Ecological Indicators 130 (2021) 108022

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Population declines among Canadian vertebrates: But data of different quality show diverging trends

Valentina Marconi [a,e,*], Louise McRae [a,*], Helen Müller [a,1], Jessica Currie [b], Sarah Whitmee [c], Fawziah (ZuZu) Gadallah [d], Robin Freeman [a]

[a] Institute of Zoology, Zoological Society of London Regent's Park, London NW1 4RY, UK
[b] WWF-Canada, 410 Adelaide Street, West Toronto, Ontario M5V 1S8, Canada
[c] Centre for Biodiversity and Environment Research at University College London, Department of Genetics, Evolution and Environment, Division of Biosciences, University College London, Gower Street, London WC1E 6BT, UK
[d] Environment and Climate Change Canada / Environnement et Changement climatique Canada, 200, boul. Sacré-Coeur, Gatineau, Quebec K1A 0H3, Canada
[e] Faculty of Natural Sciences, Department of Life Sciences (Silwood Park), Imperial College London, Buckhurst Road, Ascot, Berks SL5 7PY, UK

ARTICLE INFO

Keywords:
Biodiversity loss
Living Planet Index
National biodiversity indicators
Abundance trends
Biodiversity data bias

ABSTRACT

We produced a biodiversity indicator, the Canadian Species Index (CSI), by gathering abundance data for Canadian vertebrate populations and adapting the Living Planet Index methodology. The final indicator incorporates over 3000 abundance time series and contains data for more than 50% of Canadian native vertebrate species. Species abundance declined by an average 10% between 1970 and 2014, with trends varying across taxonomic groups. To facilitate the interpretation of the indicator and contribute to the transparency of the reporting process, here we present a discussion of the indicator's coverage, data quality and data gaps. Using data collected for other purposes means the dataset inherits the biases in biodiversity monitoring. We therefore assessed taxonomic and geographic coverage of the data underlying the indicator to highlight which areas and groups are under-represented. Birds are comprehensively monitored across Canada and are considered good indicators of the state of the environment. Other taxonomic groups are less well monitored, and the data available for these groups often consist of shorter and less full time series, representing smaller segments of the national population. A disaggregation based on data quality appears to show that trends based on species with lower quality data are more negative than for species with higher quality data. We discuss possible sources of the difference, including the relationship between taxon and data quality. Additional data collection on species contributing to the lower-quality subsets is needed to confirm negative trends.

1. Introduction

Indicators help to monitor biodiversity cost effectively and track progress towards national and international goals and commitments (Balmford et al., 2005; Jones et al., 2011; McCune et al., 2013) such as the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011–2020 and its 20 Aichi targets (CBD, 2010), and the Sustainable Development Goals (SDGs) (Sachs, 2012).

The Living Planet Index (LPI) is an established indicator of trends in global biodiversity (Butchart et al., 2010; Collen and Nicholson, 2014; Loh et al., 2005; McRae et al., 2017; Tittensor et al., 2014) calculated as the geometric mean of annual changes in vertebrate species abundance. The LPI is used to track progress towards Aichi Target 12 and it is relevant to several other targets (Proença et al., 2017). It is one of the highlighted indicators for the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) reporting and has been used to calculate regional trends (Deinet et al., 2015; Eamer et al., 2012). Guidelines have been produced in the past for the use of the LPI at the national level (McRae et al., 2008), and its methodology was recently adapted to report trends in The Netherlands (van Strien et al., 2016) and for the development of the Australian Threatened Species Index (www.tsx.org.au) (Threatened Species Recovery Hub, 2019).

We adapted the LPI methodology to produce a national biodiversity indicator, the Canadian Species Index (CSI). Here, we present the

* Corresponding authors at: Institute of Zoology, Regent's Park, London NW1 4RY, UK.
E-mail addresses: valentina.marconi@ioz.ac.uk (V. Marconi), louise.mcrae@ioz.ac.uk (L. McRae).
[1] Currently a PhD student on the London NERC Doctoral Training Partnership.

https://doi.org/10.1016/j.ecolind.2021.108022
Received 24 December 2020; Received in revised form 28 June 2021; Accepted 21 July 2021
Available online 28 July 2021
1470-160X/

indicator and analyse its taxonomic and geographic coverage. As the index relies on previously existing data, the dataset consists of time series of varying lengths, fullness, and geographic scale. Data quality varies by taxonomic group, with birds contributing most of the higher quality data (longer time series with more data points and broader geographic coverage). For this reason, we investigate the effects of data representativity and assess the value of including lower quality data.

To our knowledge, the Canadian Species Index is one of the first biodiversity indicators developed in response to a national policy need. The CSI was developed for, and is reported by, the Canadian Environmental Sustainability Indicators (CESI) programme (https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/canadian-species-index.html). CESI provides data and information to track Canada's performance on key environmental sustainability issues such as climate-change, air-quality, water quality and availability, and nature protection. These indicators are used to measure progress of the Federal Sustainable Development Strategy and respond to commitments to report on the state of the environment. Addressing conservation or management issues in Canada is beyond the scope of this manuscript. However, to support the indicator's interpretation and in the name of transparency, we discuss coverage, data quality and data gaps. This work also represents an example of the application of a global indicator at the national level. This could be useful as major international processes (CDB, IPBES, SDGs) are interested in assessing global progress towards environmental goals, creating a desire to aggregate national information to the global level (Bhatt et al., 2020; Gill, 2020).

2. Methods

2.1. Data collection and preprocessing

We gathered time series data for vertebrate species monitored within Canada from a range of sources, including published scientific literature, online databases, government reports, researchers and institutions, and grey literature. To be included a) data must have been collected using comparable methods for at least two years for the same population b) units must be of population size either a direct measure such as population counts, densities, or indices, or a reliable proxy such as e.g. breeding pairs, nests, tracks, capture per unit effort or measures of biomass for a single species (fish data are often available in one of the latter two formats) and c) the source must be referenced and traceable.

All species classified as "Presumed Extirpated", "Probably extirpated" or "Not Applicable" by the Wild Species Report (Canadian Endangered Species Conservation Council, 2016) have been excluded from the dataset. The latter category includes exotic species, hybrids, or species occurring infrequently and unpredictably in Canada, which are not suitable targets for conservation efforts. Non-native species are excluded from the analysis as the goal of the indicator is to provide an overall assessment of the status and trends of Canadian species. Three overabundant goose species (*Anser caerulescens*, *Anser rossii* and *Branta canadensis*) have been deemed to be above acceptable population bounds (Environment and Climate Change Canada, 2019). These species have benefitted from improved foraging opportunities resulting from changes in agricultural practices in staging and wintering areas along their migration routes in the whole of North America (Fox et al., 2005; Gauthier et al., 2005; Jefferies et al., 2004). The demographic explosion of these species within Canada (Canadian Wildlife Service Waterfowl Committee 2013; Canadian Wildlife Service Waterfowl Committee, 2014) has led the Canadian government to regard further increases in these species as a negative conservation outcome. For this reason, they have been excluded from the national indicator because they provide a signal counter to the purpose of the indicator: increases in the indicator are interpreted as positive, whereas increases in numbers for these species are negative. Trends calculated including these three species are provided for comparison (Fig. A3).

Ecological and geographical information for each time series was drawn from the data source or based on the species and geographic location of the specific time series. These tags (Province/Territory or Ocean, system on which the species relies etc.) were used to identify subsets for analysis. Each time series entered into the dataset was assigned to one system (Terrestrial, Freshwater or Marine). Not all species can be clearly assigned to a single system, particularly anadromous fishes and generalist birds. If the data source provided information about the habitat in which the population had been monitored, the appropriate habitat was selected from the list of habitats on the IUCN Red List (IUCN, 2018) and a system was assigned accordingly. If the source didn't provide information about the habitat, then species-level information was considered. Realms, oceans and biomes were assigned based on the selected system. Populations monitored over areas that encompass more than one biome were assigned to the biome that covers the largest proportion of the area, or the one that is most relevant to the species in question. Marine biomes have not yet been mapped. Biomes were the chosen geographical unit because they are also important for the functioning of the Earth System (Abell et al., 2008; Dinerstein et al., 2017; Mace et al., 2014; Olson et al., 2001; Steffen et al., 2015).

The initial dataset comprised Canadian vertebrate species already available in the LPI database. We then performed a taxonomic and geographic gap analysis to identify underrepresented groups and areas, and these were targeted for data searches. The gap analysis was repeated at regular intervals to inform additional data collection efforts. Time series that could contain information for the same individuals are kept in the dataset to support disaggregation, but time series used to calculate indices are selected so that they do not count the same individuals repeatedly. The decision on which one out of two (or more) time series should be marked as a replicate depends on the length of the time series (years between first and last data point), their fullness (number of data points between the first and last year) and the and the scale/area covered by the data. Most data are publicly available on www.livingplanetindex.org (WWF, 2016) and we provide a Comma Separated Value version of the dataset here. When contributing data to the project, authors had the option to mark their data as confidential, often due to concerns associated with sharing species locations. Therefore, the dataset provided excludes 201 confidential time series so results produced with this dataset may differ slightly from those presented.

2.2. Assessing taxonomic and biome representation

To describe the taxonomic and geographic representation of the dataset and identify under-represented groups and areas, we compared the number of species in the dataset with the number of known species for each taxonomic group and biome (for terrestrial and freshwater species) and ocean (for marine species) in Canada. For this analysis, freshwater species except fish were assigned to terrestrial biomes since the expected number of species in freshwater biomes was available only for fish. Expected species numbers for terrestrial and freshwater birds, mammals, amphibians and reptiles occurring in each biome were obtained from WWF Wildfinder database (World Wildlife Fund, 2006). Expected numbers of species for freshwater fish were extracted from the Freshwater Ecoregions of the World dataset (Abell et al., 2008). For marine species, representation was analysed by ocean (Arctic, Atlantic, Pacific) and expected species numbers were obtained from the Canadian Wild Species Report. Taxonomy was cross-checked with the Wild Species report (Canadian Endangered Species Conservation Council, 2016) at the national level for both freshwater and terrestrial species. For marine species, this wasn't necessary as numbers of species were sourced from the Wild Species Report. Freshwater fish species that did not have a match in the Freshwater Ecoregions of the World dataset (N = 13) were assigned to freshwater biomes based on their distribution range taken from the Red List (IUCN, 2018) or – if this was not available – Fishbase (Froese and Pauly, 2017). As for the oceans, we considered both species only occurring in oceans, and species occurring in both an ocean and a province or territory as marine.

2.3. Trend calculation

We adapted the existing LPI methodology (Collen et al., 2009; McRae et al., 2017) for national reporting on trends for vertebrates. Population trends between 1970 and 2014 were modelled using the mgcv 1.8-0 package in R version 3.5.1 (R Core Team, 2015). The R package *rlpi* (Freeman et al., 2017) was used to calculate the species trends and index. The rlpi package includes changes made to the published LPI methodology (Collen et al., 2009) as selectable options.

For each population level time series missing values were interpolated using one of two methods depending on the number of data points in the time series. Time series with 6 or more data points were modelled through a Generalised Additive Modelling (GAM) framework. For time series with fewer than 6 data points and for time series with a poor GAM fit we used linear regression. This is in contrast to the published LPI methodology (Collen et al., 2009), which uses the chain method (log-linear interpolation) for series not modelled with GAM. Our approach means all time series are modelled, thus reducing the amount of noise in the index. Zeros were treated as missing values as after inspecting the data, we found that the large majority of zeros came from large scale multi-species monitoring programmes, mostly of birds. Multi-species monitoring programmes cannot be timed to the migration patterns of all species. We acknowledge that these zero values indicate that the species was not observed in a specific year. However, as the species was present in the following years, we deemed the zero values to be more likely to be missing observations rather than population crashes. We therefore treat the zeros as missing values and interpolate over them to obtain the long-term population trend. For each time series, population-level lambdas (annual rate of change) were calculated. Fifteen population-level times series resulted in lambda values (logged – logarithm base 10 – inter annual change values) above 1 or below −1, which were capped to a maximum/minimum value of 1/−1. We thus recognised that the population had undergone a very large change, but capped its extent to 10-fold, an arbitrary threshold for changes deemed biologically realistic. No other outliers were left in the data after this procedure.

For each time series population-level lambdas (annual rate of change; d_t) were calculated:

$$d_t = \log_{10}\left(\frac{N_t}{N_{t-1}}\right) \tag{1}$$

where N is the population measure and t is the year. Trends are never extrapolated beyond the start and the end point of a time series. Where two or more population time series were available for the same species, the modelled annual trends d_t for each population were averaged to provide a single set of annual trends for each species:

$$\overline{d}_t = \frac{1}{n_t}\sum_{i=1}^{n_t} d_{it} \tag{2}$$

where n_t is the number of populations and d_{it} is the annual rate of change of population i in year t. We don't often have accurate information on the proportion of the species' population that a specific time series represents, so we are currently unable to incorporate these type of weighting into the models.

Species trends are averaged (with all species weighted equally) and finally average rates of change are converted to index values (Collen et al., 2009) by:

$$I_t = I_{t-1}10^{\overline{d}_t} \tag{3}$$

with $I_0 = 1$. All indices above species-level are calculated averaging species-level trends using the same method (Eqs. (1)–(3)) with all species weighted equally. An index was calculated for each system and taxonomic group, with all fish classes combined in one.

Bounds around the multi-species indices were generated by creating 10 000 indices obtained by bootstrapping species trends with replacement from the dataset, and using the bounds of the central 9500 index values calculated in each year. These bounds are descriptive and represent variability in species trends that could be drawn from the dataset rather than a confidence interval, which would represent the statistical uncertainty in the estimate of the true value. They are multiplicative and increase in width over time as the variability of the previous year is inherited by the rest of the trend and the possible range of trajectories increases over time.

To illustrate variability in the underlying species trends in a specific year, we also present the average annual change (mean annual lambda) with error bars (±SD) (Figs. 2, A3 and A4). In years where the mean annual lambda is above the baseline the index increases; where it is below the baseline, the index declines.

Trends for Canadian birds calculated from the available data were compared with the State of Canada's Birds report (SCBR) trends (North American Bird Conservation Initiative Canada, 2019). For the SCBR, standardized species estimates for each year are combined into a composite indicator using a Bayesian hierarchical model that accounts for differences in precision, so that imprecise estimates are given less weight (Sauer and Link, 2011; Smith, 2018; Smith et al., 2014b). We calculated two trends based on the same data as the SCBR trend. In match 1 (279 species) we matched both the species and underlying time series data used by the SCBR. In match 2 (301 species), we matched the SCBR species, but used additional data sources if the one used by the SCBR was not available to us.

2.4. Assessing data quality and its effect on trends

The dataset contains data gathered from different sources and scales, and not explicitly collected for the purpose of these analyses. It therefore consists of time series of varying lengths (interval between the first and the last observation), fullness (number of observations over the total number of years), and geographic scale. Our assumption is that longer-term monitoring and monitoring at broader spatial scales is better at capturing a species' overall trend. To investigate the effect of data representativity on the trends, we assigned a score to each time series in the dataset for: a) data volume (a measure of temporal coverage) from 1970 onwards, based on time series length and fullness (3 = more than 10 years, over 50% fullness; 2 = more than 10 years, 50% fullness or less; 1 = between 5 and 10 years; 0 = less than 5 years); and b) scale/area covered by the data (a measure of the geographic coverage of the data – 3 = national/ocean, 2 = territorial or provincial/fishery division, 1 = smaller unit). We then calculated data quality as the sum of the two scores, ranging from 1 (lowest representation) to 6 (highest representation). We then used a resampling approach: we bootstrap resampled populations in each subset of the data with replacement 10 000 times to generate a new dataset. This gave us 10 000 versions of the dataset created by random sampling from each subset of the whole dataset. We then recalculated an overall index for each of these subgroups and computed the annual mean across indices to obtain a distribution of means for each year within the subset. Comparing the annual mean values and the 2.5 and 97.5% quantiles of the bootstraps across groups allows us to determine if there are differences between them, and gives us an indication of how the trends generated using the different subsets of data differ from the overall trend. The taxonomic composition of categories varies, and differences in trend between data of different quality may reflect differences among taxonomic groups, a correlation between species trends and data availability, or it may be an artefact of poor quality data. For this reason, we also ran the same analysis exclusively for fish time series, as fish are the only group with a comparable number of populations in most (5 out of 6) data quality subsets (Table A2).

3. Results

3.1. Dataset description

The final dataset consists of 6257 time series (131 407 data points) of which 3680 were used in the overall index. Geographically, data availability is lower in the north of the country (Fig. 1). More data are available from 1970 to 2014 so the index stops at this point in time. The number of species and populations with data drops from 581 in 2014 to 231 in 2015. Within this time period, the number of species with data ranges from 430 to 676 per year (average = 543). Time series per year range from a minimum of 2106 in 1970 to a maximum of 3367 in 1993 (average = 2875). Time series length varies from 2 to 45 years.

3.2. Species representation

Of the 1779 extant native vertebrate species considered of conservation interest in Canada (Canadian Endangered Species Conservation Council, 2016), over 50% are represented by at least one time series in the dataset. The percentage of species represented in the dataset varies across taxa: it's 85% for birds, 70% for amphibians, 54% for mammals, 35% for fishes and 33% for reptiles. A description of the time series used in the trends presented in this study is shown in Table 1, but a description of the complete dataset (including redundant time series) is also provided in Table A1. The data underlying the trends were gathered from 370 different sources including peer-reviewed papers (10%), government reports and online datasets (36%), and other online databases (49%) (Table 1). Data for birds were mainly (94%) sourced from long-term monitoring programmes such as the Breeding Bird Survey (Smith et al., 2014a) and fish (especially marine species) are largely (91%) monitored within a natural resource management framework. Amphibian time series tend to be recent: 87 of 106 (82%) of amphibian time series come from studies carried out after the year 2000 – and shorter (6.93 ± 4.19 years on average). Amphibians are mostly monitored to understand population dynamics or for conservation purposes (the two categories make up over 50% of amphibian data). The main reasons for mammal data collection are baseline monitoring (50%), population dynamics (27%) and tracking declining species (8%). Data for this group tend to focus on species in need of conservation management or of particular importance for their interactions with humans. On average, time series for this taxon are shorter than those for birds and fish (Table 1). Reptiles are only represented by 33 time series in the dataset, almost half of which (48%) were collected to look at population dynamics.

When looking at representation in biome/taxonomic group combinations, terrestrial and freshwater birds appear to be the best represented group (92% of species on average) (Fig. A1a). Amphibians are the next best represented group in terms of number of species with at least some data captured in the dataset across biomes (80%), followed by mammals and reptiles. Freshwater fish (Fig. A1b) are best represented in Polar freshwaters (53%), whilst the lowest representation is in Temperate upland rivers (41%). In the oceans (Fig. A1c), mammals have the best representation (65% on average).

3.3. Abundance trends

On average, Canadian vertebrate species in our dataset have declined by 10% (0.24% per year) between 1970 and 2014 (Fig. 2). Differences are observed among systems and taxa (Figs. 3 and 4). A decline of 11% (0.26% per year) is observed in the terrestrial realm (Fig. 3a). The freshwater index (Fig. 3b) shows some fluctuations but ends near baseline values (2%, equivalent to an increase of 0.04% per year). The

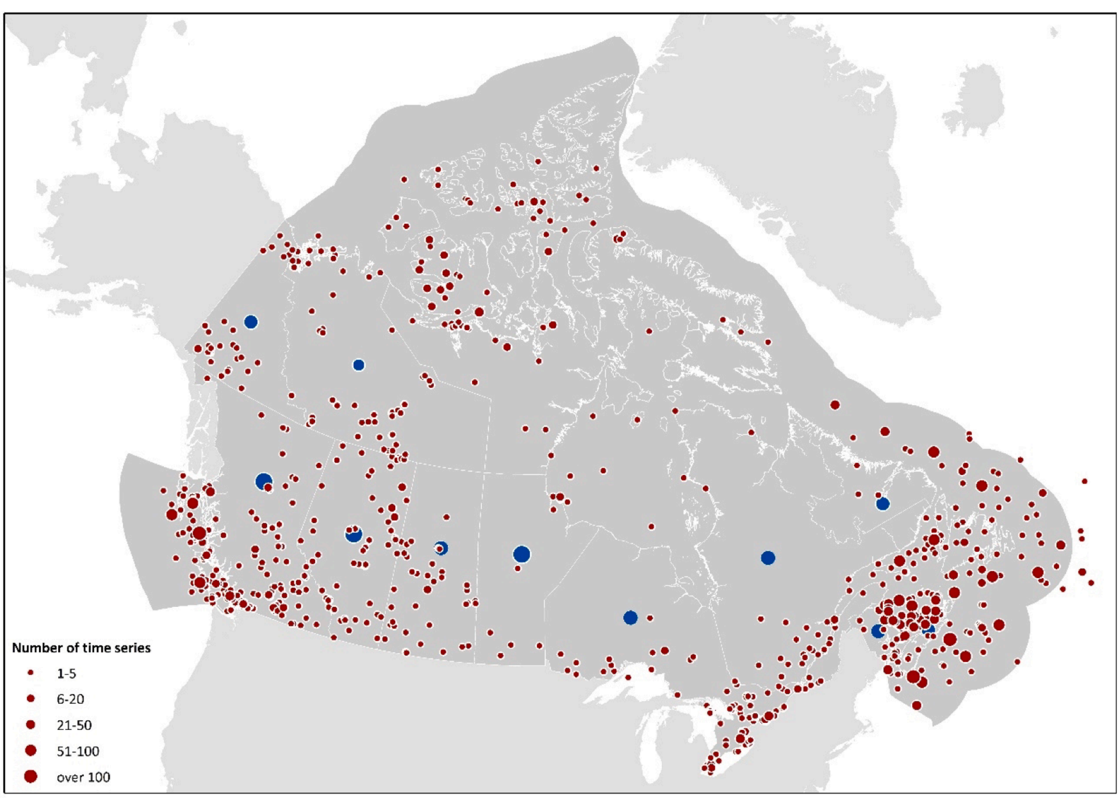

Fig. 1. Distribution of locations where time series data were collected across Canada. The dataset also includes 340 time series for species monitored at the national level (not included in the graphic), and 1758 time series monitored at the provincial/territorial level (represented by the blue dot at the midpoint of the province/territory). The size of the dots indicates the number of time series at each location. Projection: Canada Albers Equal Area Conic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Data availability, data quality and type of source for the time series used to calculate the Canadian Species Index (excluding all replicates) by taxonomic group.

		Amphibians	Birds	Fish	Mammals	Reptiles
Data availability	Number of species in dataset	32	382	362	105	14
	Number of species in Canada	46	453	1044	194	42
	% representation	70	84	35	54	33
	Number of time series	106	463	2529	549	33
Data quality	Median and range of total score	2 (1–4)	6 (1–6)	4 (1–6)	2 (1–5)	2 (1–4)
	Time series length (average ± SD)	6.9 ± 4.2	35.7 ± 14.7	14.4 ± 10.8	12.9 ± 11.2	10.7 ± 10.1
	Average time series fullness (%)	93	84.5	70.6	73.8	79.3
	Average scale score	1.01	2.02	1.44	1.05	1.06
Source type (%)	Journal	25.5	9.5	1.82	39.2	60.6
	Government report or online database	47.2	89	95.3	48.3	36.4
	Personal comm. and conf. data	22.6	0.2	1.7	9.6	3.0
	Unpublished report	4.7	1.3	1.11	2.9	0

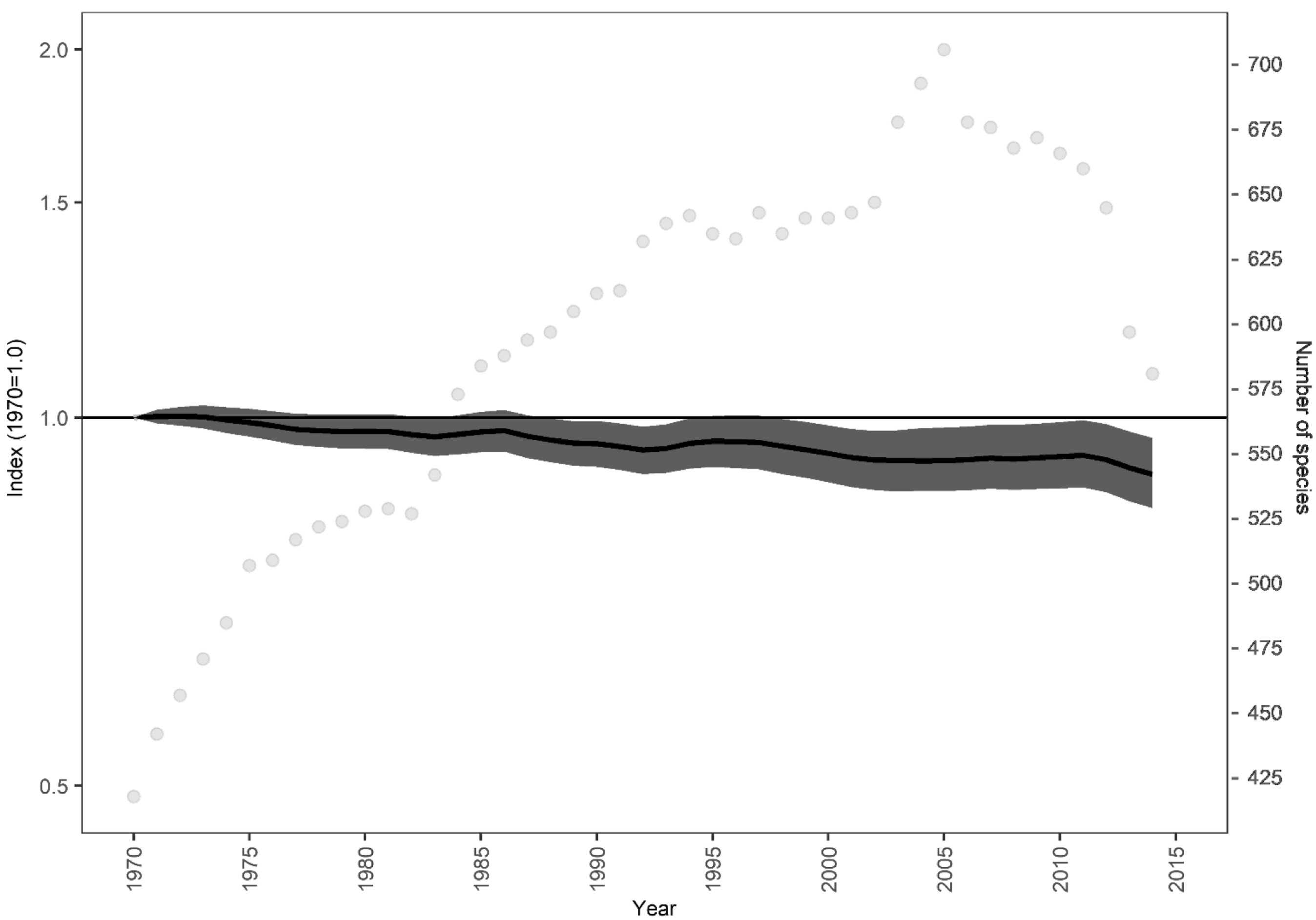

Fig. 2. Index of abundance for 3680 populations of 895 Canadian vertebrate species (black line with shaded grey area, final index value = −10%; range = −4% to −16%) monitored between 1970 and 2014 and number of species contributing to the index in each year (pale grey dots, secondary Y-axis). The shaded grey areas represent the bounds of the central 9500 index values calculated in each year by bootstrapping species trends with replacement from the dataset. The plot showing the average annual lambda (dots) ± SD (error bars) for the same time interval is show in Fig. A2. The index is plotted with a logarithmic primary Y-axis.

marine index (Fig. 3c) shows an initial increase but then declines (final value: −10%, 0.24% decline per year). The overall trend for birds shows an average 4% increase (0.1% per year) in abundance (Fig. 4a), whilst the trend for mammals shows a marked decline (−44%, with oscillations around the −30% mark observed throughout and a percentage decline of 1.33% per year) (Fig. 4b). After a brief increase, the fish index (Fig. 4c) declines to −21% in 2014 (equivalent to a decline of 0.54% per year). The herpetofauna index (Fig. 4d) shows a decline of 34% (0.93% per year) and large variability in the underlying species trends.

When we calculated trends to match the SCBR dataset using CSI available data up to 2010 (Fig. A9), we found a 6% decline in abundance when matching species (match 2), and a 7% decline when matching species and sources (match 1). The SCBR shows a 11.5% decline between 1970 and 2010.

3.4. Trends in subsets of different quality

The trends calculated from the datasets derived by sampling with replacement from subsets of different data-quality differ from one another (Fig. 5). A taxonomic breakdown of subgroups of different data quality is presented in Table A2. The trend for the datasets derived from subgroup 1 (lowest quality, score = 1) (Fig. A8) has an overall negative

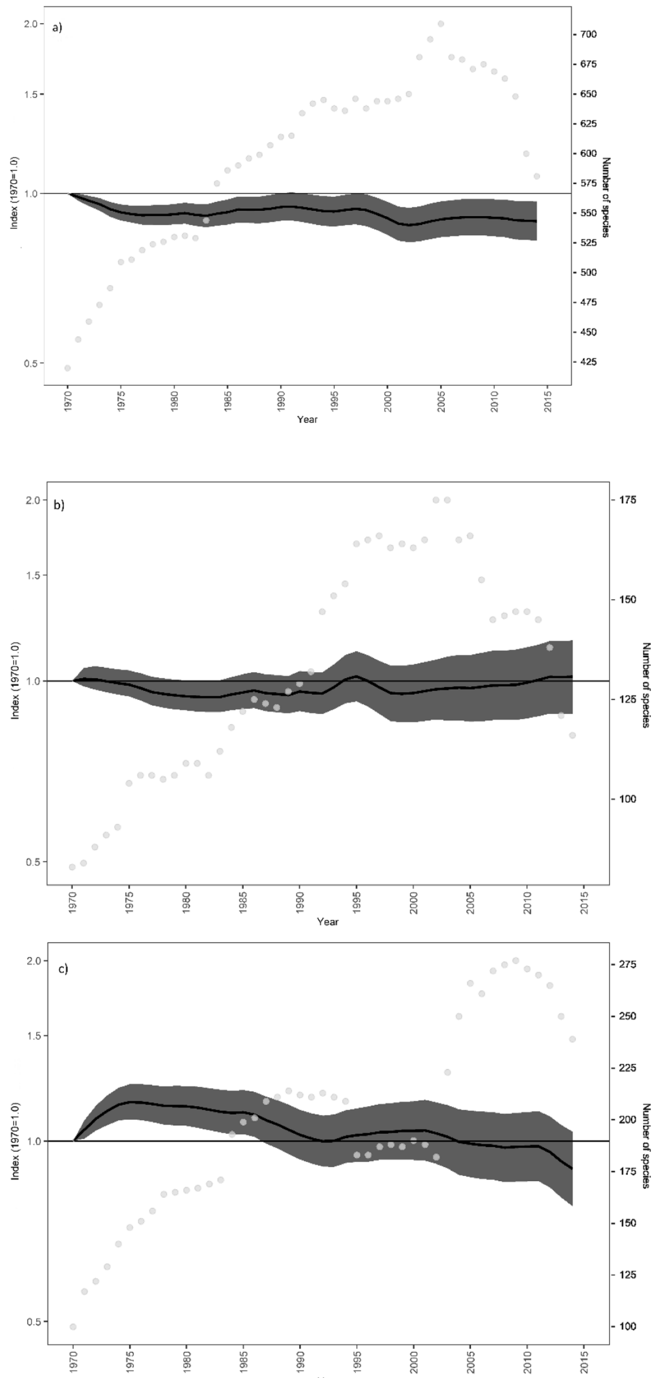

Fig. 3. Indices (black line with shaded grey area) of abundance with number of species contributing to the index in each year (pale grey dots, secondary Y-axis) for species monitored in a) the terrestrial environment (772 populations of 330 species, final index value = −11%; range = −18% to −3%), b) the freshwater environment (595 populations of 221 species, final index value = 2%; range = −12% to 17%) and c) in the marine environment (2313 populations of 364 species, final index value = −10%; range = −22% to 4%) within Canadian borders. Average annual lambda plot ± SD are shown in the Supplementary Materials (Fig. A4a–c). Indices are plotted with a logarithmic primary Y-axis.

trajectory from 1986 onwards but shows a very noisy trend and has large bounds that encompass the baseline in most of the years considered. Trends in subgroups 2, 3, and 4 (Fig. 5) show an overall negative trajectory, with the exception of the last section of the trend (from 2002) in group 4. The average values for subgroups 2, 3, and 4 are consistently below the overall CSI (blue boxplots in Fig. 5). On the other hand, the average values for groups of data quality 5 and 6 are consistently above the overall average. The temporal (data volume) and spatial (scale) components of the quality score are positively but not strongly correlated (Spearman correlation: 0.63). When considering results of analysis on the separate components of the quality score (Fig. A7), the temporal aspect appears to be more important in determining the pattern we observe. Trends in the subgroups with a lower temporal score appear to be more negative (except for the lowest subgroup, which shows a downward trend but is incomplete and has high levels of variation), and subsets get progressively more positive as the score increases. The temporal score varies between 0 and 3 (from lower to higher data volume) and the subsets of the data based on this component of the score are more even in size (Fig. A7 above). The spatial component of the score only varies between 0 and 2 (from small to large scale) and the subsets of data that are based on it are more uneven in size and present more homogenous trends (Fig. A7 below).

An analysis of data quality for fish time series (Fig. A8, with number of time series included in each group reported in Table A2) was able to compare scores in the range 3–5, as only 2 populations had data quality score = 6 and the times-series with scores = 1 and 2 do not cover the entire period 1970–2014. In the three subsets that could be examined, we observed a similar pattern: groups with scores of 3 and 4 are overall more negative than the overall fish trend, whilst populations of data quality 5 are more positive. Only partial conclusions can be drawn from the comparison between these trends and the overall trend for fish. Furthermore, as this disaggregation was only possible for fish species, more analyses are needed to confirm the pattern we observed.

4. Discussion

With representation of over 50% of Canadian vertebrate species, the trend we calculated is to our knowledge among the most comprehensive national-level indicators of its kind. As pointed out by our analysis on data quality, these time series are representative of the species' trend data to varying degrees. And of course, vertebrates only represent a small proportion of biodiversity. It is estimated that there are about 80 000 known species in Canada (Canadian Endangered Species Conservation Council, 2016), 68% of which belong to the animal kingdom.

The overall trend and system disaggregations presented here match those reported by CESI. The same methodology has also been adopted by WWF-Canada to calculate trends for Canadian vertebrate species for the Living Planet Report Canada, launched on 14th September 2017 (WWF-Canada, 2017).

Monitored populations of Canadian vertebrate species have declined by an average 10% between 1970 and 2014. Similar trends over comparable time periods have been found in other regions. Hayhow et al. (2019) for instance, produced an abundance indicator for the UK based on 697 terrestrial and freshwater species that shows a decline in average abundance of 13% between 1970 and 2016. It is possible that this is a general trend for countries or areas where biodiversity was depleted well before the time frame considered by such indicators, but a more systematic study based on a wider sample would be needed to confirm this trend. Although 1970 baseline abundance levels are not a target, trend interpretation needs to take starting points into account. Baseline abundance levels may have been low compared to historic abundance (Abell et al., 2008; Lotze and Worm, 2009). Most monitoring programmes started centuries after the onset of anthropogenic pressures (Marsh and Trenham, 2008; Mihoub et al., 2017) and historic abundance data are often available only in the form of harvest data that do not represent a sufficiently reliable proxy for abundance to be readily integrated in LPI-type indicators. Our indicator captures only recent changes in biodiversity and underestimates the overall anthropogenic impact.

As recommended for the development of monitoring and indicators (Biodiversity Indicators Partnership, 2011), the data collection was based on repeated gap analyses, in order to gather information on under-

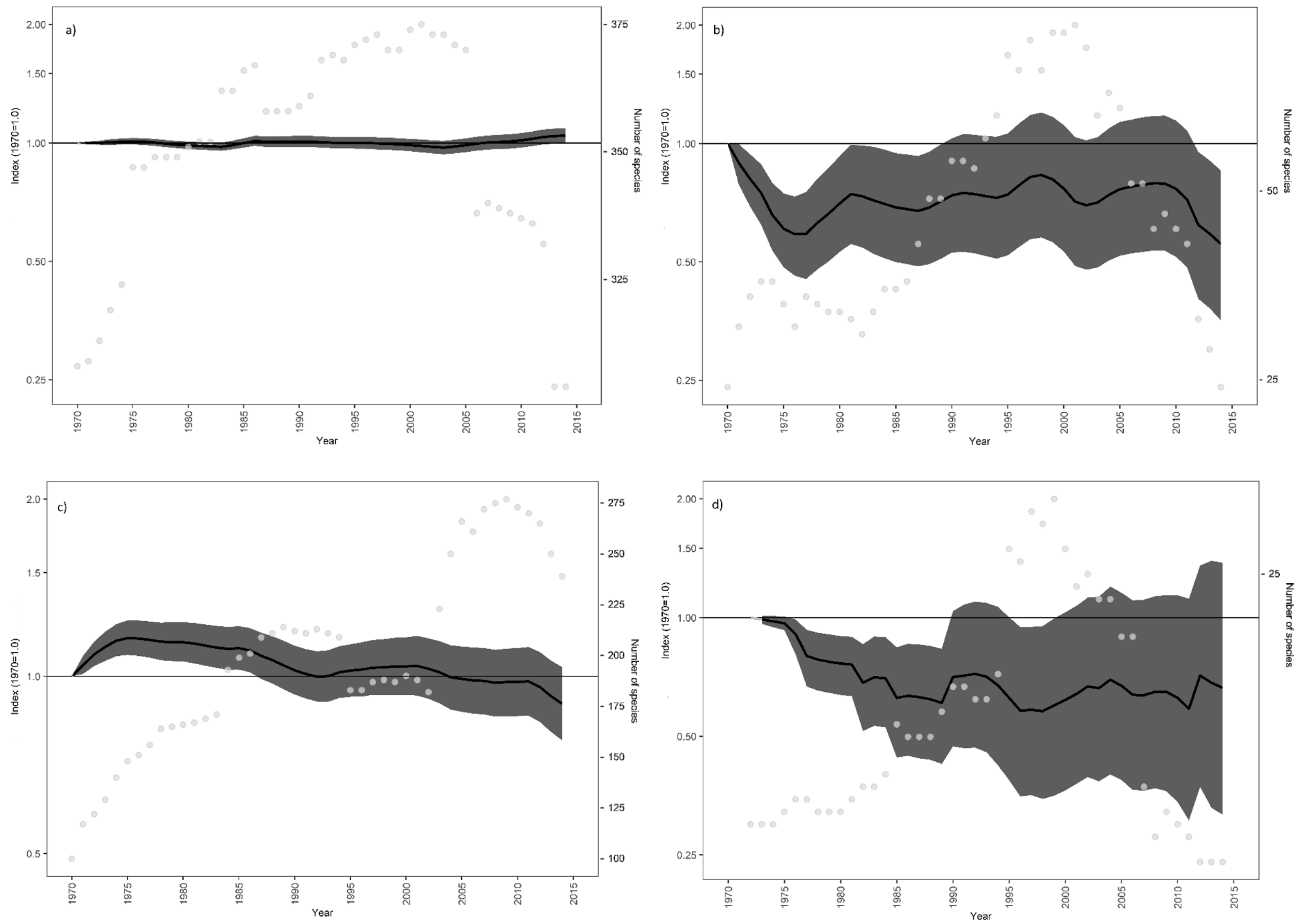

Fig. 4. Indices of abundance (black line with shaded grey area) with number of species contributing to the index in each year (pale grey dots, secondary Y-axis) for a) birds excluding three overabundant geese species (463 populations of 382 species, final index value = 4%; range = 0% to 9%) b) mammals (549 populations of 105 species, final index value = −44%; range = −64% to −15%), c) fish (2529 populations of 362 species, final index value = −21%; range = −33% to −6%) and d) amphibians and reptiles combined (139 populations of 46 species, final index value = −34%; range = −30% to 40%) monitored within Canada. Note that the amphibian and reptile trend starts in 1973 as there are no abundance data available prior to this. Average annual lambda plot ± SD are shown in the Supplementary Materials (Fig. A5a–d). Indices are plotted with a logarithmic primary Y-axis.

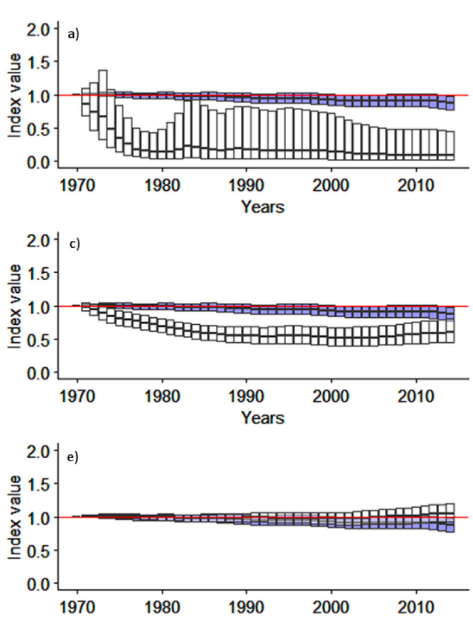

Fig. 5. Boxplots with yearly average and 2.5 and 97.5% quantiles for 10 000 indices obtained by bootstrapping population lambdas from each of the subsets of data with a different total representation score. Reading left to right, from data quality score = 2 (lower quality) in plot a), quality score = 3 in plot b), quality score = 4 in plot c), quality score = 5 in plot d) and quality score = 6 (higher quality) in plot e). Baseline (in red) and boxplots of corresponding indices obtained by bootstrapping population lambdas from the entire dataset (blue) are shown in each plot for comparison. The plot of the lowest quantile alone is shown for completeness in Fig. A6 in the Supplementary Materials but the subset has not been taken into account in the interpretation of the results as variability around the trend is too high for the scale used here. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

represented groups and areas. The dataset used to calculate the trends presented in this manuscript is hosted on the LPI database (www.livingplanetindex.org) and is publicly available (except for those time series that were provided to the authors under the agreement that they would be kept confidential). The database is continuously augmented, as part of the ongoing effort to improve the coverage of the global LPI by filling data gaps (McRae et al., 2017) and by adding recent data. As data availability increases, our ability to estimate trends for particular subsets improves. This may help resolve the influence of certain habitats, geographic areas or groups of species on the overall trend or show if trends in these subgroups diverge substantially from it, providing important information on declines or recoveries in specific geographic areas, biomes or species. However, the LPI and its derived indicators, such as the CSI, are designed to detect broad-scale, long-term trends in biodiversity. Although several papers in the literature have highlighted the most prevalent threats for Canadian vertebrate species (Currie et al., 2020; Gibbs et al., 2009; Imre and Derbowka, 2011; Kerr and Cihlar, 2004; Kerr and Deguise, 2004; McCune et al., 2013; Venter et al., 2006), links between the observed trends and these drivers are currently speculative.

The interpretation of the CSI trends cannot be decoupled from considerations on data quality and taxonomic and geographic coverage of the dataset. Collecting published data means that the dataset inherits the geographic and taxonomic biases that are known to occur in biodiversity data (Boakes et al., 2010; Donaldson et al., 2017; Troudet et al., 2017; Yesson et al., 2007). The index is biased towards managed species, species that are easier to observe, and species with aesthetic appeal. As long-term monitoring trends are available for most Canadian bird species, we know that their overall stable trend is the combined result of steep declines in abundance in shorebirds, grassland birds, and aerial insectivores, with strong increases in waterfowl and birds of prey and little or moderate change in the remaining groups (North American Bird Conservation Initiative Canada, 2019). Similar patterns in the numbers of increasing and declining species and similar trends in major biomes were highlighted by a recent study (Rosenberg et al., 2019) analysing bird trends across the whole of North America. Rosenberg et al. (2019) calculated a 29% net loss in total bird abundance, with the biggest losses happening in common species, including invasive species (excluded from our study). Information on trends for other taxa is not as comprehensive. Whilst time series for fish are often long, the dataset includes mainly fish species of commercial interest, so the picture we have for this group is biased towards these species. On the other hand, there is a general lack of data for all freshwater taxa including fish (Monk and Baird, 2014). The remaining groups – although some well-represented in terms of number of species – are less well-represented spatially. Data for some species are limited to a local study covering a small fraction of the species' range and total population. The trend for Canadian mammals is declining and points to high variability in the data. The lack of data we observed for reptiles is in line with recent findings by Saha et al. (2018), who highlighted the scarcity of basic abundance studies for this group globally.

As expected, the overall trend of the CSI is driven by data with better temporal and spatial representation; this is because these data are longer and fuller time series, and therefore contribute a higher number of datapoints to the overall trend (109 471 of the 131 407 datapoints that make up the current dataset belong to subgroup 5 and 6). Birds are extensively monitored in Canada and are considered good indicators of the state of the environment (Gregory and Strien, 2010). They contribute most of the "higher quality" data to the dataset. Our analysis comparing CSI results with SCBR results shows that the two methods result in trends with the same direction and similar trajectories (although the final percentage change values differ), so what is the value of including "lower-quality" data that do not have a strong effect on the overall trend and that are less representative of the overall taxon or species trend?

Examination of trends in subgroups of differing data quality provides hints that species with low-quality data may be declining while species with high-quality data are increasing, suggesting that correlations exist between species trends and the factors that affect monitoring decisions. With the exception of the lowest quality category, these quality subgroups show consistent trends. All trends in lower quality data except one show a negative trajectory from the start to the end of the considered time frame. The temporal aspect of the quality score appears to have a stronger influence on this pattern. However, it has to be noted that the way in which spatial data has been recorded allows only for a coarse disaggregation of the data based on scale (three subgroups of varying size). In the future we hope to store spatial polygons representing the precise survey area alongside the database records, in order to be able to disaggregate the data based on scale to a finer degree.

Fish populations of data quality 3 and 4 are also more negative than the overall fish trend, whilst populations of data quality 5 are more positive. As the index is based on data collected for purposes other than a biodiversity indicator (with the exception of the bird data), the pattern we observe in the data could be the result of known biases in biodiversity research. Although data quality is defined at the population level and therefore species can be represented in more than one data quality category, time series from specific taxonomic groups are clustered within the low or high quality subsets (Table A2), so in some cases entire species groups are represented for the most part in the low or high quality categories.

Better data are available for certain groups, such as birds and mammals, whilst data for amphibians, a group known to be more threatened than both mammals and birds (Stuart et al., 2004), are concentrated within the lower quality subsets. Lower quality data are also more often derived from publications, which frequently report results from a fixed-term project. Compared to baseline monitoring programmes, scientific papers have been reported to be biased towards threatened species (Fazey et al., 2005). For example, 8% of mammal data in our dataset come from sources primarily aimed at tracking declining species.

The picture is however more nuanced. An analysis of the LPI database (McRae et al., 2017) showed that threatened species (as defined by the IUCN Red List) are indeed over-represented in the database for all groups but not for amphibians (one of the two groups that are absent in the two highest quality subcategories). The analysis did not take into account fish as most species had not been assessed by the Red List. A similar analysis for the US only found that threatened species are in fact under-represented in the country-specific conservation literature (Lawler et al., 2006). Also, as we conducted targeted data collection from unpublished sources especially for groups that were initially under-represented in the dataset (amphibians and reptiles in particular), data for these groups were therefore not exclusively sourced from publications, but also from baseline monitoring programmes occurring in national parks, and citizen science programmes. Similarly, a study looking at the research impact of mammal species in Australia found no effect of IUCN status on the h-index for different species, which increased with body size and geographic range (Fleming and Bateman, 2016).

The currently available data highlight declines in specific groups, many of which tend to have poor quality data in terms of temporal and spatial coverage. Targeted field data collection could help differentiate biological trends from data artefacts A recent study comparing known long-term trends in bird abundance with samples of these complete time series (Wauchope et al., 2019) suggests that if a significant trend is detected by the sample it is likely to reliably describe the direction (positive or negative) of the complete trend, but most likely won't accurately match annual percentage change. By definition, lower-quality time series in the dataset are not as representative of the overall species trends as long-term monitoring data. However, these data don't appear to introduce systematic bias in multispecies trends and they increase representation of some neglected taxa. Collecting all available data might help us to depict a more accurate picture of in-country biodiversity and flag up potential local declines.

CRediT authorship contribution statement

Valentina Marconi: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Software, Writing - original draft, Writing - review & editing. **Louise McRae:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Helen Müller:** Investigation, Data curation, Writing - review & editing. **Jessica Currie:** Investigation, Data curation, Writing - review & editing. **Sarah Whitmee:** Conceptualization, Writing - review & editing. **Fawziah (ZuZu) Gadallah:** Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision, Resources, Project administration, Funding acquisition. **Robin Freeman:** Conceptualization, Methodology, Software, Visualization, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: All authors are employed or have been employed by government departments or environmental nongovernmental organizations (or received funding from such sources as academic scientists) that could be viewed as having competing interests.

Acknowledgements

We are very grateful to individuals who have provided data or advised on data availability, and in particular the hundreds of skilled volunteers in Canada who have participated in the Breeding Bird Survey over the years and those who have served as provincial or territorial coordinators for the BBS. We also acknowledge the contributions of the Canadian working group for the Canadian Species Index for feedback and comments on the dataset and analysis and in particular the contributions from Adam Smith (Environment and Climate Change Canada). We are grateful to Robin Abell and Michele Thieme who provided the dataset behind the Freshwater Ecoregions of the World. We would also like to thank Xavier Harrison, Piero Visconti, Stefanie Deinet, Monika Böhm, and David Jacoby for providing useful feedback on a draft of this manuscript.

Role of the funding source

Funding for the development of the Canadian indicator was provided by Environment and Climate Change Canada (grant numbers: K1A50-13-9013, 3000621511 and 3000676058). ECCC contributed to study design, data collection, methodology, and preparation of the manuscript and was supported in its contribution by a Canadian working group that provided feedback and comments on the dataset and analysis. LM is funded by WWF UK and WWF NL. JC is funded by WWF-Canada.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108022.

References

Abell, R., Thieme, M.L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., Coad, B., Mandrak, N., Contreras Balderas, S., Bussing, W., Stiassny, M.L.J., Skelton, P., Allen, G.R., Unmack, P., Naseka, A., NG, R., Sindorf, N., Robertson, J., Armijo, E., Higgins, J.V., Heibel, T.J., Wikramanayake, E., Olson, D., Lopez, H.G., Reis, R.E., Lundberg, J. G., Sabaj Perez, M.H., Petry, P., 2008. Freshwater Ecoregions of the World: A New Map of Biogeographic Units for Freshwater Biodiversity Conservation. BioScience 58, 403-414.

Balmford, A., Bennun, L., ten Brink, B., Cooper, D., Côté, I.M., Crane, P., Dobson, A., Dudley, N., Dutton, I., Green, R.E., Gregory, R.D., Harrison, J., Kennedy, E.T., Kremen, C., Leader-Williams, N., Lovejoy, T.E., Mace, G., May, R., Mayaux, P., Morling, P., Phillips, J., Redford, K., Ricketts, T.H., Rodríguez, J.P., Sanjayan, M., Schei, P.J., van Jaarsveld, A.S., Walther, B.A., 2005. The Convention on Biological Diversity's 2010 target. Himalayan J. Sci. 3.

Bhatt, R., Gill, M.J., Hamilton, H., Han, X., Linden, H.M., Young, B.E., 2020. Uneven use of biodiversity indicators in 5th National Reports to the Convention on Biological Diversity. Environ. Conserv. 47 (1), 15–21. https://doi.org/10.1017/S0376892919000365.

Biodiversity Indicators Partnership, 2011. Cambridge, UK.

Boakes, E.H., McGowan, P.J.K., Fuller, R.A., Chang-qing, D., Clark, N.E., O'Connor, K., Mace, G.M., 2010. Distorted Views of Biodiversity: Spatial and Temporal Bias in Species Occurrence Data. PLoS Biol. 8 (6), e1000385. https://doi.org/10.1371/journal.pbio.1000385.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vie, J.-C., Watson, R., 2010. Global Biodiversity: Indicators of Recent Declines. Science 328 (5982), 1164–1168. https://doi.org/10.1126/science:1187512.

Canadian Endangered Species Conservation Council, 2016. Wild Species 2015: The General Status of Species in Canada. N.G.S.W. Group.

Canadian Wildlife Service Waterfowl Committee, 2013. Population status of migratory game birds in Canada: November 2013.

Canadian Wildlife Service Waterfowl Committee, 2014. Population Status of Migratory Game Birds in Canada: November 2014.

CBD, 2010. COP decision X/2. Strategic plan for biodiversity 2011–2020 and the Aichi biodiversity targets.

Collen, B., Loh, J., Whitmee, S., McRae, L., Amin, R., Baillie, J., 2009. Monitoring Change in Vertebrate Abundance: the Living Planet Index. Conserv. Biol. 23, 317–327.

Collen, B., Nicholson, E., 2014. Taking the measure of change. Science 346 (6206), 166–167. https://doi.org/10.1126/science:1255772.

Currie, J., Marconi, V., Kerr, J., 2020. An analysis of threats and factors that predict trends in Canadian vertebrates designated as at-risk. FACETS 5 (1), 49–66. https://doi.org/10.1139/facets-2019-0017.

Deinet, S., Zöckler, C., Jacoby, D., Tresize, E., Marconi, V., McRae, L., Svobods, M., Barry, T., 2015. The Arctic Species Trend Index: Migratory Birds Index. Akureyri, Iceland.

Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., Wikramanayake, E., Hahn, N., Palminteri, S., Hedao, P., Noss, R., Hansen, M., Locke, H., Ellis, E.C., Jones, B., Barber, C.V., Hayes, R., Kormos, C., Martin, V., Crist, E., Sechrest, W., Price, L., Baillie, J.E.M., Weeden, D., Suckling, K., Davis, C., Sizer, N., Moore, R., Thau, D., Birch, T., Potapov, P., Turubanova, S., Tyukavina, A., de Souza, N., Pintea, L., Brito, J.C., Llewellyn, O.A., Miller, A.G., Patzelt, A., Ghazanfar, S.A., Timberlake, J., Klöser, H., Shennan-Farpón, Y., Kindt, R., Lillesø, J.-P.-B., van Breugel, P., Graudal, L., Voge, M., Al-Shammari, K.F., Saleem, M., 2017. An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67, 534–545. https://doi.org/10.1093/biosci/bix014.

Donaldson, M.R., Burnett, N.J., Braun, D.C., Suski, C.D., Hinch, S.G., Cooke, S.J., Kerr, J. T., Hutchings, J., 2017. Taxonomic bias and international biodiversity conservation research. FACETS 1 (1), 105–113. https://doi.org/10.1139/facets-2016-0011.

Eamer, J., Russell, D.E., McRae, L., Böhm, M., Deinet., S., Collen, B., Gill, M.J., 2012. The Arctic Species Trend Index 2011: Update of the ASTI, an in-depth look at marine species and development of spatial analysis techniques. Iceland.

Environment and Climate Change Canada, 2019. Population status of Canada's migratory birds, ed. Canadian Environmental Sustainability Indicators.

Fazey, I., Fischer, J., Lindenmayer, D.B., 2005. What do conservation biologists publish? Biol. Conserv. 124, 63–73, https://doi.org/10.1016/j.biocon.2005.01.013.

Fleming, Patricia A., Bateman, Philip W., 2016. The good, the bad, and the ugly: which Australian terrestrial mammal species attract most research? Mammal Rev. 46 (4), 241–254. https://doi.org/10.1111/mam.12066.

Fox, A.D., Madsen, J., Boyd, H., Kuijken, E., Norriss, D.W., Tombre, I.M., Stroud, D.A., 2005. Effects of agricultural change on abundance, fitness components and distribution of two Arctic-nesting goose populations. Glob. Change Biol. 11 (6), 881–893.

Freeman, R., McRae, L., Deinet, S., Amin, R., Collen, B.R.p., rlpi: Tools for calculating indices using the Living Planet Index method.

Froese, R., Pauly, D., 2017. FishBase, World Wide Web electronic publication, www.fishbase.org.

Gauthier, Gilles, Giroux, Jean-Francois, Reed, Austin, Bechet, Arnaud, Belanger, Luc, 2005. Interactions between land use, habitat use, and population increase in greater snow geese: what are the consequences for natural wetlands? Glob. Change Biol. 11 (6), 856–868.

Gibbs, K.E., Mackey, R.L., Currie, D.J., 2009. Human land use, agriculture, pesticides and losses of imperiled species. Divers. Distrib. 15, 242–253.

Gill, M., 2020. Analysis of Indicators in Sixth National Reports - Summary.

Gregory, R.D., Strien, A.v., 2010. Wild Bird Indicators: Using Composite Population Trends of Birds as Measures of Environmental Health. Ornithol. Sci. 9, 3–22, 10.2326/osj.9.3.

Hayhow, D., Eaton, M., Stanbury, A., Burns, F., Kirby, W., Bailey, N., Beckmann, B., Bedford, J., Boersch-Supan, P., Coomber, F., Dennis, E., Dolman, S., Dunn, E., Hall, J., Harrower, C., Hatfield, J., Hawley, J., Haysom, K., Hughes, J., Johns, D., Mathews, F., McQuatters-Gollop, A., Noble, D., Outhwaite, C., Pearce-Higgins, J., Pescott, O., Powney, G., Symes, N., 2019. The State of Nature 2019.

Imre, István, Derbowka, Darren, 2011. Major threats facing terrestrial mammals in Canada. Canad. Field-Nat. 125 (3), 213. https://doi.org/10.22621/cfn.v125i3.1223.
IUCN 2018, The IUCN Red List of Threatened Species. Version 2018-1.
Jefferies, R.L., Rockwell, R.F., Abraham, K.F., 2004. Agricultural food subsidies, migratory connectivity and large-scale disturbance in Arctic coastal systems: a case study. Integr. Comp. Biol. 44, 130–139.
Jones, J.P.J., Collen, B., Atkinson, G., Baxter, P.J., Bubb, P.J., Illian, J.B., Katzner, T.E., Keane, A., Loh, J., McDonald-Madden, E., Nicholson, E., Pereira, H.M., Possingham, H.P., Pullin, A.S., Rodrigues, A.S.L., Ruiz-Gutierrez, V., Sommerville, M., Milner-Gulland, E., J., 2011. The Why, What, and How of Global Biodiversity Indicators Beyond the 2010 Target. Conserv. Biol. 25, 450–457.
Kerr, J.T., Cihlar, J., 2004. Patterns and causes of species endargement in Canada. Ecol. Appl. 14, 743–753.
Kerr, Jeremy T., Deguise, Isabelle, 2004. Habitat loss and the limits to endangered species recovery. Ecol. Lett. 7 (12), 1163–1169.
Lawler, Joshua J., Aukema, Juliann E., Grant, Jacqualine B., Halpern, Benjamin S., Kareiva, Peter, Nelson, Cara R., Ohleth, Kris, Olden, Julian D., Schlaepfer, Martin A., Silliman, Brian R., Zaradic, Patricia, 2006. Conservation science: a 20-year report card. Front. Ecol. Environ. 4 (9), 473–480. https://doi.org/10.1890/1540-9295(2006)4[473:CSAYRC]2.0.CO;2.
Loh, Jonathan, Green, Rhys E, Ricketts, Taylor, Lamoreux, John, Jenkins, Martin, Kapos, Valerie, Randers, Jorgen, 2005. The Living Planet Index: using species population time series to track trends in biodiversity. Philos. Trans. Royal Soc. B 360 (1454), 289–295. https://doi.org/10.1098/rstb.2004.1584.
Lotze, Heike K., Worm, Boris, 2009. Historical baselines for large marine animals. Trends Ecol. Evol. 24 (5), 254–262. https://doi.org/10.1016/j.tree.2008.12.004.
Mace, Georgina M., Reyers, Belinda, Alkemade, Rob, Biggs, Reinette, Chapin, F. Stuart, Cornell, Sarah E., Díaz, Sandra, Jennings, Simon, Leadley, Paul, Mumby, Peter J., Purvis, Andy, Scholes, Robert J., Seddon, Alistair W.R., Solan, Martin, Steffen, Will, Woodward, Guy, 2014. Approaches to defining a planetary boundary for biodiversity. Global Environ. Change 28, 289–297. https://doi.org/10.1016/j.gloenvcha.2014.07.009.
Marsh, David M., Trenham, Peter C., 2008. Current Trends in Plant and Animal Population Monitoring. Conserv. Biol. 22 (3), 647–655.
McCune, Jenny L., Harrower, William L., Avery-Gomm, Stephanie, Brogan, Jason M., Csergő, Anna-Mária, Davidson, Lindsay N.K., Garani, Alice, Halpin, Luke R., Lipsen, Linda P.J., Lee, Christopher, Nelson, Jocelyn C., Prugh, Laura R., Stinson, Christopher M., Whitney, Charlotte K., Whitton, Jeannette, 2013. Threats to Canadian species at risk: An analysis of finalized recovery strategies. Biol. Conserv. 166, 254–265.
McRae, Louise, Deinet, Stefanie, Freeman, Robin, Doi, Hideyuki, 2017. The Diversity-Weighted Living Planet Index: Controlling for Taxonomic Bias in a Global Biodiversity Indicators Partnership. PLoS ONE 12 (1), e0169156. https://doi.org/10.1371/journal.pone.0169156.
McRae, L., Loh, J., Bubb, P.J., Baillie, J., Kapos, V., Collen, B., 2008. Living Planet Index Guidance for national and regional use Version 1.1, ed. UNEP-WCMC, p. 11, Cambridge, UK.
Mihoub, J.-B., Henle, K., Titeux, N., Brotons, L., Brummitt, N.A., Schmeller, D.S., 2017. Setting temporal baselines for biodiversity: the limits of available monitoring data for capturing the full impact of anthropogenic pressures. 7, 41591, 10.1038/srep41591 https://www.nature.com/articles/srep41591#supplementary-information.
Monk, W.A., Baird, D.J., 2014. Biodiversity in Canadian lakes and rivers. Ottawa, ON. http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1.
North American Bird Conservation Initiative Canada, 2019. The State of Canada's Birds, 2019. Ottawa, Canada. www.stateofcanadasbirds.org.
Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial Ecoregions of the World: A New Map of Life on EarthA new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. Bioscience 51, 933–938. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.
Proença, Vânia, Martin, Laura Jane, Pereira, Henrique Miguel, Fernandez, Miguel, McRae, Louise, Belnap, Jayne, Böhm, Monika, Brummitt, Neil, García-Moreno, Jaime, Gregory, Richard D., Honrado, João Pradinho, Jürgens, Norbert, Opige, Michael, Schmeller, Dirk S., Tiago, Patrícia, van Swaay, Chris A.M., 2017. Global biodiversitymonitoring: From data sources to Essential Biodiversity Variables. Biol. Conserv. 213, 256–263. https://doi.org/10.1016/j.biocon.2016.07.014.
R Core Team, R: A language and environment for statistical computing. https://www.R-project.org/.
Rosenberg, Kenneth V., Dokter, Adriaan M., Blancher, Peter J., Sauer, John R., Smith, Adam C., Smith, Paul A., Stanton, Jessica C., Panjabi, Arvind, Helft, Laura, Parr, Michael, Marra, Peter P., 2019. Decline of the North American avifauna. Science 366 (6461), 120–124. https://doi.org/10.1126/science:aaw1313.
Sachs, Jeffrey D, 2012. From millennium development goals to sustainable development goals. Lancet 379 (9832), 2206–2211.
Saha, Anwesha, McRae, Louise, Dodd, C. Kenneth, Gadsden, Hector, Hare, Kelly M., Lukoschek, Vimoksalehi, Böhm, Monika, 2018. Tracking Global Population Trends: Population Time-Series Data and a Living Planet Index for Reptiles. J. Herpetol. 52 (3), 259. https://doi.org/10.1670/17-07610.1670/17-076.s1.
Sauer, John R., Link, William A., 2011. Analysis of the North American Breeding Bird Survey Using Hierarchical Models. Auk 128 (1), 87–98. https://doi.org/10.1525/auk.2010.09220.
Smith, A., 2018. State of Canada's Birds Report 2019 dataset, ed. Environment and Climate Change Canada.
Smith, A.C., Hudson, M.-A.R., Aponte, V., Francis, C.M., 2014a. North American Breeding Bird Survey - Canadian Trends Website, ed. Environment and Climate Change Canada, Gatineau, Quebec, K1A 0H3.
Smith, Adam C., Hudson, Marie-Anne R., Downes, Constance, Francis, Charles M., 2014b. Estimating breeding bird survey trends and annual indices for Canada: how do the new hierarchical Bayesian estimates differ from previous estimates? Canad. Field-Nat. 128 (2), 119. https://doi.org/10.22621/cfn.v128i2.1565.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 10.1126/science.1259855.
Stuart, Simon N., Chanson, Janice S., Cox, Neil A., Young, Bruce E., Rodrigues, Ana S.L., Fischman, Debra L., Waller, Robert W., 2004. Status and Trends of Amphibian Declines and Extinctions Worldwide. Sciencexpress 306 (5702), 1783–1786.
Threatened Species Recovery Hub, 2019. Australian Threatened Index. Accessed September 2019. https://tsx.org.au/.
Tittensor, D.P., Walpole, M., Hill, S.L., Boyce, D.G., Britten, G.L., Burgess, N.D., Butchart, S.H., Leadley, P.W., Regan, E.C., Alkemade, R., 2014. A mid-term analysis of progress toward international biodiversity targets. Science 346, 241–244.
Troudet, J., Grandcolas, P., Blin, A., Vignes-Lebbe, R., Legendre, F., 2017. Taxonomic bias in biodiversity data and societal preferences. Sci. Rep. 7, 9132. https://doi.org/10.1038/s41598-017-09084-6.
van Strien, Arco J., Meyling, Adriaan W. Gmelig, Herder, Jelger E., Hollander, Hans, Kalkman, Vincent J., Poot, Martin J.M., Turnhout, Sander, van der Hoorn, Berry, van Strien-van Liempt, Willy T.F.H., van Swaay, Chris A.M., van Turnhout, Chris A.M., Verweij, Richard J.T., Oerlemans, Natasja J., 2016. Modest recovery of biodiversity in a western European country: The Living Planet Index for the Netherlands. Biol. Conserv. 200, 44–50.
Venter, Oscar, Brodeur, Nathalie N., Nemiroff, Leah, Belland, Brenna, Dolinsek, Ivan J., Grant, James W.A., 2006. Threats to Endangered Species in Canada. Bioscience 56 (11), 903. https://doi.org/10.1641/0006-3568(2006)56[903:TTESIC]2.0.CO;2.
Wauchope, Hannah S., Amano, Tatsuya, Sutherland, William J., Johnston, Alison, Yoccoz, Nigel, 2019. When can we trust population trends? A method for quantifying the effects of sampling interval and duration. Methods Ecol. Evol. 10 (12), 2067–2078. https://doi.org/10.1111/mee3.v10.1210.1111/2041-210X.13302.
World Wildlife Fund, 2006. WildFinderOnline database of species distributions, www.worldwildlife.org/WildFinder.
WWF-Canada, 2017. Living Planet Report Canada - A national look at wildlife loss.
WWF, 2016. Living Planet Report 2016. Risk and resilience in a new era, Gland, Switzerland.
Yesson, Chris, Brewer, Peter W., Sutton, Tim, Caithness, Neil, Pahwa, Jaspreet S., Burgess, Mikhaila, Gray, W. Alec, White, Richard J., Jones, Andrew C., Bisby, Frank A., Culham, Alastair, Beach, James, 2007. How Global Is the Global Biodiversity Information Facility? PLoS ONE 2 (11), e1124. https://doi.org/10.1371/journal.pone.0001124.