Maximising time-series inclusion reduces geographic and taxonomic biases in the Living Planet Index

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Measuring how and why biodiversity is changing is critical to protecting it. Among the tools developed to measure biodiversity, one indicator has come under recent scrutiny. The Living Planet Index (LPI) is an indicator based on vertebrate population trends used as evidence for policy and a resource for scientific research; it has a high profile and global reach in the media by conveying a simple message about biodiversity loss[1]. Toszogyova et al recently published a critique on the indicator's approach to data inclusion and weighting, asserting that the LPI provides a biased estimate of global vertebrate abundance change. As the scientists behind the ongoing development of the LPI, we appreciate efforts to improve the index. Whilst the authors rightly highlight the sensitivity of the LPI to characteristics of time-series data, their conclusions are not substantiated. Here, we identify aspects of their method which preclude a direct comparison to the published LPI, contest the conclusions drawn and provide a rationale advising against adopting their approach.

Toszogyova et al first revisit a previous study which demonstrated a sensitivity of the LPI (and other multi-species indices) to random fluctuations in populations[2], noting that the LPI captures stationary fluctuations accurately but is negatively biased in the case of non-stationarity. This feature is useful to highlight and has been addressed elsewhere[2]. They then perform three sets of sensitivity tests: exploring the effect of removing time-series of different durations and number of data points; sensitivity to a few declining populations from the 1970s; and the treatment of zero values. The authors find that the sensitivity tests result in global and system LPIs that are less negative and that, when the index is unweighted, some of the results show positive trends. As a result, they conclude that the LPI is biased towards decreasing trends. We argue that the effects the sensitivity tests have on the LPI are magnified by not following all published steps to calculate the global index and that the approach to zero treatment is unjustified. We also challenge the narrative taken and the misuse of an example showing sensitivity to an initial declining population. We note that some of these points were originally included in a comment on the preprint to Toszogyova et al.

Concerns on treating zeros as missing values

Toszogyova et al[3] state they have conducted a detailed inspection of the LPI data and methods; however, several steps are missing from their replication of the published LPI method. We acknowledge that this could be a result of the steps being described across multiple publications so here we include the full process with references (see Supplementary Information). Approximating the dataset used by the authors (not enough information was included to be able to replicate it exactly; Table S1), we investigate methodological issues with the analysis, which have implications on the comparisons made and the corresponding conclusions. Importantly, Toszogyova et al did not appear to remove 'replicates' from the dataset, which are recorded in the LPI database as time-series for the same species which overlap substantially in both space and time. They are retained in the database to support finer-scale analysis but removed when calculating the global, system and realms LPIs to minimise double-counting the same individuals. Our replication of the manuscript analysis suggests that this has a small impact on the results; the difference between the original LPI and those with modified zero treatment and removal of sparse time-series is greater and more positive when replicates are included (Figure S1, Table S2). Although the impact is small, we recommend that these replicated time-series are removed from global and system LPIs on principle.

The authors correctly identify a sensitivity of a geometric mean to zero values[4] and we agree that the treatment of zeros is conceptually important in multi-species indices. A zero in a time-series can represent different scenarios: a local extinction; a precursor to colonisation; or a missing observation. Recognising that zero values can reflect low abundance or local extinctions, and after different options were tested, a decision was taken to not disregard this information in the LPI and add a small value (1% of the mean of the time-series) to all values in time-series containing zeros[5]. Other indicators use a similar process[4,6] and new approaches have been proposed that are, however, only suitable for indices based on count data[4]. Nevertheless, treating all zeros as missing values doesn't represent a better alternative as it potentially overlooks cases of low abundance or local extinctions. This could be explored further, by treating leading, middle and trailing zeros differently. For example, zeros at the end of a time-series, particularly if consecutive, might be more likely to represent local extinctions and therefore could be retained. There is often insufficient information in the data source to determine the scenario represented by a zero value, which is why a generalised approach of assuming that all zeros are 'real' zeros has been taken so far. In the development of the Canadian application of the LPI, where close inspection of all time-series was possible, we explored treating all zeros as missing values as we deemed them likely to be missing observations rather than population crashes[7]. The difference in treatment of zeros produced a negligible difference in the resulting index, but the effect on the global index is more pronounced and varies according to the position of the zero values (Supplementary materials; Figure S2), highlighting that a decision made in principle can have varied impacts in practice.

The authors suggest that the treatment of zeros used in the LPI will lead to large fluctuations ('two orders of magnitude'). However, it is important to note that in the current LPI method, logged interannual change values are capped to 1/- 1. This way, the LPI captures larger population changes but limits their extent to 10-fold. While this threshold is still arbitrary, and an ecologically large annual change, it is not two orders of magnitude but one[7]. This capping is a default setting in the rlpi code; however, Toszogyova et al turned this setting off in their analysis, but it was not stated why in the methods. We note that this amplified the impact of their modifications to the method by 9% for the global LPI (Figure 1, Table S2). The authors also split time-series following the removal of middle zeros (i.e. a time-series with a central zero, is split into two distinct population time-series), which leads to an increase in time-series falling below the minimum threshold of five data points (Figure S5), and therefore an increase in the amount of data removed. Our analysis revealed that fragmenting time-series in this way following the removal of zeros not only compounds the effect of removing zeros alone across the global and system LPIs as time-series became shorter in length and sparser (Figure 1; Figure S1, Figure S5, Table S2), but renders the results unsuitable to compare to the published LPI.

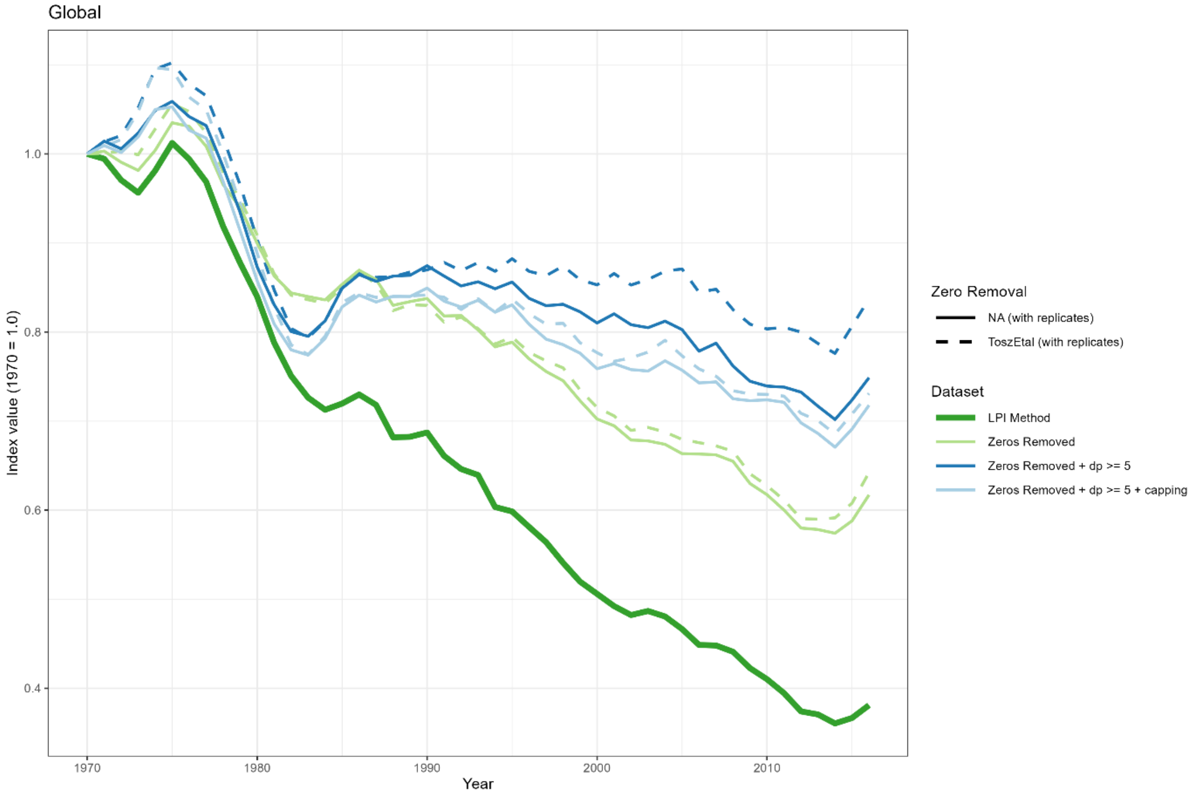

Figure 1. The effect of treating zeros as missing values (NA: solid lines) compared with treating zeros as missing values plus splitting time-series which contain zeros in the middle (ToszEtAl: dashed lines). These approaches are compared with the removal of time-series with fewer than 5 data points (blues), with the capping setting on (light blue) and with the current LPI method (bold green) where 1% of the mean of a time-series containing a zero value is added to every value in that time-series. The approach used by Toszogyova et al of splitting time-series (dashed lines) amplifies the impact of zero removal in the LPI especially when this is combined with the removal of time-series with fewer than 5 data points (dashed vs solid medium blue). Turning off the capping setting also exacerbates the positive effect of the Toszogyova et al approach (light blue dashed vs medium blue dashed).

Replacing one bias with another

The authors point out that time-series with fewer data points tend to be declining on average. This is something that has been highlighted previously[7]. However, it is difficult to disentangle the taxonomic make up of this subset from the trends. The decline could be a feature of the species represented by those time-series, and not of sparser time-series per se. By their nature, short and sparse time-series have greater uncertainty but a recent paper has shown that degrading time-series by removing data points results in trends that often show the same trajectory of the original longer, fuller trend[8]. While it is true that excluding time-series with fewer data points will have an impact on the final trends, arguably this is not sufficient justification for removing them, as it would result in the exclusion of a set of species and taxa that would therefore not be represented in the trends at all. We demonstrate that the removal of data in Toszogyova et al disproportionately impacts highly biodiverse realms with many data sets more than halving in size; the greatest impact is seen in the Neotropics with almost 80% removal of terrestrial populations (Table 1; Supp mat; Figure S3-4; Table S3-4). If the goal – as is the case for the LPI – is to have an indicator that is representative of as broad a set of vertebrate species as possible, then the inclusion of these data improves representation of taxa that are underrepresented in biodiversity data in general[9]. Critically, this exposes a trade-off between where we have higher-quality data – often temperate places like Europe and North America, often for birds and mammals, and more frequently in protected areas[9,10]; and where we see declines – often more tropical or for species that are harder to monitor like amphibians and reptiles. The authors recognise this and suggest that the lack of representation can be addressed by the diversity-weighted approach. Weighting can be a useful tool towards mitigating the bias in a data set[11] but if data in the heavily weighted regions have been substantially reduced through removal of short time-series, weighting may not help and could even exacerbate the issue.

In the LPI, a cautious approach is taken to the removal of any population data; they often capture important information, and it is essential to thoroughly explore the implications of their removal. For example, information on declines over 20 to 40 years in African savanna raptors[12] would be removed if population trends with two data points were excluded. This would remove an important insight into what is happening to 42 African bird species. Overall, removing shorter, sparser population time-series results in an overall trend dominated by species and regions that have seen less severe recent declines (Figure S3-4). Regions and countries with fewer resources, where declines are often starker, often have lower data availability, so excluding this information would give us a less complete picture of biodiversity trends globally.

There is also evidence that the less well monitored species are often the most threatened, and tropical species are disproportionately at risk of extinction[13,14].

Table 1. Impact of removal of populations from terrestrial taxa and realm subsets following the modified method recommended by Toszogyova et al (treating all zeros as missing values, splitting time-series containing zero values in the middle into fragmented time-series and removing time-series with fewer than 5 data points). See also Figure S3

		Aves	Herptiles	Mammalia	**Total**
Original data set	Afrotropical	161	56	794	**1011**
	Indo-Pacific	466	84	278	**828**
	Nearctic	2233	127	690	**3050**
	Neotropical	375	225	211	**811**
	Palearctic	1358	54	855	**2267**
	Total	**4593**	**546**	**2828**	**7967**
Amended data set	Afrotropical	62	39	334	**435**
	Indo-Pacific	203	40	90	**333**
	Nearctic	1965	60	371	**2396**
	Neotropical	55	46	71	**172**
	Palearctic	1218	42	593	**1853**
	Total	**3503**	**227**	**1459**	**5189**
Percentage of populations removed	Afrotropical	61.5	30.4	57.9	**57.0**
	Indo-Pacific	56.4	52.4	67.6	**59.8**
	Nearctic	12.0	52.8	46.2	**21.4**
	Neotropical	85.3	79.6	66.4	**78.8**
	Palearctic	10.3	22.2	30.6	**18.3**
	Total	**23.7**	**58.4**	**48.4**	**34.9**

Challenging the narrative

The manuscript's narrative appeared unsubstantiated by the analysis at times. For example, it is difficult to evidence that vertebrate decline is being over- or under-estimated by the LPI, given we don't have complete biodiversity data to calculate the "true" trend. Some studies have suggested that trends could be more negative than estimated by the LPI due to over-representation of data from protected areas[10]; this may be compounded by uneven sampling of data from sites or land-use gradients[15]. Others suggest that the real trends are likely to be less negative due to sensitivities of the LPI method[3,16]. We argue that the LPI should demonstrate the best estimate of average change in vertebrate populations given the available data and present sensitivities in a transparent way. Given the difficulty of estimating the actual trend in vertebrate populations, efforts should be spent on improving the estimate by assessing and improving data representation and associated bias.

The authors characterise the decisions behind calculating the LPI as subjective but arguably the modifications they advocate for are no less so. Whilst all indicators are developed using subjective decisions to some degree (e.g. using species as a unit of measure), there are rationales behind the decisions made for data inclusion and calculation of the LPI and these have been peer-reviewed[5,11]; they are not inherently wrong because they are subjective or because reversing a decision changes the index.

Toszogyova et al correctly identify the sensitivity of the start of the LPI (and any geometric mean indicator) when the number of populations or species is low. Identifying influential populations and species is important in preventing any single species driving a broad scale trend[17]. We use several different processes in the calculation of the index to explore the undue influence of particular species and populations on the global trend, including species- and population-level jack-knifing (recalculating after removing a single population or species). Influential populations or species are excluded from the global index and one example is that of the *Vipera berus* population identified by the authors, meaning that the effect they demonstrate is not reflected in the published versions of the LPI. The authors do acknowledge this, but still use it as an example, which could mislead readers into assuming a real effect on the published LPI.

Finally, it was also suggested that low values in the LPI could be the result of sparse data in the 1970s but don't provide evidence to support this. We tested this assumption by calculating a global LPI using data from different baselines and found similar average annual rates of change of between 2.54% and 2.78% per year when excluding data from the 1970s, 1980s and 1990s (Table 2). This suggests that that the decline in the global LPI is not attributable to poor quality data in the 1970s. Indeed, the mean annual percentage decline is marginally greater in the indices which do not contain data from the 1970s (Table 2).

Table 2 Final index value and average decline per year for the global Living Planet Index, based on the 2024 dataset and using data from different baselines.

Global LPI baseline	*Final index value in 2020*	*Time-series length (years)*	*Percentage decline per year*
1970	0.277	50	-2.535
1980	0.337	40	-2.683
1990	0.429	30	-2.782
2000	0.598	20	-2.538

Conclusion

We welcome any work to critically evaluate the LPI and are open to collaborations on doing so, particularly where new approaches to increase the data representation and improve the index are explored. The LPI data and code are freely available, and we emphasise our willingness to help or collaborate within the data use agreement. We submitted a comment to the pre-print article of Toszogyova et al in which we highlighted some of the concerns expressed here and note that some were also flagged within the open peer-review process. Overall, the approach presented in Toszogyova et al does not in our view provide a better estimate of monitored vertebrate population trends but exacerbates the existing taxonomic and geographic bias; therefore, we do not recommend adopting this approach to calculating the LPI. If, as the authors seem to suggest, we discount taxonomic weightings, remove shorter or sparser time-series or remove zeros from those time-series, this could result in a *more* biased and *less* reliable understanding of global vertebrate population declines.

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Supplementary Materials for 'Maximising time-series inclusion reduces geographic and taxonomic biases in the Living Planet Index'

1. Methods

1.1 Dataset

In order to replicate the analysis in the Toszogyova et al. paper we used the code "LPI_Changed.R" in the Supplementary materials of their article[1] and a version of the Living Planet Database that we believe approximates the dataset they used from January 2022. We used a download of the Living Planet Database from 9th February 2022[2], and removed confidential records as these are not publicly available and would not have been available to Toszogyova et al. for analysis. We could not recreate the exact numbers in their analysis, as we did not know the exact date of the download, but the numbers are very similar with the dataset for this study containing 13 more species and 98 more populations (Table S1).

From the 22,273 populations, we removed 24 prior to analysis which had 0 or 1 post-1950 data point, or only 0 values post-1950. We also excluded 3 terrestrial populations from the Antarctic as these were the only ones representing this biogeographic realm. The complete dataset for analysis was 22,246.

1.2 Replicating the methods in Toszogyova et al.

Other than the modifications described by Toszogyova et al., we identified two methodological steps that were not included in their analysis, but which are key parts of the method for calculating the global Living Planet Index (LPI). Firstly, 'replicate' populations are usually removed (see 1.6 Current published method for global and system LPIs: Step 1) and secondly, logged interannual changes for populations are normally capped to 1 or -1 if they exceed these values (see 1.6 Current published method for global and system LPIs: Step 9).

We replicated the methodological steps outlined in Toszogyova et al. to explore the effect of missing these two steps. In addition, we explored the effect of splitting time-series which contain zeros values in the middle of the time-series, by calculating the LPI with and without this feature. Using the data set from this study (Table S1), we calculated global and system indices using 14 approaches:

1. 'Toszogyova et al.': Modified method as recommended by Toszogyova et al.: diversity-weighted; treating zeros as missing values and splitting time-series containing zero values in the middle into fragmented time-series

    a. With and without removing time-series with fewer than 5 data points;
    b. Compare including and excluding replicates
    c. Compare with and without the capped lambda flag (limits annual change to 1/-1)
2. Modified method of Toszogyova et al.: diversity-weighted; treating zeros as missing values (replacing all 0s in a population time-series with NA) but not splitting time-series.
    a. With and without removing time-series with fewer than 5 data points;
    b. Compare including and excluding replicates
    c. Compare with and without the capped lambda flag (limits annual change to 1/-1)
3. Current published LPI method: diversity-weighted; including time-series with 2 or more data points; adding 1% of the mean to every value in time-series which contain zeros
    a. Compare including and excluding replicates

1.3 Impact of the position of zero values

In order to test the impact of removing zeros which occur in different positions within a time-series, we compared the effect of removing only those zeros that occur in the middle of time-series with removing those that occur at the start or end of a time-series. We produce global LPIs for the following permutations:

1. 'Toszogyova et al.' Modified method as recommended by Toszogyova et al.: diversity-weighted; treating all zeros as missing values and splitting time-series containing zero values in the middle into fragmented time-series
    a. With and without removing time-series with fewer than 5 data points
2. 'Toszogyova et al.' Modified method as recommended by Toszogyova et al.: diversity-weighted; treating only middle zeros as missing values and splitting time-series containing zero values in the middle into fragmented time-series
    a. With and without removing time-series with fewer than 5 data points
3. 'Toszogyova et al.' Modified method as recommended by Toszogyova et al.: diversity-weighted; treating only leading or trailing zeros as missing values
    a. With and without removing time-series with fewer than 5 data points

1.4 Impact of data removal on the taxonomic and geographic representation of the LPI dataset

We summarised the number of populations in each system, biogeographic realm and taxa that are removed as a result, using all of the following filters on the data set:

1. removing time-series with fewer than 5 data points
2. treating zeros as missing values
3. splitting time-series containing zero values in the middle into fragmented time-series

1.5 Baselines

To investigate whether the decline in the global LPI is a result of sparse data in the 1970s, we explored re-running the index with the removal of 1970s data. We also tested the removal of data from the 1950s, 1960s, 1980s and 1990s, and compared the average annual rate of change between the indices with the four different baselines.

Usually, the global LPI starts from 1970 using a dataset starting in 1950; for this iteration we excluded pre-1970 data. We used the rlpi package[3] and followed the current published LPI method (see below). We were unable to run an index using a baseline of 2010 as data was unavailable for one of the taxa-realm subsets (Pacific north temperate herptiles), which generated an error in the code.

1.6 Current published method for global and system LPIs

Step	Stage	Action	Details
1	Data filtering	Remove replicates	Populations for the same species monitored in the same location over the same period of time are considered 'replicates'. Only one of them is used in the global LPI calculations, to avoid potentially double-counting individuals. Replicates that are excluded in the global analysis are marked as 1 in the 'Replicate' column in the public dataset.[4]
2	Data filtering	Remove influential populations	A single population can have an undue effect on the overall trend, meaning that their exclusion will cause a noticeable shift in the trend trajectory (usually over a short period) or final value of the global or realm-level trends. These populations are marked with a 1 in the "Exclude" column in the public dataset[4]
3	Data filtering	Remove pre-1950 data	Exclude 9 population time-series which only have pre-1950 data points
4	Data filtering	Remove non-native species	To better align with Goal A of the CBDs Global Biodiversity Framework ("…the abundance of native wild species is increased to healthy and resilient levels…"), populations outside of their native range, as defined by the species

			account on the IUCN Red List, are removed[4]
5	Data processing	Subset the data	Each time-series is assigned to a terrestrial, freshwater or marine biogeographic realm and to a taxonomic group, creating 57 subsets of the data. This excludes 4 terrestrial Antarctic populations. See McRae et al. (2017) for full details of how subsets are delineated[5]
6	Data processing	Treatment of zeros	Each population time-series is logged; for time-series which contain a zero, 1% of the mean value of the time-series is added to every data point[6,7]
7	Data analysis	Modelling	A generalised additive modelling framework is used to model each population time-series and interpolate missing data. A generalised additive model is used for time-series containing 6 or more data points; for time-series with fewer than 6 data points and for time-series with a poor GAM fit we use log-linear interpolation[6,8]
8	Data analysis	Generate interannual change values	The difference between each annual modelled data point is taken to produce a series of lambda values (interannual changes) for each time-series[6]
9	Data analysis	Cap interannual change values	If a lambda value exceeds 1 or -1, these values are capped to 1 and -1 respectively[8]
10	Aggregation	Use geometric mean to calculate species level trends	Within each of the 57 subsets, the logged interannual changes across all populations of each species are averaged for each year[5]
11	Aggregation	Use geometric mean to calculate subset trends	The interannual changes across all species within a subset are averaged, creating 57 series of logged annual trends[5]
12	Aggregation	Use geometric mean with proportional weights to calculate system trends	Using weight values which are proportional to the species richness within each of the system-realm-taxa subset, the 57 series are aggregated to produce logged annual trends for terrestrial (15 subsets), freshwater (20 subsets) and marine (22 subsets) populations[5]
13	Aggregation	Use geometric mean to calculate global trends	The logged annual trends terrestrial, freshwater and marine indices are aggregated equally to produce the global set of logged annual trends[6,7]
14	Aggregation	Calculating index values	With 1970 set to 1, subsequent index values are calculated multiplying each

			logged annual value with the index value from the previous year[6,7]
15	Generating confidence limits	Bootstrap species trends	Annual species trends (from step 10) are bootstrapped by resampling with replacement 10,000 times and then generating a global LPI using the bounds of the central 9,500 index values calculated in each year using steps 11-14[5,6]

1.7 Packages and versions used

Analysis was performed in R version 4.4.2. For calculating the LPI, we used rlpi version 0.0.3 and mgcv version 1.9-1.

2. Results and discussion

2.1 Concerns on treating zeros as missing values

Treating zeros as missing values results in less negative, and sometimes positive, overall trends when calculating the LPI (Figure 1; Figure S1). This effect is magnified by two other modifications which are not explicitly addressed in Toszogyova et al.. The first is the approach of splitting time-series which contain zero values in the middle of the time-series. We were unsure of the purpose of this step as it was mentioned in the results, but not explained in the methods. We found that fragmenting time-series in this way leads to a higher number of short and sparse time-series, so more time-series with fewer than 5 data points were removed as a result. This seems to be an unnecessary step when zero values can be treated as missing values without the need for time-series to be split; while having no apparent advantage, this step amplifies the effect of zero removal (Figure 1; Figure S1, Table S2).

The second decision is that the capping setting was turned off according to the code in Toszogyova et al.. This setting is turned on by default in the rlpi package and limits logged interannual changes to a maximum of 1 and minimum of -1. The rlpi package allows for this to be turned off or for other values to be set as the maximum and minimum. The consequence of turning this setting off resulted in overall trends that were more positive than with the setting on; this is especially noted in the terrestrial and global LPI (Figure 1; Figure S1, Table S2).

The impact of including ‘replicates’ in the dataset was minimal in the current LPI method, but the effect was increased when the modifications from Toszogyova et al.. were implemented. This was more pronounced in the strictest filter: treating all zeros as missing values, splitting time-series containing zero values in the middle into fragmented time-series and removing time-series with fewer than 5 data points (Figure S1, Table S2).

There are 2,964 time-series in the data set which contain zeros and of these 1,577 contain zeros in the middle and 1,387 contain either leading or trailing zeros. We assert that zero treatment is an important issue, but that care should be taken to propose a method that considers the nature of the zero value. We found that the removal of leading or trailing zeros has a greater positive impact than removing only zeros in the middle of time-series (Figure S2); this effect is less clear when time-series with fewer than 5 data points are removed (Figure S2). This implies that trends are on average more negative in time-series with leading or trailing zeros. The latter are more likely to be true zero values and so it may not be appropriate to treat them as missing values. Whilst other approaches that treat zeros as missing values do not show a large difference in trends compared to using the 1% of the mean approach[8], it would be prudent to explore a more nuanced treatment of zeros regardless of the impact on trends.

2.2 Impact of data removal on the taxonomic and geographic representation of the LPI dataset

We show that the removal of data in Toszogyova et al. disproportionately impacts high biodiverse regions, in particular the Neotropics and Afrotropics (Table 1; Figure S3 and S4; Table S3 and S4). The terrestrial dataset is the least impacted by data removal overall, with about a third of populations removed (Table 1), compared to 38.5% of freshwater (Table S3) and 42.6% of marine populations (Table S4). However, 78.8% of terrestrial Neotropical populations are removed as a result of the modifications (Table 1) and given that this is the most heavily weighted realm in the terrestrial LPI, the effect on the trend is striking whereby the index changes from a negative to a positive trend overall (Figure S1). The more tropical biogeographic realms (Afrotropical, Neotropical, Indo-Pacific) are more heavily impacted proportionally than the more temperate realms (Nearctic and Palearctic) among both terrestrial (Table 1) and freshwater (Table S3) populations. Amongst marine populations, 74.9% of populations are removed from the Atlantic tropical and sub-tropical realm and 48.4% from the Tropical and sub-tropical Indo-Pacific realm, greater proportions than the temperate or polar realms (Table S4).

Our concern about the removal of populations in this way are two-fold. Firstly, the disproportionate removal of data from tropical realms, which have higher weight in the LPI, result in a large impact on the trends, especially in the terrestrial LPI. Secondly, and more importantly, removing these populations severely diminishes the evidence base for the most biodiverse regions on the planet and in our view, their exclusion is therefore not justified.

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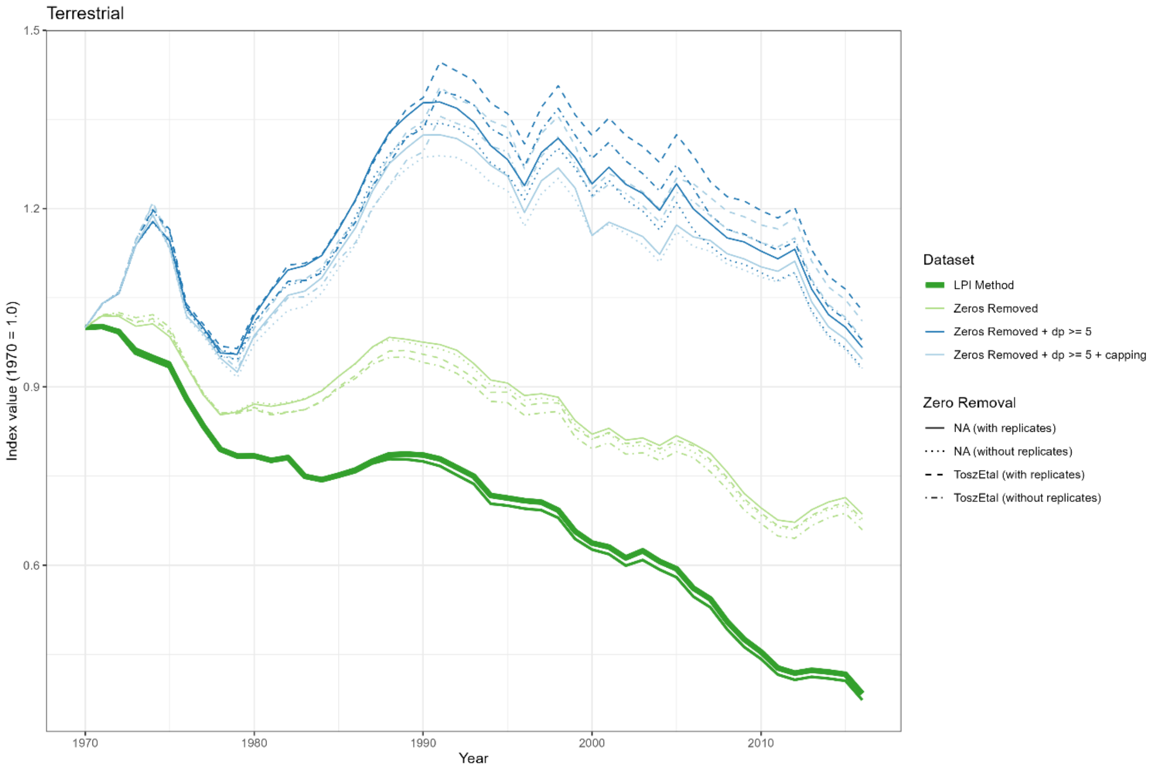
Extended data for ‘Maximising time-series inclusion reduces geographic and taxonomic biases in the Living Planet Index’.


Terrestrial
1.5
1.2
0.9
0.6
Index value (1970 = 1.0)
1970
1980
1990
2000
2010
Year
Dataset
LPI Method
Zeros Removed
Zeros Removed + dp >= 5
Zeros Removed + dp >= 5 + capping
Zero Removal
NA (with replicates)
NA (without replicates)
ToszEtal (with replicates)
ToszEtal (without replicates)


Freshwater
1.0
0.5
Index value (1970 = 1.0)
1970
1980
1990
2000
2010
Year
Dataset
LPI Method
Zeros Removed
Zeros Removed + dp >= 5
Zeros Removed + dp >= 5 + capping
Zero Removal
NA (with replicates)
NA (without replicates)
ToszEtal (with replicates)
ToszEtal (without replicates)

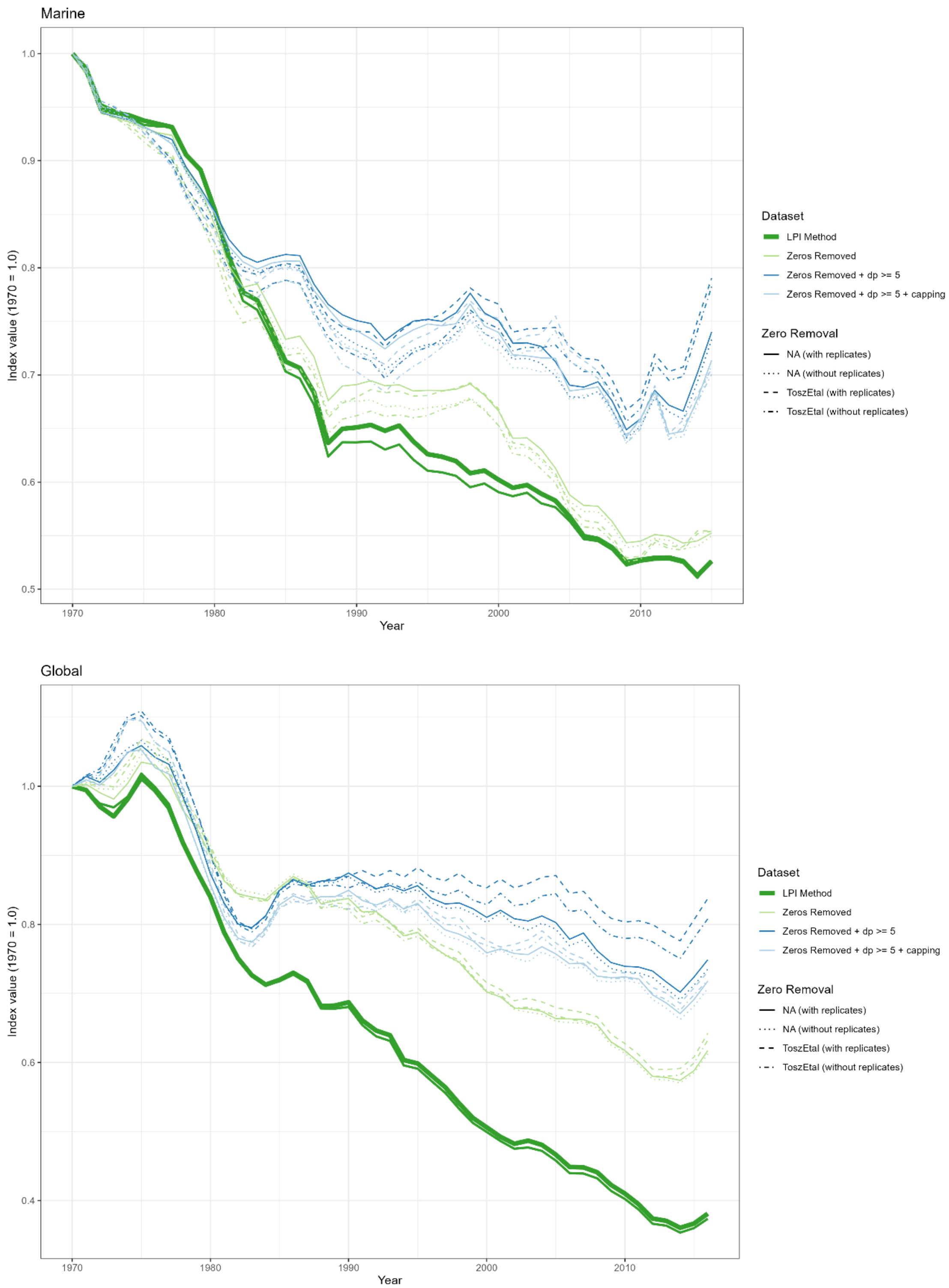


Figure S1 **Comparing the modified method as recommended by Toszogyova et al with (medium blue, light blue) and without (light green) the removal of time-series with fewer than 5 data points. Results are shown with the capping setting on (light blue) and with replicates excluded (dotted and dot-dashed), treating zeros as missing values without splitting time-series which contain zeros in the middle ("NA"; solid line), and treating zeros as missing values with splitting time-series (ToszEtal; dashed line). These are all compared to the current LPI method where 1% of the mean of a time-series which contains a zero value is added to every value in that time-series, with (bold green) and without (green) replicates. See also Table S2 for interpretation.**

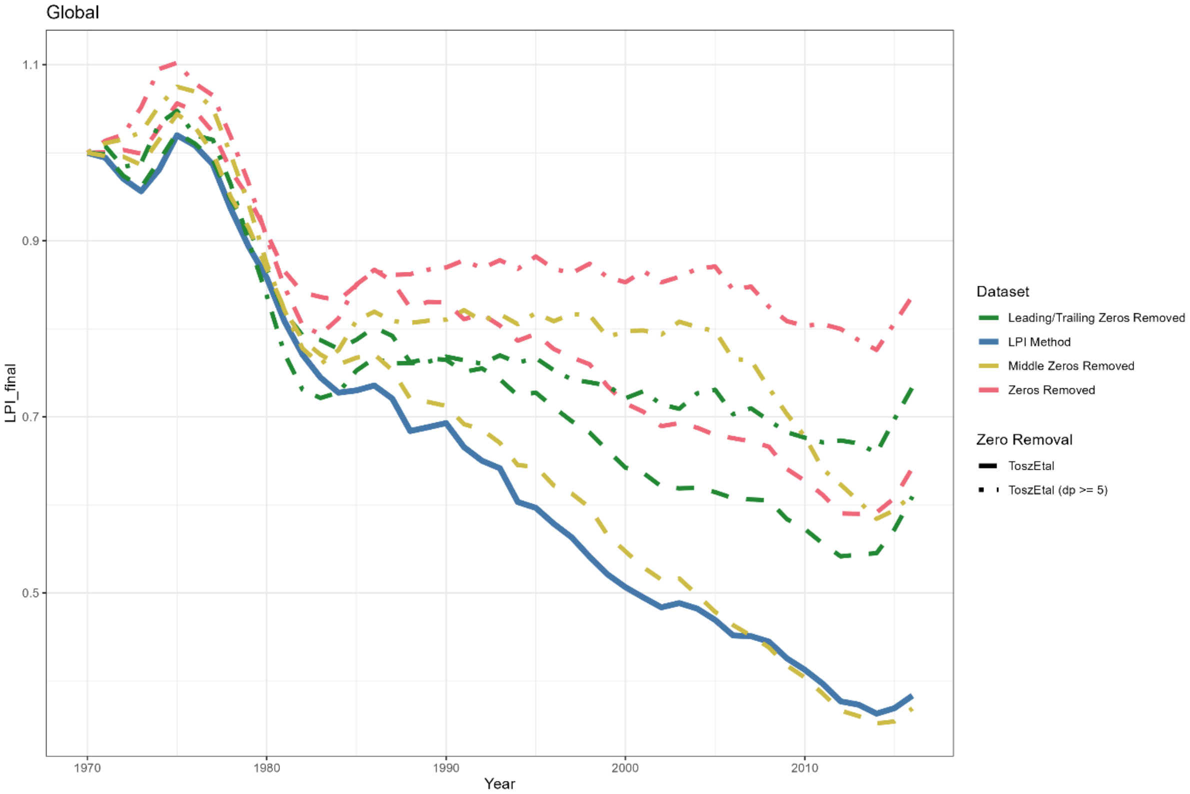
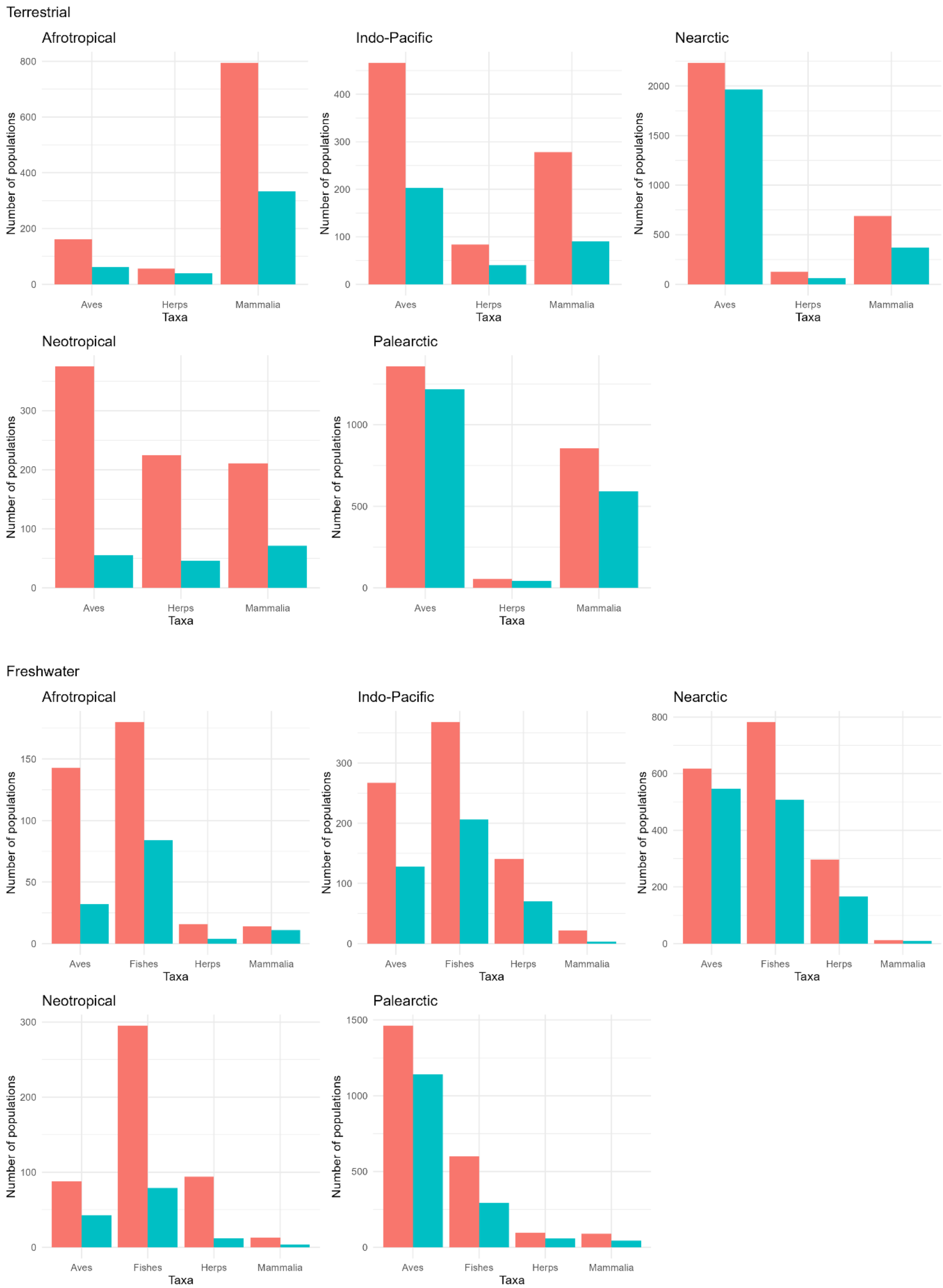


Figure S2. The influence of position within the time-series on the removal of zero values from the global LPI. The three zero treatments are all zeros removed (red), only leading or trailing zeros removed (green) and only middle zeros removed (yellow). The impact of removing time-series with fewer than 5 data points from the index is shown with all time-series included (dashed) and with time-series of fewer than 5 data points removed (dot dashed). The original LPI is shown by the solid blue line.


Terrestrial
Afrotropical
Indo-Pacific
Nearctic
Neotropical
Palearctic
Freshwater
Afrotropical
Indo-Pacific
Nearctic
Neotropical
Palearctic
Number of populations
Taxa
Aves
Fishes
Herps
Mammalia

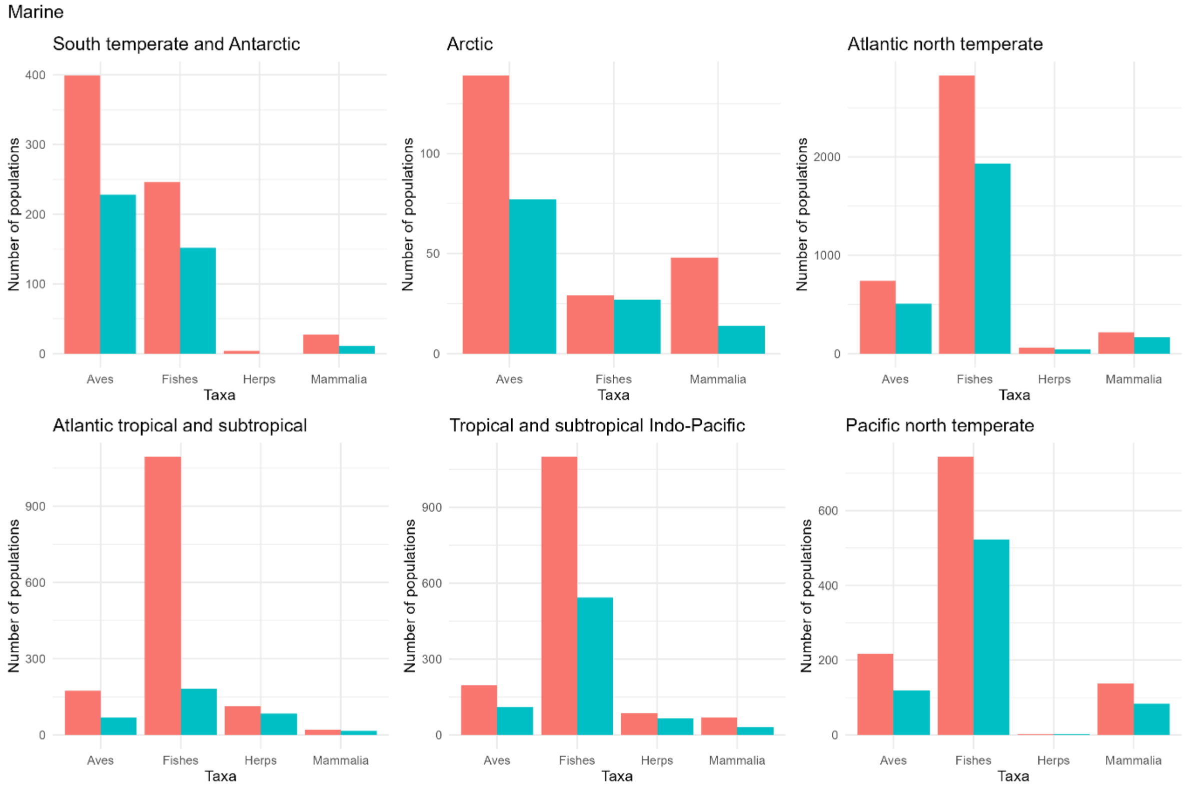


Figure S3 The number of populations in each taxa-realm subset in the original LPI data set (orange) and the amended data set (treating all zeros as missing values, splitting time-series containing zero values in the middle into fragmented time-series and removing time-series with fewer than 5 data points) in Toszogyova et al (green). See also Table 1 and Tables S3-S4

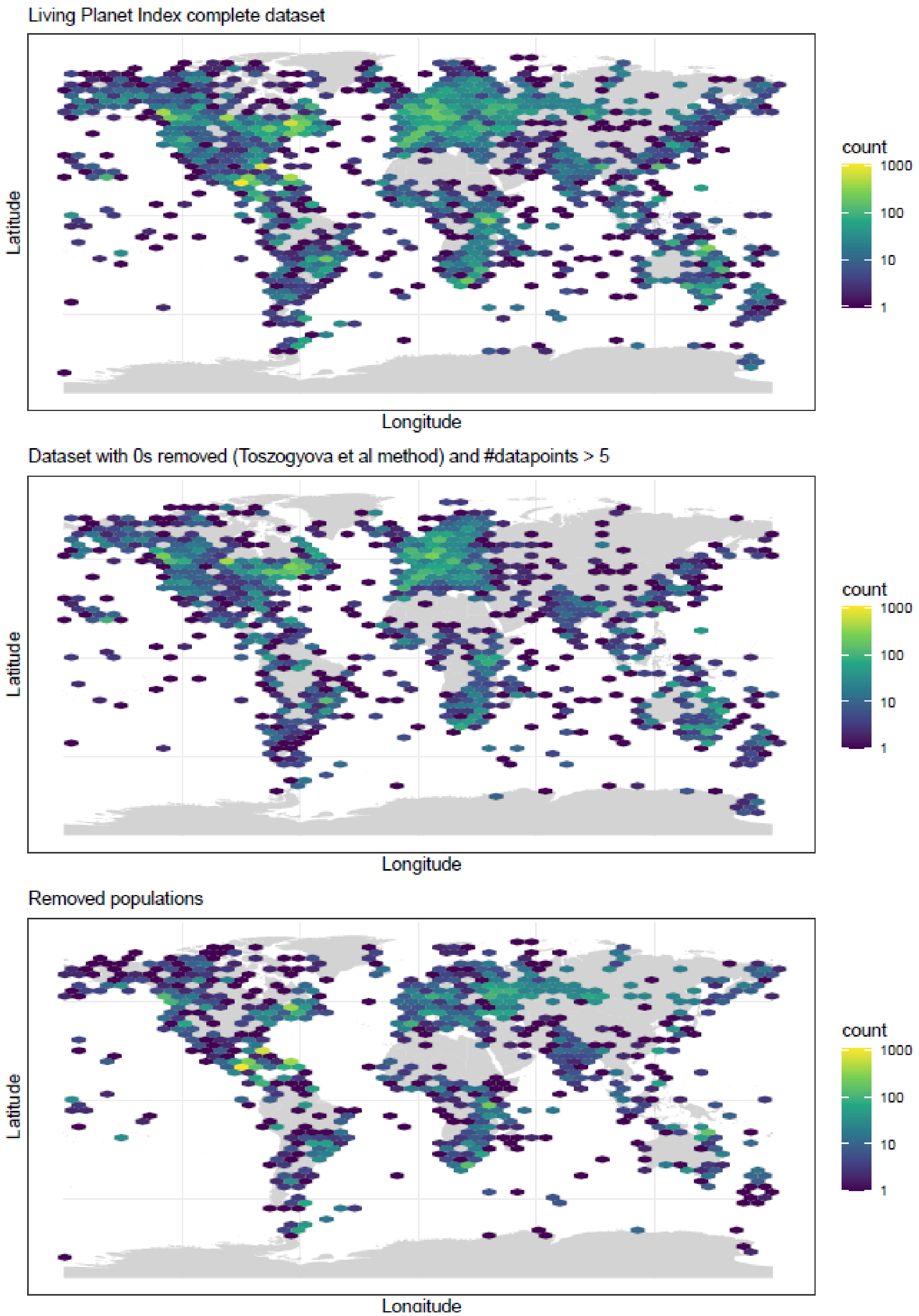


Figure S4. Density of population time-series in the original LPI data set (top), the amended data set in Toszogyova et al (middle) and the removed populations (bottom).

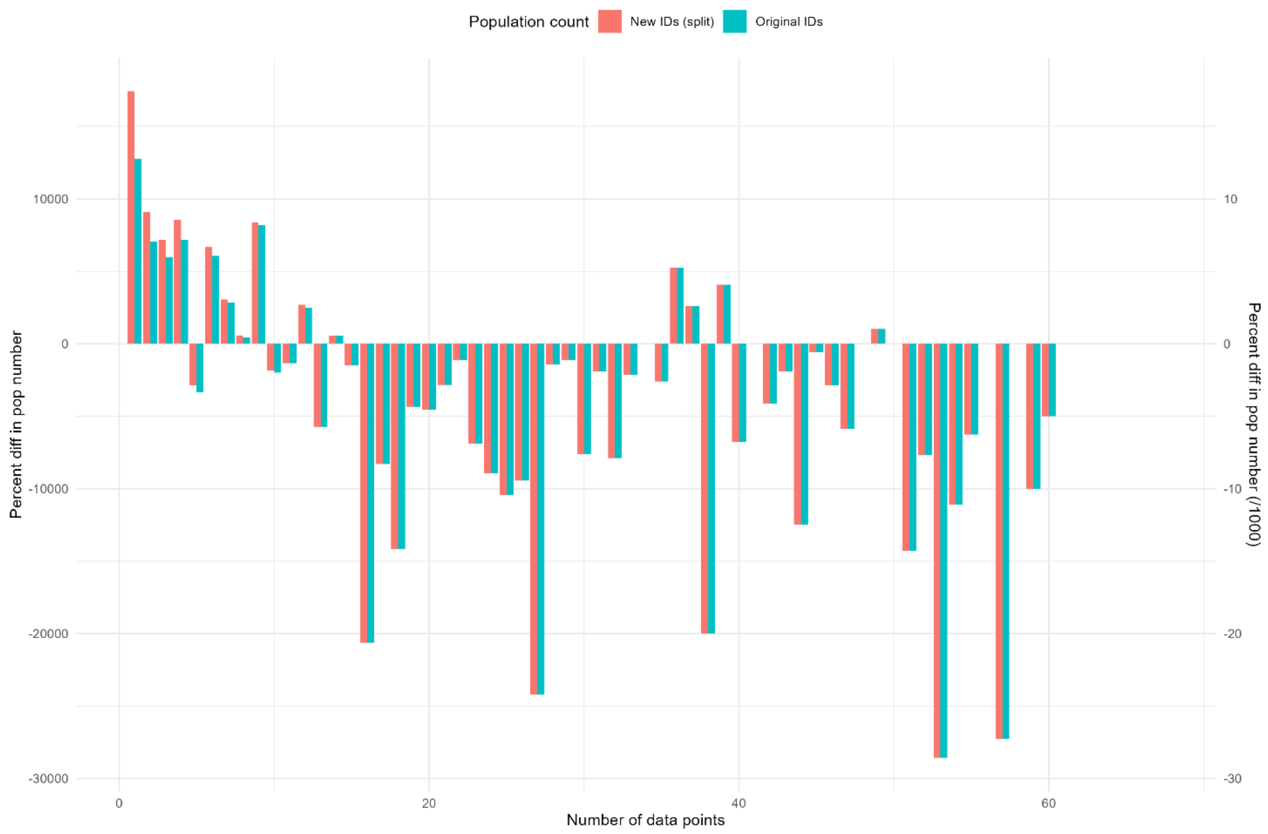


Figure S5 The percentage change in the number of populations in each data point category, from 1 to 60, after the zero-removal process from Toszogyova et al (treating zeros as missing values and splitting time-series with middle zeros). The series show the change in the original number of populations (green) and the change including the new populations created after splitting (orange). Values for 1 data point relate to the primary y axis, all other values relate to the secondary y axis.

Table S1 The number of populations and species used in Toszogyova et al (top) and this study (bottom). The dataset from this study contains 13 more species and 98 more populations than the Toszogyova et al dataset.

Toszogyova et al						
	Terrestrial		Freshwater		Marine	
	populations	species	populations	species	populations	species
Mammals	2797	554	149	25	517	69
Birds	4587	1155	2575	341	1862	251
Herptiles	536	323	642	218	267	15
Fish			2219	582	6024	1244
Totals	**7920**	**2032**	**5585**	**1166**	**8670**	**1579**

This study						
	Terrestrial		Freshwater		Marine	
	populations	species	populations	species	populations	species
Mammals	2834	556	163	26	517	69
Birds	4595	1162	2577	341	1864	251
Herptiles	546	324	643	218	267	15
Fish			2226	583	6041	1245
Totals	**7975**	**2042**	**5609**	**1168**	**8689**	**1580**

Table S2 The final index value in 2016 and difference to the original global LPI for each of the 14 approaches to this analysis. The impact of zero removal, including replicates and capping are highlighted in the comments.

Result #	Name	Index value (2016)	1-Index value	% change (decline)	Difference to original global LPI	Difference to other results - comment
1	LPI	0.38	0.62	61.90	0.00	
2	LPI (no replicates)	0.37	0.63	62.64	-0.74	Removing replicates from the global LPI (1) leads to a very small, more negative difference <1%
3	Toszogyova et al	0.64	0.36	35.77	26.12	Removing 0s by splitting leads to final estimate which is 26% less negative than (1)
4	Toszogyova et al (dp>=5)	0.84	0.16	16.26	45.64	Removing 0s by splitting and removing time-series with few data points leads to final estimate which is 46% less negative than (1)
5	Toszogyova et al (dp>=5 with capping)	0.73	0.27	26.89	35.01	Capping reduces impact of (4) by ~9%
6	Toszogyova et al (no replicates)	0.63	0.37	36.77	25.13	Removing replicates reduces impact of (3) by ~1%
7	Toszogyova et al (dp>=5, no replcates)	0.81	0.19	19.19	42.71	Removing replicates reduces impact of (4) by ~ 3%
8	Toszogyova et al (dp>=5, no replcates, with capping)	0.72	0.28	28.07	33.82	Removing replicates and capping reduces impact of (4) by ~12%
9	0s replaced with NAs	0.62	0.38	38.29	23.61	Removing 0s by replacing with NA leads to final estimate 24% less negative than the original LPI (1)
10	0s replaced with NAs (dp>=5)	0.75	0.25	25.12	36.77	Removing 0s by replacing with NA and removing time-series with fewer data points leads to final estimate 37% less negative than the original LPI (1)
11	0s replaced with NAs (dp>=5, capping)	0.72	0.28	28.22	33.67	Capping reduces impact of (10) by ~3%
12	0s replaced with NAs (no replicates)	0.61	0.39	38.74	23.16	Removing replicates reduces impact of (9) by ~1%
13	0s replaced with NAs (dp>=5, no replicates)	0.74	0.26	26.48	35.41	Removing replicates reduces impact of (10) by ~ 1.5%
14	0s replaced with NAs (dp>=5, no replicates, capped)	0.71	0.29	29.30	31.74	Removing replicates and capping reduces impact of (10) by ~4%

Table S3. Impact of removal of populations from freshwater taxa and realm subsets following the modified method recommended by Toszogyova et al (treating all zeros as missing values, splitting time-series containing zero values in the middle into fragmented time-series and removing time-series with fewer than 5 data points). See also Figure S3

		Aves	Fishes	Herptiles	Mammalia	**Total**
Original data set	Afrotropical	143	180	16	14	**353**
	Indo-Pacific	267	368	141	22	**798**
	Nearctic	618	782	296	13	**1709**
	Neotropical	88	295	94	13	**490**
	Palearctic	1461	601	96	90	**2248**
	Total	**2577**	**2226**	**643**	**152**	**5598**
Amended data set	Afrotropical	32	84	4	11	**131**
	Indo-Pacific	128	206	70	3	**407**
	Nearctic	547	508	167	10	**1232**
	Neotropical	43	79	12	4	**138**
	Palearctic	1140	293	57	44	**1534**
	Total	**1890**	**1170**	**310**	**72**	**3442**
Percentage of populations removed	Afrotropical	77.6	53.3	75.0	21.4	**62.9**
	Indo-Pacific	52.1	44.0	50.4	86.4	**49.0**
	Nearctic	11.5	35.0	43.6	23.1	**27.9**
	Neotropical	51.1	73.2	87.2	69.2	**71.8**
	Palearctic	22.0	51.2	40.6	51.1	**31.8**
	Total	**26.7**	**47.4**	**51.8**	**52.6**	**38.5**

Table S4. Impact of removal of populations from marine taxa and realm subsets following the modified method recommended by Toszogyova et al (treating all zeros as missing values, splitting time-series containing zero values in the middle into fragmented time-series and removing time-series with fewer than 5 data points). See also Figure S3

		Aves	Fishes	Herptiles	Mammalia	**Total**
Original data set	South temperate and Antarctic	399	246	4	27	**676**
	Arctic	139	29	-	48	**216**
	Atlantic north temperate	740	2828	62	215	**3845**
	Atlantic tropical and subtropical	173	1094	113	21	**1401**
	Tropical and subtropical Indo-Pacific	196	1100	86	68	**1450**
	Pacific north temperate	217	744	2	138	**1101**
	Total	**1864**	**6041**	**267**	**517**	**8689**
Amended data set	South temperate and Antarctic	228	152	0	11	**391**
	Arctic	77	27	-	14	**118**
	Atlantic north temperate	509	1930	41	166	**2646**
	Atlantic tropical and subtropical	70	182	84	15	**351**
	Tropical and subtropical Indo-Pacific	109	544	64	31	**748**
	Pacific north temperate	119	522	2	83	**726**
	Total	**1112**	**3357**	**191**	**320**	**4980**
Percentage of populations removed	South temperate and Antarctic	42.9	38.2	100.0	59.3	**41.6**
	Arctic	44.6	6.9	-	70.8	**45.4**
	Atlantic north temperate	31.2	31.8	33.9	22.8	**31.2**
	Atlantic tropical and subtropical	59.5	83.4	25.7	28.6	**74.9**
	Tropical and subtropical Indo-Pacific	44.4	50.5	25.6	54.4	**48.4**
	Pacific north temperate	45.2	29.8	0.0	39.9	**34.1**
	Total	**40.3**	**44.4**	**27.0**	**38.1**	**42.6**