, a number cannot be divided by zero. In order to address population counts of zero in the analysis, it is possible to either treat zeros as missing values or add a small quantity to zeros for mathematical purposes. Methodological approaches can also be made conditionally, where zeros are treated differently dependent upon where they are found within the time series.

Importantly, geometric mean of relative abundance indices are sensitive to the quantity chosen to replace a zero,<sup>xvii</sup> and there is no consensus on the singular best approach.<sup>xviii</sup>



Within the C-LPI, the proportion of zeros (number of zero data points divided by the number of data points) fluctuates year to year, with the majority found in more recent years (Figure 8). Seventy-three time series ended in zeros, however, upon close examination of that data — they were considered local extirpations, and thus the C-LPI treats zeros as missing values. In total, 204 time series contained zeros, the majority of which were for mammals (39.2%), followed by fish (27.9%; Figure 9).

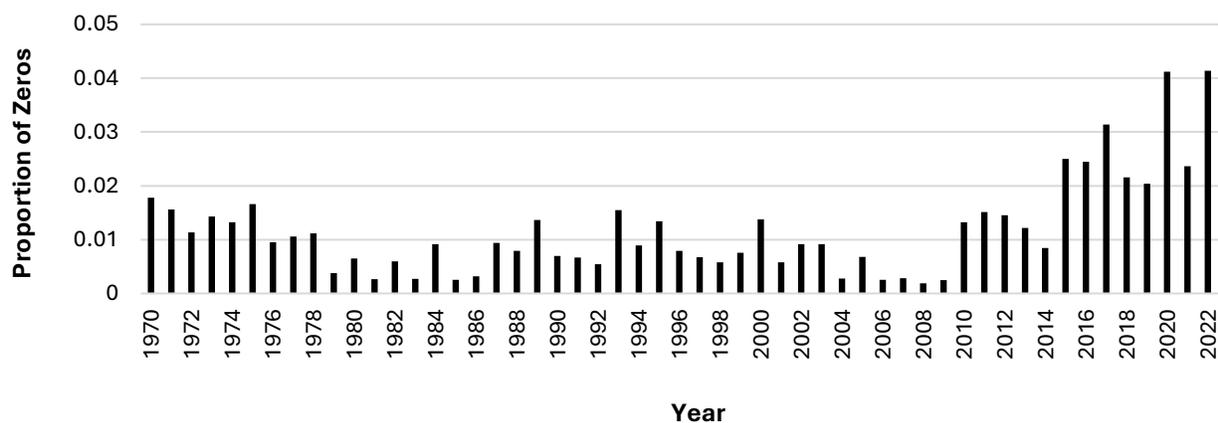


Figure 8. Proportion of zeros (number of zero data points divided by the number of data points), per year.

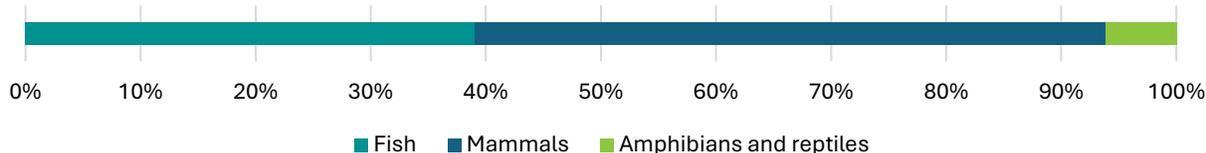


Figure 9. Taxonomic breakdown for the 204 population time series containing zero values. Fish (teal), mammals (blue), amphibians and reptiles (green).

### Interpolation

Changes in population abundance were calculated using a geometric mean of relative abundance from 1970 to 2022. Time series with at least six data points (64%) were modelled using a Generalized Additive Model (GAM). Fitted GAM values were used to interpolate values for all years between the start and end year of the time series. Linear regression was applied to short time series or those that result in a poor GAM fit (36%). Importantly, not all time series began in 1970 and ended in 2022. The C-LPI was calculated by averaging trends in monitored populations to create a trend in abundance for each unique species. These trends were then averaged across all species to generate the C-LPI.

### Time series extent: Data points and length

The number of data points contributing to a time series and its length are measures of data quality. Within the Canadian data set, birds have the longest and fullest (i.e., number of data points) time series, owing to data from the State of Canada’s Birds (Figure 10). On average, time series contain 13.69 data points and have a length of 18.20 years. As a reminder, the C-LPI requires a minimum of three data points, but has no set criterion regarding time series length.

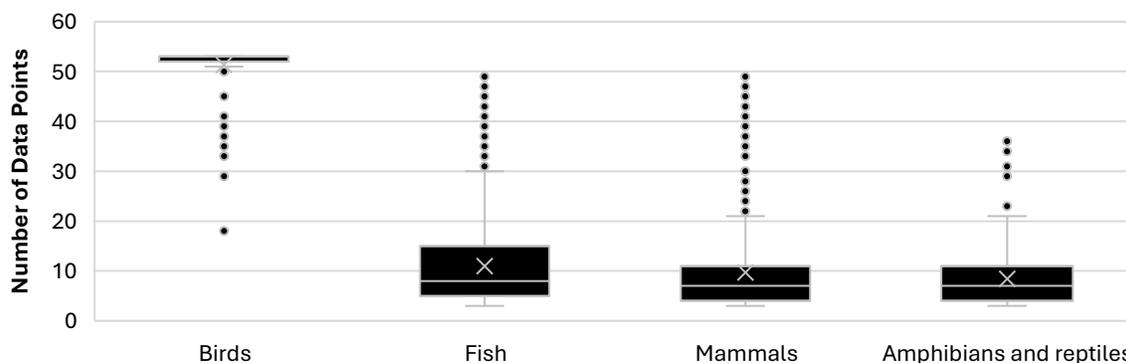


Figure 10. Number of data points per time series, by taxonomic group.

### Credible intervals

All C-LPIs are presented with 95% credible intervals calculated from bootstrapping species (keeping the series of lambda values over time together for each species) and creating an index for each of the 10,000 bootstrapped resamples. This approach differs from the global method, where bootstrapping is conducted by randomly sampling species for each year, independently, and does not account for autocorrelations in lambdas over time for a given species.<sup>xix</sup> The credible intervals include the range of indices that can be fit into the existing dataset, capturing the variability within the data — they do not incorporate the uncertainty associated with population counts of individual studies. The credible intervals are multiplicative and increase in width over time as the uncertainty of previous years are inherited by the rest of the trend. The credible intervals around the final index value represent uncertainty around that value in relation to the baseline. Similarly, the final index value reported is relative to the baseline value in 1970.

### Weighting

The C-LPI, calculated as a geometric mean of relative abundance, is useful to track large-scale changes in average population abundance. However, the use of averages can mask detailed nuances of the compiled data. For instance, let’s assume we have two population time series for one species. One time series accounts for 90% of the population, and shows a drastic decline, whereas the other time series accounts for 10% of the population and exhibits a slight increase. The C-LPI weights these two population time series equally to give an average trend in abundance for the species, thereby masking the fact that most of the population is in decline.



Recent studies utilizing the LPI — including the global Living Planet Report — have employed proportional weighting to address taxonomic and geographic bias in biodiversity data by accounting for the estimated number of species within systems and relative diversity of taxonomic groups.<sup>xx</sup> The results of a proportionally weighted C-LPI do not differ significantly from an unweighted index (Figure 11), and thus the C-LPI weights all species equally, representing the data actually included.

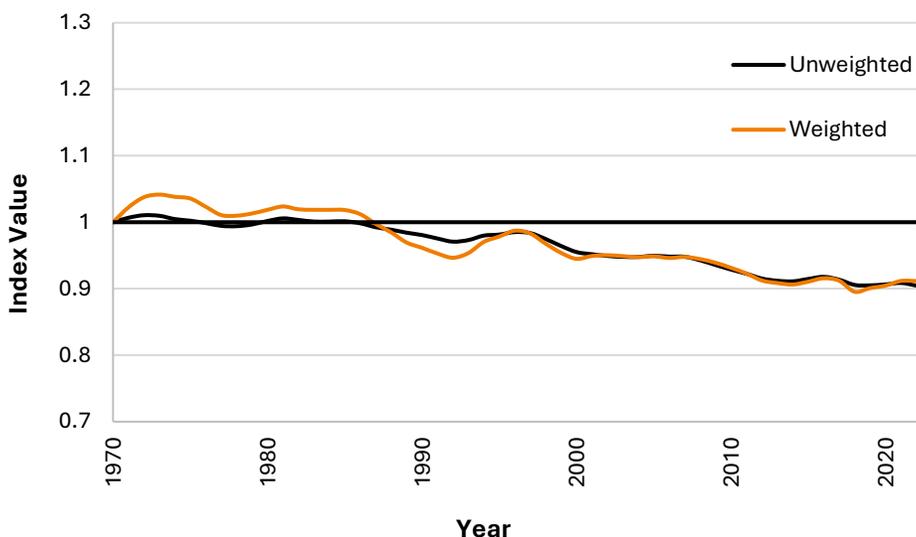


Figure 11. Evaluation of alternative options for weighting species to account for representation: (black) unweighted (C-LPI), and (orange) proportionally-weighted species richness.

### Outliers

Removing extreme values (those that are considered extreme increases or decreases in abundance) has no significant effect on the final index value (consistently a 10% decline, on average) but does help refine the credible intervals so that they no longer cross the baseline value in 1970 (Figure 12), thereby improving confidence in the declining result. The C-LPI retains all data and does not remove outliers.

### Habitats

Habitat associations were retrieved from the IUCN Red List<sup>xxi</sup> and individual species searches where data were unavailable. Habitat associations were subsequently refined through expert evaluation of all 910 species included within the dataset. Consequently, habitat associations were based on known habitats the species occupies or relies on, rather than the particular landcover where the population was monitored.

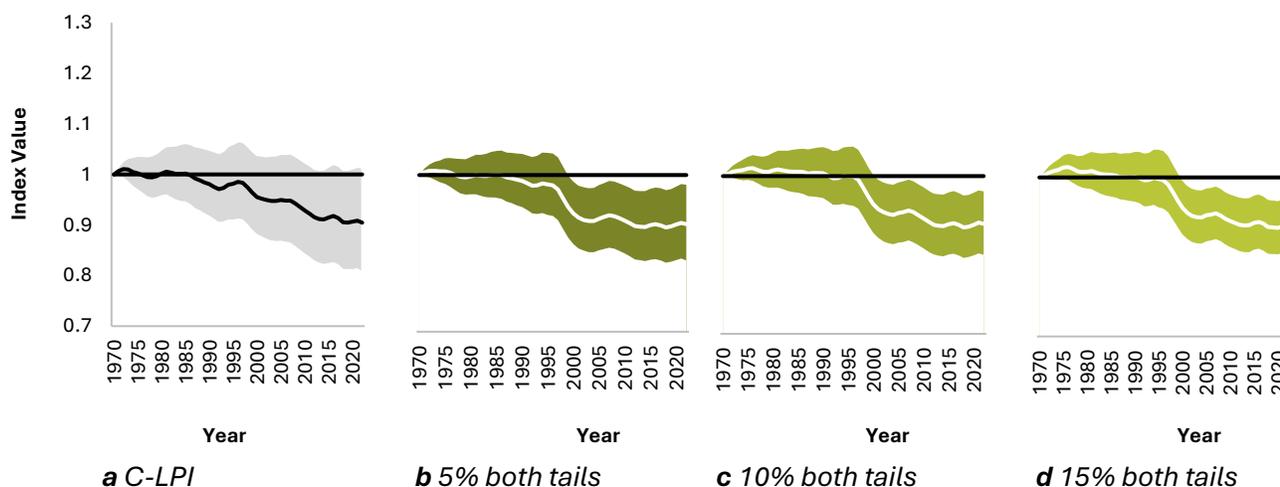


Figure 12. Evaluation of outlier removal, from both positive and negative extremes, including (a) no removal, compared to removal from both tails (b) 5%, (c) 10%, (d) 15%.

### Repeatability

Methodological approaches, decisions, population trend data and associated R-scripts for calculating a Living Planet Index are all publicly available online, contributing to an era of open-access data and transparent science.

The data underlying the C-LPI is accessible on the [LPI Data Portal](#), which is periodically updated, and thus lag times from data compilation and validation to publication exist. Moreover, some contributors recognize that their data enhances the accuracy of the C-LPI, but have requested that their data remain confidential — frequently due to sensitivities and concerns associated with sharing species locations and trends. In the C-LPI, 28% of population time series are classified as confidential records and have therefore been withheld. Notably, half of those stem from one source. Confidential records comprise of 100 species (11% of species in the dataset) and a total of 29 sources (6% of data sources).

Code for running LPIs is available through the *rlpi* package.<sup>xxii</sup> The *rlpi* package includes selectable options for differing methodological decisions, including the number of data points, linear regression modelling for short time series, and baseline selection, among others.

If using the data for publication purposes, we encourage you to reach out to the Indicators & Assessment Unit of the Zoological Society of London to ensure that all caveats, limitations and requirements for pre-processing have been discussed.



## Results

### What indices are included in the LPRC 2025?

The Living Planet Report Canada 2025 includes a national C-LPI, which is used to track the state of wildlife across the country. The data contributing to the national C-LPI have also been subset to reflect trends in the following habitats: grasslands, rocky areas, marine and coastal areas, forests, freshwater, and human-dominated landscapes. We show the C-LPI by habitat, and also provide taxonomic breakdowns, where data permits. Within the report, each trend is accompanied by pie charts depicting taxonomic contributions to the index, as well as the proportion of increasing, declining and stable trends.

### What are the final results reported?

The C-LPI examines the average trend in population abundance for 5,099 population time series of 910 native vertebrate species — over half of Canada’s vertebrate species — and shows an average decline of 9.53% (rounded to 10% for public reporting) from 1970 to 2022. Differences in the final index value among taxonomic groups are marginal relative to habitats. Results for all C-LPIs included in the Living Planet Report Canada 2020 are summarized in Table 2.

Table 2. Summary of the four Canadian Living Planet Indices included within the Living Planet Report Canada 2025. Each categorical trend has a corresponding number of species, population time series and percent change relative to 1970. Uncertainty bounds around the final index value, which represent uncertainty around that value in relation to the baseline.

Trend	Species (count)	Time Series (count)	Change relative to 1970 (%)	95% credible intervals		Direction
				Lower	Upper	
National	910	5,099	-9.53%	-19.17%	+1.41%	Decline
Birds	374	374	-11.53%	-20.80%	-0.99%	Decline
Fish	394	3,949	-6.27%	-27.30%	+21.83%	Decline
Mammals	104	599	-13.63%	-56.85%	+77.83%	Decline
Amphibians & reptiles	38	177	-13.98%	NA	NA	Decline
IUCN Red-List	60	396	-43.32%	-55.73%	-27.13%	Decline
Grasslands	85	300	-62.46%	-77.40%	-35.42%	Decline
Rocky areas	90	352	-30.78%	-49.48%	-5.16%	Decline
Marine and coastal	432	2,563	-4.18%	-21.21%	16.83%	Stable
Forest	186	686	-5.73%	-21.57%	+14.29%	Decline
Freshwater	243	2,405	+5.38%	-16.72%	+32.49%	Stable
Human-dominated	242	539	-17.33%	-29.52%	-2.82%	Decline

## Interpreting the results

### What does the C-LPI indicate?

The C-LPI is an indicator of wildlife abundance over time and does not reflect species extinctions, especially given that population counts of zero have been removed. In addition, an average of population trends is not synonymous with an average of total numbers of animals lost. For instance, a loss of 20 to 10 individuals in a population would have the same proportional loss as a decline of 10,000 to 5,000 but the total number of animals lost differs substantially. These discrepancies and clarifications are noteworthy given that the LPI is often misinterpreted.

From 1970 to 2022, the national C-LPI shows an average decline of 10% (Figure 13). Upon examination of the trends for individual species, we can gain an understanding of the aggregate C-LPI measure. The overall trend is likely attributable to the fact that 52% of species are declining in population abundance, which is marginally higher than species considered stable or increasing (Figure 14). The distribution of the per cent change in monitored population abundance from 1970 to 2022 is anticipated to be skewed, hence the use of a geometric mean of relative abundance. Abundance can decline by nearly 100% but can increase infinitely. According to the data underlying the C-LPI, there are a greater number of populations (N = 1,639) experiencing more substantial rates of decline ( $\leq 1/2x$ ) than those with more moderate and incremental declines (N = 1,130; between 0 to  $1/2x$ ). While the opposite is also true (there are a greater number of populations experiencing more significant increases in comparison to those with moderate changes), conservation should focus on reversing trends for species currently in decline, particularly given that a greater number of species are experiencing more substantial rates of decline (Figure 15). Finally, within the dataset, the percentage of negative years was greater than positive years for the population time series (Figure 16).

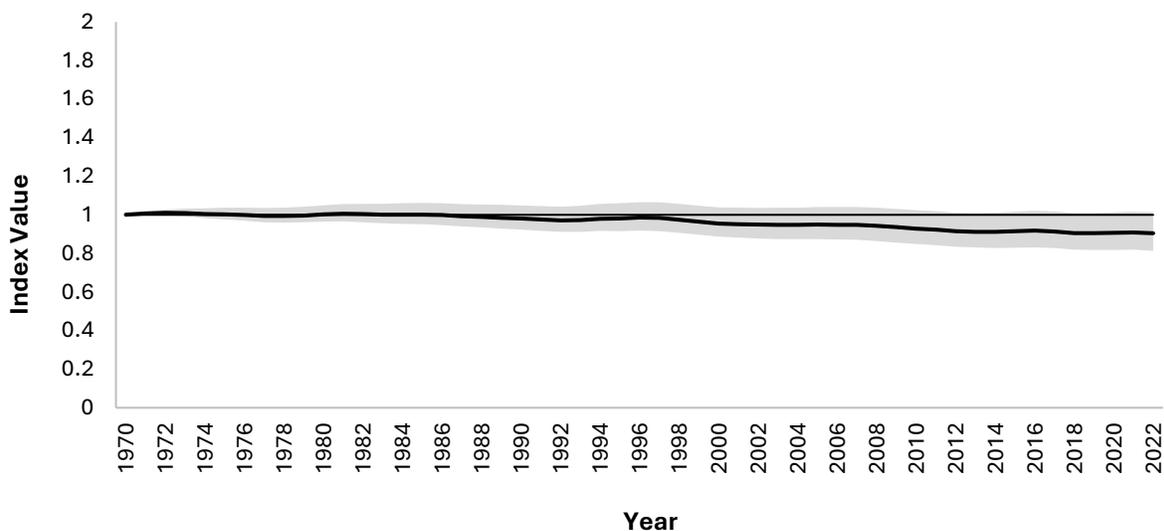


Figure 13. From 1970 to 2022, the Canadian Living Planet Index shows an average decline of 10% (5,099 population time series; 910 species).

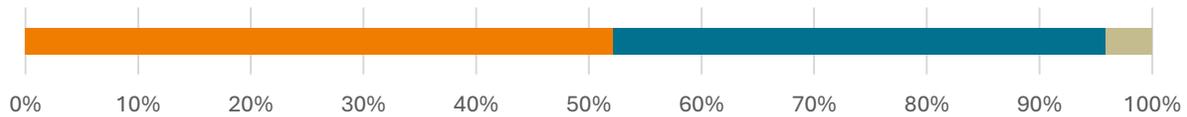


Figure 14. Relative proportion of declining (orange), increasing (blue) and stable (grey) trends included in the Canadian Living Planet Index.

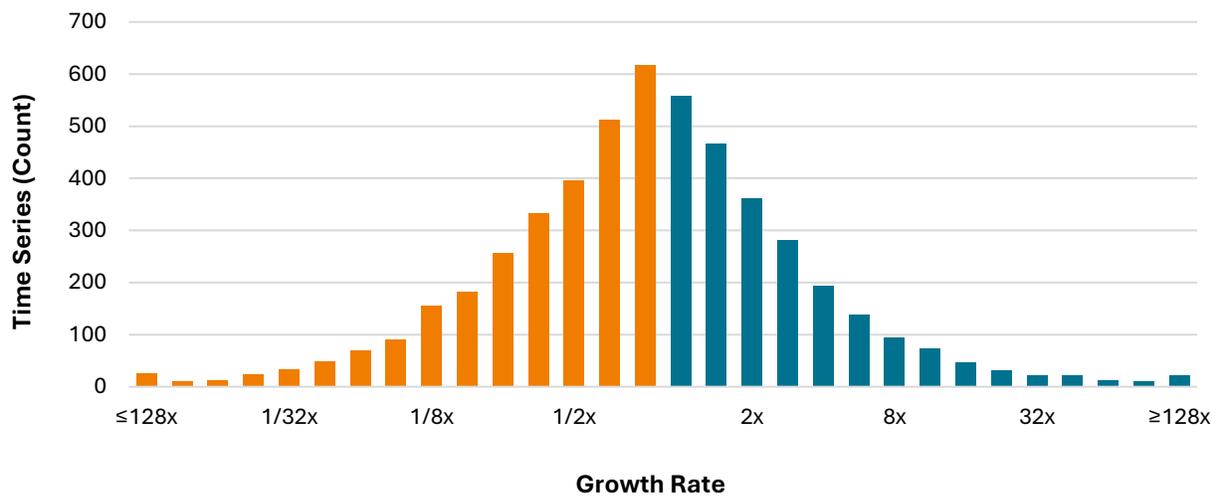
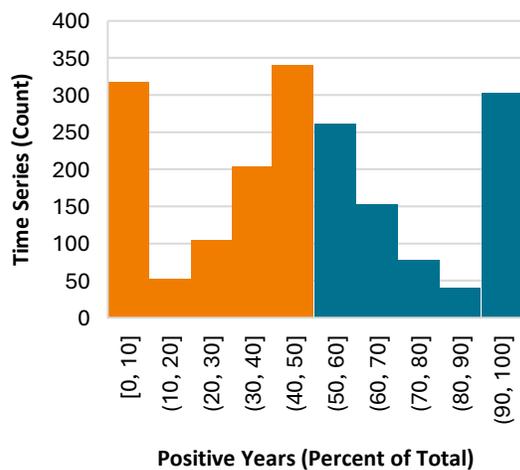
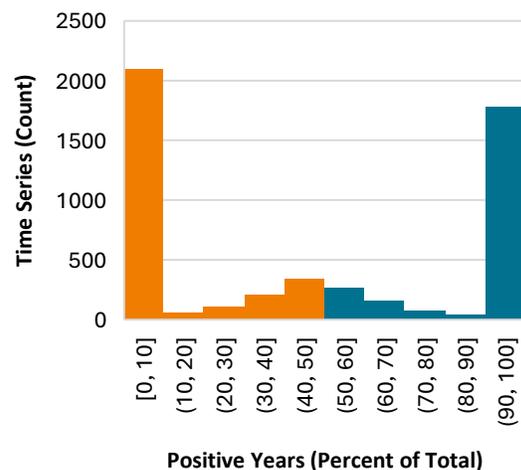


Figure 15. Distribution of the growth rate in monitored population abundance from 1970 to 2022 for the 5,099 population times series included in the Canadian Living Planet Index. Orange bars are indicative of a decline, and blue showcase a positive growth rate.



a



b



Figure 16. (a) Percent of positive years (years with a positive interannual change in abundance) for the 1,853 population time series modelled using the Generalized Additive Model (GAM). (b) Percent of positive years (years with a positive interannual change in abundance) for all 5,099 population time series included in the C-LPI. Orange bars are indicative of a decline, and blue showcase a positive trend.

## Bumble bee and butterfly occupancy models

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## Methods

### Data

#### Species observations

Bumble bee occurrence observations from 1960 to 2020 were obtained from the Bumble Bees of North America (BBNA) dataset<sup>xxiii</sup> — a collated resource with data from scientific surveys, museum specimens, and citizen science. In total, 200,469 observations of 46 species of bumble bee were obtained.

Butterfly occurrence data was curated from a variety of sources, including Global Biodiversity Information Facility (GBIF), private collections from amateur and professional Lepidopterist groups (e.g. the Toronto Entomological Association), and data from various scientific surveys and museum collections.<sup>xxiv xxv</sup> To remove potentially false identifications from this data, a combination of manual cleaning and automated filtering were used. For manual cleaning, published distributions were first consulted to remove suspicious records<sup>xxvi xxvii xxviii xxix xxx xxxi</sup>. For automated filtering, observations that fell within a level 3 ecoregion (obtained from the United States Environmental Protection Agency classification system<sup>xxxii</sup>) that had less than 0.1% of the total observations were also removed. In total, 1,295,661 unique butterfly observation records spanning 1960 to 2020 remained after filtering.



Data were further restricted to exclude species not typically found in Canada. To be included, the species in question must have been observed in Canada on at least five separate sampling visits, further constraining the final dataset to 38 bumblebees and 282 butterflies (Table 3).

### Environmental Variables

Climate variables (1960-2006) included: (i) decadal mean of the average maximum temperature of the warmest month per year, and (ii) decadal monthly mean precipitation. Data produced by the ACCESS1-3 model from Karger *et al.*<sup>xxxiii</sup> were used for historic and future conditions and the RCP45 scenario was adopted for 2006 to 2020.

Agricultural census data were obtained from the United States Department of Agriculture (USDA) and Statistics Canada and joined to spatial boundaries. In the US, spatial boundaries were identified by counties. In Canada, spatial boundaries were defined through Census Consolidated Subdivisions (CCS), with the exception of the 1961 Canadian Census of Agriculture, which only has courser Census Division boundaries digitally delineated.<sup>xxxiv</sup> Data for 1966, 1971, and 1976 were removed due to a lack of digital boundary delineations for Canada. Variables of interest included: (i) area of agricultural land (crops and pasture), and (ii) area of pesticide use. Variables were converted to areal proportions to align with species observations and climate variables. These values were resampled to a 50x50 km grid (see Models) and then re-converted to area by multiplying the area of each grid cell by the resampled proportions.

All data were cropped to the study area (Canada, contiguous US, and Alaska below 72.5 degrees latitude), and reprojected into EPSG:5070 (Albers Equal Area for North America).

### Models

Occupancy models were used to evaluate temporal population trends. Models relied on repeated sampling visits at a given site to estimate sampling biases — known as detection probability — and improve accuracy of occupancy models.<sup>xxxv</sup>

Occupancy models quantify occupancy probability, which refers to the probability that a given species is found at a site. For the invertebrate analysis, six occupancy models were run — one for bumble bees, and five for butterflies, correlating to the five major butterfly families in Canada. Occupancy probability was estimated for each species, site, and time period of interest.

Sites were generated by overlaying a 50x50 km grid onto North America, while time periods were binned by decades from 1960 to 2020. For each decade, occupancy was estimated using species observations at each site during sampling visit as per Kery *et al.* 2010.<sup>xxxvi</sup> Species observations are denoted by presence or absence of species detection. While presence data was available, absence was inferred. For bumble bees, non-detections (i.e., absence) were inferred when at least one other species of bumblebee was observed on each sampling visit, but the focal species was not. For butterflies, non-detections were inferred when at least one other species of the same family was observed on a sampling visit, but the focal species was not.

Models were run using the *rjags* R Package.<sup>xxxvii</sup>

## Occupancy submodel

Occupancy probability was modelled as a function of time (decade) for each species in a given location. Environmental variables (average maximum temperature, precipitation, agricultural land and pesticide use) were included as predictors.

Occupancy was modelled:

$$\begin{aligned} \text{logit}(\psi_{ijk}) = & \psi_{\text{species}}[i] + \\ & \psi_{\text{area}} \times \text{area}[j] + \\ & \psi_{\text{decade}}[i, r] \times k + \psi_{\text{decade}2}[i, r] \times k^2 + \\ & \psi_{\text{temp}}[i] \times \text{temp}[j, k] + \\ & \psi_{\text{temp}2} \times \text{temp}[j, k]^2 + \\ & \psi_{\text{precip}}[i] \times \text{precip}[j, k] + \\ & \psi_{\text{agtotal}}[i] \times \text{agtotal}[j, k] + \psi_{\text{pesticide}}[i] \times \text{pesticide}[j, k] \end{aligned}$$

where,  $\psi_{\text{species}}[i]$  denotes a species-level random effect centered on a grand intercept  $\psi_0$ ,  $\psi_{\text{area}}$  denotes a fixed effect of site area to account for sites truncated by water (area[j] denotes the area of site j), and  $\psi_{\text{decade}}[i, r]$  denotes a species- and location-specific effect (random slopes) of era.  $\psi_{\text{temp}}[i]$  and  $\psi_{\text{precip}}[i]$  denote species-specific linear effects of temperature and precipitation, respectively, and  $\psi_{\text{temp}2}$  denotes a quadratic effect of temperature (not species-specific). The species random effect was centered on the intercept to avoid model convergence issues.<sup>xxxviii</sup>

Assumptions included:

- Normal distribution of the grand intercept, with a mean of zero.
- Normal distribution of species-specific intercepts, with a mean equal to the grand intercept.
- Normal distribution of random slopes for environmental variables, according to their respective means and standard deviations.

Specifically,

$$\begin{aligned} \psi_0[i] & \sim N(0, \sigma_{\psi_0}) \quad \psi_{\text{sp}}[i] \\ & \sim N(\psi_0, \sigma_{\psi_{\text{sp}}}) \\ \psi_{\text{era}}[i] & \sim N(\mu_{\psi_{\text{decade}}}, \sigma_{\psi_{\text{decade}}}) \quad \psi_{\text{era}2}[i] \\ & \sim N(\mu_{\psi_{\text{decade}2}}, \sigma_{\psi_{\text{decade}2}}) \\ \psi_{\text{era}2}[i, r] & \sim N(\mu_{\psi_{\text{decade}2}}, \sigma_{\psi_{\text{decade}2}}) \end{aligned}$$



$$\begin{aligned} \psi_{\text{temp}}[i] &\sim N(\mu_{\psi_{\text{temp}}}, \sigma_{\psi_{\text{temp}}}) \quad \psi_{\text{precip}}[i] \\ &\sim N(\mu_{\psi_{\text{precip}}}, \sigma_{\psi_{\text{precip}}}) \\ , \psi_{\text{agtotal}}[i] &\sim N(\mu_{\psi_{\text{agtotal}}}, \sigma_{\psi_{\text{agtotal}}}), \\ \psi_{\text{pesticide}}[i] &\sim N(\mu_{\psi_{\text{pesticide}}}, \sigma_{\psi_{\text{pesticide}}}), \end{aligned}$$

where  $\mu_{\psi_{\text{era}}}$ ,  $\mu_{\psi_{\text{temp}}}$ ,  $\mu_{\psi_{\text{precip}}}$ ,  $\mu_{\psi_{\text{agtotal}}}$ ,  $\mu_{\psi_{\text{pesticide}}}$  denote the mean effect of each corresponding predictor, across species, and  $\sigma$  denotes the variances about these means.

### Detection submodel

Detection probability was modelled:

$$\begin{aligned} \text{logit}(p_{ijk}) &= p_0 + \\ & p_{\text{species}}[i] + \\ & p_{\text{site.decade}}[j, k] \end{aligned}$$

where  $p_0$  denotes the mean detection probability and  $p_{\text{site}}[j, k]$  denotes a site- and time-specific random effect. The latter term allows detection to vary independently across sites and between decades. It treats each site-decade combination as originating from a common distribution, so there is no information sharing between sites or between decades, only among all site-decade combinations. Specifically,

$$\begin{aligned} p_0 &\sim N(0, \sigma_{p_{\text{sp}}}) \\ p_{\text{sp}}[i] &\sim N(0, \sigma_{p_{\text{sp}}}) \\ p_{\text{site.era}}[j, k] &\sim N(\mu_{p_{\text{site.decade}}}, \sigma_{p_{\text{site.decade}}}) \end{aligned}$$

Bumble bee models were run for 20,000 iterations, with a burn-in of 20,000 iterations. Due to the comparatively large dimension (number of sites, species and sampling visits) of each of the butterfly models, fewer iterations were adopted (10,000 each) to manage computational limits. Convergence was examined using the potential scale reduction factor, where  $< 1.1$  indicated model convergence.<sup>xxxix</sup>

### Model interpretation

Model outputs were used to calculate the occupancy probability of each species at a given site within Canada (within their geographical range boundaries), per decade. Species' occupancy probabilities were averaged across all sites within their range to obtain temporal trends in occupancy probability (all species were weighted equally). Trends are displayed with 95% credible intervals.



Table 3. List of species included in analysis, by genus for bumble bees and family for butterflies.

<b>Bombus sp.</b>	<b>Nymphalidae</b>	<b>Lycaenidae</b>	<b>Hesperiidae</b>	<b>Pieridae</b>	<b>Papilionidae</b>
<i>Bombus affinis</i>	<i>Aglaia milberti</i>	<i>Agriades glandon</i>	<i>Amblyscirtes hegon</i>	<i>Abaeis nicippe</i>	<i>Battus philenor</i>
<i>Bombus appositus</i>	<i>Asterocampa celtis</i>	<i>Agriades optilete</i>	<i>Amblyscirtes oslari</i>	<i>Anthocharis sara</i>	<i>Eurytides marcellus</i>
<i>Bombus auricomus</i>	<i>Asterocampa clyton</i>	<i>Callophrys affinis</i>	<i>Amblyscirtes vialis</i>	<i>Anthocharis stella</i>	<i>Papilio brevicauda</i>
<i>Bombus bifarius</i>	<i>Boloria alaskensis</i>	<i>Callophrys augustinus</i>	<i>Anatrytone logan</i>	<i>Colias alexandra</i>	<i>Papilio canadensis</i>
<i>Bombus bimaculatus</i>	<i>Boloria alberta</i>	<i>Callophrys eryphon</i>	<i>Ancyloxypha numitor</i>	<i>Colias canadensis</i>	<i>Papilio crespontes</i>
<i>Bombus bohemicus</i>	<i>Boloria astarte</i>	<i>Callophrys gryneus</i>	<i>Atalopedes campestris</i>	<i>Colias christina</i>	<i>Papilio eurymedon</i>
<i>Bombus borealis</i>	<i>Boloria bellona</i>	<i>Callophrys henrici</i>	<i>Atrytonopsis hianna</i>	<i>Colias eurytheme</i>	<i>Papilio glaucus</i>
<i>Bombus centralis</i>	<i>Boloria chariclea</i>	<i>Callophrys irus</i>	<i>Carterocephalus palaemon</i>	<i>Colias gigantea</i>	<i>Papilio indra</i>
<i>Bombus citrinus</i>	<i>Boloria epithore</i>	<i>Callophrys johnsoni</i>	<i>Epargyreus clarus</i>	<i>Colias hecla</i>	<i>Papilio machaon</i>
<i>Bombus cryptarum</i>	<i>Boloria eunomia</i>	<i>Callophrys lanoraieensis</i>	<i>Erynnis afranius</i>	<i>Colias interior</i>	<i>Papilio multicaudata</i>
<i>Bombus fervidus</i>	<i>Boloria freija</i>	<i>Callophrys mossii</i>	<i>Erynnis baptisiae</i>	<i>Colias meadii</i>	<i>Papilio polyxenes</i>
<i>Bombus flavidus</i>	<i>Boloria frigga</i>	<i>Callophrys nelsoni</i>	<i>Erynnis brizo</i>	<i>Colias nastes</i>	<i>Papilio rutulus</i>
<i>Bombus flavifrons</i>	<i>Boloria improba</i>	<i>Callophrys niphon</i>	<i>Erynnis funeralis</i>	<i>Colias occidentalis</i>	<i>Papilio troilus</i>
<i>Bombus frigidus</i>	<i>Boloria natazhati</i>	<i>Callophrys polios</i>	<i>Erynnis horatius</i>	<i>Colias palaeno</i>	<i>Papilio zelicaon</i>
<i>Bombus griseocollis</i>	<i>Boloria polaris</i>	<i>Callophrys sheridanii</i>	<i>Erynnis icelus</i>	<i>Colias pelidne</i>	<i>Parnassius clodius</i>
<i>Bombus huntii</i>	<i>Boloria selene</i>	<i>Callophrys spinetorum</i>	<i>Erynnis juvenalis</i>	<i>Colias philodice</i>	<i>Parnassius eversmanni</i>
<i>Bombus impatiens</i>	<i>Cercyonis oetus</i>	<i>Celastrina echo</i>	<i>Erynnis lucilius</i>	<i>Colias tyche</i>	<i>Parnassius phoebus</i>
<i>Bombus insularis</i>	<i>Cercyonis pegala</i>	<i>Celastrina ladon</i>	<i>Erynnis martialis</i>	<i>Euchloe ausonides</i>	<i>Parnassius smintheus</i>
<i>Bombus jonellus</i>	<i>Cercyonis sthenele</i>	<i>Celastrina lucia</i>	<i>Erynnis pacuvius</i>	<i>Euchloe creusa</i>	
<i>Bombus kirbiellus</i>	<i>Chlosyne acastus</i>	<i>Celastrina neglecta</i>	<i>Erynnis persius</i>	<i>Euchloe lotta</i>	
<i>Bombus mckayi</i>	<i>Chlosyne damoetas</i>	<i>Celastrina serotina</i>	<i>Erynnis propertius</i>	<i>Euchloe naina</i>	
<i>Bombus melanopygus</i>	<i>Chlosyne gorgone</i>	<i>Cupido amyntula</i>	<i>Euphyes bimacula</i>	<i>Euchloe olympia</i>	
<i>Bombus mixtus</i>	<i>Chlosyne harrisii</i>	<i>Cupido comyntas</i>	<i>Euphyes conspicua</i>	<i>Nathalis iole</i>	
<i>Bombus neoboreus</i>	<i>Chlosyne hoffmanni</i>	<i>Erora laeta</i>	<i>Euphyes dion</i>	<i>Neophasia menapia</i>	
<i>Bombus nevadensis</i>	<i>Chlosyne nycteis</i>	<i>Euphilotes ancilla</i>	<i>Euphyes dukesi</i>	<i>Phoebis sennae</i>	
<i>Bombus occidentalis</i>	<i>Chlosyne palla</i>	<i>Euphilotes battoides</i>	<i>Euphyes vestris</i>	<i>Pieris angelika</i>	
<i>Bombus pensylvanicus</i>	<i>Coenonympha nipisiquit</i>	<i>Feniseca tarquinius</i>	<i>Hesperia assiniboia</i>	<i>Pieris marginalis</i>	
<i>Bombus perplexus</i>	<i>Coenonympha tullia</i>	<i>Glaucopsyche lygdamus</i>	<i>Hesperia colorado</i>	<i>Pieris oleracea</i>	
<i>Bombus polaris</i>	<i>Danaus plexippus</i>	<i>Glaucopsyche piasus</i>	<i>Hesperia dacotae</i>	<i>Pieris rapae</i>	
<i>Bombus rufocinctus</i>	<i>Erebia disa</i>	<i>Icaricia icarioides</i>	<i>Hesperia juba</i>	<i>Pieris virginiensis</i>	
<i>Bombus sandersoni</i>	<i>Erebia discoidalis</i>	<i>Icaricia lupini</i>	<i>Hesperia leonardus</i>	<i>Pontia beckerii</i>	
<i>Bombus sitkensis</i>	<i>Erebia epipsodea</i>	<i>Icaricia saepiolus</i>	<i>Hesperia manitoba</i>	<i>Pontia occidentalis</i>	
<i>Bombus suckleyi</i>	<i>Erebia fasciata</i>	<i>Icaricia shasta</i>	<i>Hesperia nevada</i>	<i>Pontia protodice</i>	
<i>Bombus sylvicola</i>	<i>Erebia lafontainei</i>	<i>Leptotes marina</i>	<i>Hesperia sassacus</i>	<i>Pontia sisymbrii</i>	
<i>Bombus ternarius</i>	<i>Erebia mackinleyensis</i>	<i>Lycaena cupreus</i>	<i>Hesperia uncas</i>	<i>Pyrisitia lisa</i>	
<i>Bombus terricola</i>	<i>Erebia magdalena</i>	<i>Lycaena dione</i>	<i>Hylephila phyleus</i>	<i>Zerene cesonia</i>	
<i>Bombus vagans</i>	<i>Erebia mancinus</i>	<i>Lycaena dorcas</i>	<i>Lerema accius</i>		
<i>Bombus vosnesenskii</i>	<i>Erebia occulta</i>	<i>Lycaena dospassosi</i>	<i>Oarisma garita</i>		
	<i>Erebia pawlowskii</i>	<i>Lycaena editha</i>	<i>Oarisma poweshiek</i>		
	<i>Erebia rossii</i>	<i>Lycaena epixanthe</i>	<i>Ochlodes sylvanoides</i>		
	<i>Erebia vidleri</i>	<i>Lycaena helloides</i>	<i>Panoquina ocola</i>		



<i>Bombus</i> sp.	Nymphalidae	Lycaenidae	Hesperiidae	Pieridae	Papilionidae
	<i>Erebia youngi</i>	<i>Lycaena heteronea</i>	<i>Pholisora catullus</i>		
	<i>Euphydryas anicia</i>	<i>Lycaena hyllus</i>	<i>Poanes hobomok</i>		
	<i>Euphydryas chalcedona</i>	<i>Lycaena mariposa</i>	<i>Poanes massasoit</i>		
	<i>Euphydryas editha</i>	<i>Lycaena nivalis</i>	<i>Poanes viator</i>		
	<i>Euphydryas gillettii</i>	<i>Lycaena phlaeas</i>	<i>Polites draco</i>		
	<i>Euphydryas phaeton</i>	<i>Lycaena rubidus</i>	<i>Polites mystic</i>		
	<i>Euptoieta claudia</i>	<i>Parrhasius malbum</i>	<i>Polites origenes</i>		
	<i>Junonia coenia</i>	<i>Plebejus idas</i>	<i>Polites peckius</i>		
	<i>Lethe anthedon</i>	<i>Plebejus melissa samuelis</i>	<i>Polites rhesus</i>		
	<i>Lethe appalachia</i>	<i>Polyommatus icarus</i>	<i>Polites sabuleti</i>		
	<i>Lethe eurydice</i>	<i>Satyrium acadica</i>	<i>Polites sonora</i>		
	<i>Libytheana carinenta</i>	<i>Satyrium behrii</i>	<i>Polites themistocles</i>		
	<i>Limenitis archippus</i>	<i>Satyrium calanus</i>	<i>Pompeius verna</i>		
	<i>Limenitis arthemis</i>	<i>Satyrium californica</i>	<i>Pyrgus centaureae</i>		
	<i>Limenitis lorquini</i>	<i>Satyrium caryaevorus</i>	<i>Pyrgus communis</i>		
	<i>Limenitis weidemeyerii</i>	<i>Satyrium edwardsii</i>	<i>Pyrgus ruralis</i>		
	<i>Megisto cymela</i>	<i>Satyrium favonius</i>	<i>Staphylus hayhurstii</i>		
	<i>Neominois ridingsii</i>	<i>Satyrium liparops</i>	<i>Thorybes bathyllus</i>		
	<i>Nymphalis antiopa</i>	<i>Satyrium saepium</i>	<i>Thorybes pylades</i>		
	<i>Nymphalis californica</i>	<i>Satyrium semiluna</i>	<i>Thymelicus lineola</i>		
	<i>Nymphalis l-album</i>	<i>Satyrium sylvinus</i>	<i>Wallengrenia egeremet</i>		
	<i>Oeneis chryxus</i>	<i>Satyrium titus</i>			
	<i>Oeneis alberta</i>	<i>Strymon melinus</i>			
	<i>Oeneis alpina</i>				
	<i>Oeneis bore</i>				
	<i>Oeneis calais</i>				
	<i>Oeneis chryxus</i>				
	<i>Oeneis jutta</i>				
	<i>Oeneis macounii</i>				
	<i>Oeneis melissa</i>				
	<i>Oeneis nevadensis</i>				
	<i>Oeneis philipi</i>				
	<i>Oeneis polixenes</i>				
	<i>Oeneis uhleri</i>				
	<i>Phyciodes batesii</i>				
	<i>Phyciodes cocyta</i>				
	<i>Phyciodes mylitta</i>				
	<i>Phyciodes pallida</i>				
	<i>Phyciodes pulchella</i>				
	<i>Phyciodes tharos</i>				
	<i>Polygonia comma</i>				
	<i>Polygonia faunus</i>				
	<i>Polygonia gracilis</i>				
	<i>Polygonia interrogationis</i>				
	<i>Polygonia oreas</i>				
	<i>Polygonia progne</i>				
	<i>Polygonia satyrus</i>				
	<i>Speyeria aphrodite</i>				
	<i>Speyeria atlantis</i>				
	<i>Speyeria callippe</i>				
	<i>Speyeria cybele</i>				
	<i>Speyeria edwardsii</i>				
	<i>Speyeria hesperis</i>				
	<i>Speyeria hydaspes</i>				



<i>Bombus</i> sp.	Nymphalidae	Lycaenidae	Hesperiidae	Pieridae	Papilionidae
	<i>Speyeria idalia</i>				
	<i>Speyeria mormonia</i>				
	<i>Speyeria zerene</i>				
	<i>Vanessa annabella</i>				
	<i>Vanessa atalanta</i>				
	<i>Vanessa cardui</i>				
	<i>Vanessa virginiensis</i>				

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