Sources of confusion in global biodiversity trends

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Abstract

Populations and ecological communities are changing worldwide, and empirical studies exhibit a mixture of either declining or mixed trends. Confusion in global biodiversity trends thus remains, while assessing such changes is of major social, political, and scientific importance. Part of this variability may arise from the difficulty to reliably assess global biodiversity trends. Here, we conducted a literature review of studies documenting the temporal dynamics of global biodiversity. We classified the differences among approaches, data and methodology used by the reviewed papers to reveal common findings and sources of discrepancies. We show that reviews and meta-analyses, along with the use of global indicators, are more likely to conclude that trends are declining. On the other hand, the longer the data are available, the more nuanced are the trends they generate. Our results also highlight the lack of studies providing information on the impact of synergistic pressures on a global scale, making it even more difficult to understand the driving factors of the observed changes and how to decide conservation plan accordingly. Finally, we stress the importance of taking into account the sources of confusion identified, as well as the complexity of biodiversity changes, in order to implement effective conservation strategies. In particular, biodiversity dynamics are almost systematically assumed to be linear, while non-linear trends are largely neglected. Clarifying the sources of confusion in global biodiversity trends should strengthen large scale biodiversity monitoring and conservation.

Introduction

Providing a coherent synthesis of the ongoing biodiversity crisis through the quantification of various aspects of temporal changes of biological diversity is a challenge of both scientific and political importance. The accumulation of studies reporting a loss of biodiversity, either in species number (IUCN, 2019), population abundances (WWF, 2022) or at the assemblage or community scale (Mckinney & Lockwood, 1999; Olden et al., 2004; Sax & Gaines, 2003), leave no doubt regarding the fact that biodiversity is being depleted. However, empirical reports of temporal changes in biological diversity depict a nuanced and complex picture regarding the magnitude and direction of biodiversity loss, encompassing findings that may intuitively be seen as opposite. In addition to studies quantifying a global decline of biological diversity, others have suggested that biodiversity is not, on average, in decline (Blowes et al., 2019; Dornelas et al., 2014, 2019; Vellend et al., 2013). While highlighting a significant turnover in species composition, these analyses found no evidence of a systematic decline in species richness. Other recent studies revealed that only a few declining species were mostly responsible for the negative trends in overall indices (Leung et al., 2020), and demonstrated a rather balanced number of increasing and decreasing population trends worldwide (Daskalova et al., 2020; Dornelas et al., 2019).

These heterogeneities in results entails several risks if their sources and uncertainties are not addressed. Firstly, it could lead to sub-optimal or, worse, ineffective conservation policies, as many conservation measures rely on the estimation of indicators or discussion of scenarios covering global biodiversity trend for all taxa on a global scale (Agardy, 2005; Pressey et al., 2007). Furthermore, avoiding to question the sources of the heterogeneity of these results and the uncertainties in the conclusions could encourage a "biodiversity-skepticism" by creating the idea that there is a lack of scientific consensus on the existence of a biodiversity crisis. Similarly, climate-skepticism partly emerged from the belief that there were significant disagreements about global warming among scientists (Joslyn & LeClerc, 2016; Leiserowitz et al., 2013). Such distorted perception was reduced by incorporating uncertainties into IPCC reports, clarifying the fact that much of the variability was due to predictive processes rather than fundamental differences in scientific opinion (Howe et al., 2019; Reilly et al., 2001). Thus, conservation science and knowledge on biodiversity loss should also benefit from such clarification and be consolidated by adopting a transparent and quantitative approach to major biases in the global estimates.

If these heterogeneous results have also caused a vivid controversy in the scientific community (Cardinale, 2014; Cardinale et al., 2018; Gonzalez et al., 2016), it is to some extent probably resulting from the multiple meanings of the term *biodiversity*. The formal definition largely popularized by the Rio Earth Summit in 1992 equates biodiversity to "the variability among living organisms from all sources […] this includes diversity within species, between species and of ecosystems" (CBD, 1992). This definition itself creates a lot of confusion (Díaz & Malhi, 2022; Mammola et al., 2023). For example, the WWF considers biodiversity at the population level (WWF, 2020, 2022). In contrast, others (e.g. Dornelas et al., 2014) consider biodiversity at the species or community level. As declines in population sizes and species richness are not necessarily related, both an increase and decrease in “biodiversity” can be concluded depending on the ecological level of interest. Clarifying the trends for each level of biodiversity should, in principle, limit the confusion. In practice however, trends within the same ecological levels show both a decline globally or no net changes; either at species scale (IUCN, 2019; Dornelas et al., 2014; Vellend et al., 2013) or at population scale (Daskalova et al., 2020; He et al., 2019; Leung et al., 2020; Wagner et al., 2021). Beyond the ecological level considered other factors are therefore also generating confusion in the observed results.

The same difficulties affect the understanding of which and how environmental and anthropogenic pressures drive temporal changes of biodiversity on a global scale. The drivers of biodiversity loss are widely documented (Ceballos et al., 2015; IPBES, 2019; Pereira et al., 2012; Pievani, 2014; Pimm et al., 2006). The effects of climate change and of other anthropogenic drivers – e.g. habitat fragmentation – have been studied at the individual level – e.g. through changes in physiology (Willis & Bhagwat, 2009) –, at the species and population levels, or at the community level – e.g. through changes in interspecific relationships (Gilman et al., 2010; Walther, 2010) –, or either spatially – e.g. through range shifts (Erauskin-Extramiana et al., 2020; Paprocki et al., 2014) –, or temporally – e.g. through changes in phenology (Du et al., 2019; Radchuk et al., 2019; Wolf et al., 2017). However, the responses of different ecological levels to specific drivers are mostly documented at the local scale. The understanding of how global change drivers influence the heterogeneous biodiversity patterns at the global scale is therefore also limited, and filled with controversies. For instance, some studies suggest that habitat fragmentation may be beneficial to biodiversity (Fahrig, 2017; Haddad et al., 2017) or that protected areas often fail to reduce biodiversity loss (Brooke et al., 2008; Mora & Sale, 2011) and can even be detrimental to biodiversity (Geldmann et al., 2019).

Acknowledging our current sources of (mis)understanding of the temporal changes of biodiversity and of their drivers at the global scale is urgently needed (Tekwa et al., 2023). International legislation and objectives (such as those discussed at United Nations Biodiversity Conference of the

Parties) directly rely on our general knowledge and understanding of global biodiversity dynamics. The objective of this study is therefore to critically examine this general knowledge. More specifically, we want to review how global biodiversity change is currently quantified, and to identify the most salient sources of confusion when assessing biodiversity trends or the effect of its drivers.

Several hypotheses can be formulated. First, with regard to trends, the data used can be expected to affect the results. The prevalence of certain threatened groups (Houlahan et al., 2000; Marsh, 2001), the lack of spatial representation (e.g. tropics are highly biodiverse (Laurance, 2007) but lack data representation (Feeley & Silman, 2011)), or the temporal extent of the time series used (Duchenne et al., 2022; Gonzalez et al., 2016; Vellend et al., 2013) are likely to impact the conclusions. We also hypothesise that the methods with which trends are quantified play a role. Several studies have already pointed out that summarizing complex data using global indicators can hide meaningful variation (Daskalova et al., 2020; Leung et al., 2020), but it is not clear to what extent and whether this is the case for other methods. Finally, different approaches, from meta-analyses and reviews of local studies to the analysis of globally aggregated empirical data, might also affect the conclusions.

Regarding the influence of drivers, we also expect that the biodiversity data used impact the results. Focusing research on specific areas of the world can bias our knowledge. For example, the Arctic is projected to warm at two up to four times the rate of the global average but it is understudied (IPCC, 2021). A patchy data collection across taxa (or periods) also risks missing particularly (un)sensitive groups (or (un)stable periods) (Mihoub et al., 2017). Variations are also expected depending on the approach, the methods and the drivers considered.

Here, we conduct a literature review to clarify those sources of confusion, and to review the remaining challenges for future research and conservation science.

Methods

Literature review

We conducted a literature review aiming to identify papers providing an assessment of recent temporal changes of biodiversity globally. We were looking both for papers that studied the changes themselves, but also those that sought to explain the changes by studying the impact of the drivers. Different searches were initially launched in the *Web of Science*. We tested different search terms to refine the results. We wanted to minimise the number of irrelevant references while ensuring that some commonly known relevant articles (e.g. Dornelas et al., 2019) fell within our scope. In the process, we identified broad terms (e.g. "population") that encompassed areas of research beyond our topic. We also found that restricting the search to terms in the titles and abstracts, rather than in the topics of the articles in general, allowed us to limit the search to a manageable number of articles (Appendix S1). The final search we launched in the *Web of Science* on the 08/03/2022 under the institution of the University of Montpellier was thus: TI=((biodiversity OR population* OR communit* OR indicator* OR natur* OR richness OR species OR "biological diversity" OR abundance OR assemblage OR *flora OR *fauna) AND (trend* OR dynamic* OR "time series" OR declin* OR loss OR extinct* OR increas* OR gain OR coloni* OR change* OR fluctuat* OR trajector* OR tempo*)) AND AB=(("temporal" OR time) AND ("analys*" OR "model*" OR stud* OR quantifi*)) NOT TI=("human population" OR "urban population") AND (TI=(global OR worldwide) OR AB=(global OR worldwide)) NOT WC=("meteorology atmospheric sciences" OR "infectious disease" OR "biochemistry molecular biology" OR "paleontology" OR "microbiology"). TI is title, AB is abstract and WC is Web of Science Categories. This query resulted in 2,008 matches.

Each of these papers was then reviewed individually by titles, abstracts and then subjected to a full review to check their relevance to our study objective. We included studies that either assess or discuss the assessment of (i) temporal changes of biodiversity ; (ii) during the last century ; (iii) on a broad scale (at least two continents or two oceans) and (iv) at population, species and/or community level. We included studies analysing temporal changes on biodiversity relying on empirical data, but also reviews based on empirical assessments as well as methodological studies explicitly questioning the assessment of global biodiversity changes. For studies relying on data, we excluded those using exclusively human-manipulated or simulated data. We also excluded studies on functional, phylogenetic and network diversity as these levels of biodiversity do not suffer from the same confusions in the assessment of the changes, these were thus not the levels we aimed to target. Figure 1A summarises this selection process and shows the number of articles excluded on the basis of their failure to meet the above criteria. In addition, we included four reports from the ‘Grey literature’ (IPBES, 2019; *IUCN, 2022*; Pörtner et al., 2021; WWF, 2020), produced by organisations among the best known that provide assessments of temporal changes of biodiversity globally. 91 references constituted the final database, that we classified into four different categories: (i) biodiversity empirical analysis (n=48) ; (ii) reviews (n=20) ; (iii) methodological papers (n=19) ; (iv) reports (n=4).

Metadata extraction

Methodological papers were considered for discussion purposes. For the other references, we extracted detailed metadata and information to investigate potential sources of heterogeneities regarding the Global Biodiversity Changes (Fig. 1B). We distinguished papers mostly focused on biodiversity trends from those mostly focused on drivers. Papers mostly focused on drivers were those considering only the effect of drivers without concluding particularly on how biodviversity was changing. On the contrary, some papers were studying both trends and drivers, giving valuable insigths in their conclusions regarding global biodiversity changes. These were considered both for analysing trends but also for analysing drivers, as we analyzed these issues separately (n=6).

For papers analyzing biodiversity trends, we recorded bibliometric data, the main conclusions, the type of assessment approach, and, when relevant, information regarding the data and methods used to quantify the changes (Fig. 1B). Conclusions were classified into decreasing trends, increasing trends**,** mixed trends (i.e. there were as many increasing trends as decreasing, or a majority of no trends) and factor-dependent trends (i.e. directions that varied according to certain factors, such as location).

While retrieving those information, we identified two main assessment approaches adopted in the corresponding studies to produce a global picture of biodiversity changes. First, a bottom-up approach, which correspond to reviews or meta-analyses aggregating results of studies analyzing individual datasets with varying methodologies from one study to the other (e.g. Pereira et al., 2012; Pievani, 2014). Second, a top-down approach that produces a global result analyzing heterogeneous data aggregated in large databases within the same methodological framework (e.g. Dornelas et al., 2019; Wilson & Fox, 2021). We recorded the assessment approach for each reference and decided to investigate to what extent these could explain part of the observed heterogeneous results.

When relevant and available, we also retrieved information on the data used, the ecological level targeted and the methodological processes used to quantify the changes. We recorded the databases used, temporal scope, taxonomic scope, and number of species. The time span was often expressed through the length of the longest time series, which is why we expressed it through broad categories (less than 30 years; between 30 and 50 ; more than 50 years) rather than exact numbers. The taxonomic scope was entered as a list of groups among the following: mammals, birds, amphibians, reptiles, fishes, invertebrates, plants (or unknown when not specified). We then categorized the papers into groups regarding the number of taxa that were assessed (1 taxa; 2-3 taxa; 4 + taxa).

There are many measures of biodiversity, but in the papers selected we found measures of biodiversity at the population scale (abundance, density or biomass), at the species scale (mostly species richness), and at the community scale (assemblage composition, studied through similarity indices).

We categorised the methods used to quantify the changes into three main categories. The first category we identified concerns papers that studied the changes through linear trends of individual ecological level. These papers performed linear regressions (and all variations, e.g. state space models (Daskalova et al., 2020) or logged annual growth rate (Williams et al., 2022)) on biodiversity measures either population by population or species by species. These results were then used to reach conclusions about the general direction of change. We will refer to these methods as "linear models on individual time series". The second category we identified corresponds to papers producing global indicators built upon populations (e.g. Living Planet Index (LPI) (Loh et al., 2005)) or species (e.g. Red List Index (RLI)), and estimating global trends of those single aggregated metrics. The last category we identified are the other methods that were used more sporadically, quantifying other aspects than the linear changes in abundance or species richness (e.g. quantifying the coefficient of variation (Marsh, 2001), non-linear changes (Keith et al., 2015), or other aspects like resistance and recovery (Capdevila et al., 2022)).

For papers analyzing drivers of biodiversity changes, we recorded bibliometric data, the main conclusions, the type of assessment approach, and, when relevant, information regarding the biodiversity data used and the identity of the studied drivers (Fig. 1B). Conclusions were classified into different categories based on the nature of the impacts into negative, none or positive, and factor-dependent. The assessment approaches and information regarding the biodiversity data were the same as the ones described regarding the examination of the trends in biodiversity. The information provided on the drivers and the methods used to quantify the drivers' impacts on biodiversity was scarce and heterogeneous. As a result, we did not address the issue of the sensitivity of the results to the drivers data and methods used in depth. We rather examined the impact of the identity of the drivers studied. We categorized the drivers between climate change, other anthropogenic pressures (mainly land use change) and conservation policies (protected areas).

We performed chi square tests in order to test whether the conclusions drawn depended on either (1) the assessment approach, (2) the dataset used, (3) the number of taxonomic groups (split in qualitative categories), (4) the time span (split in qualitative categories), (5) the ecological level, and (6) either the methods or the identity of the studied drivers. We performed these tests both for the trends and the drivers assessments. All analyses were performed under R version 4.3.2.

Results

Global overview

Interestingly, we found only 91 papers that analyze temporal changes of biodiversity globally, while a plethora of examples accumulate at more local scales (e.g. Donald et al., 2001; Koleček et al., 2021). These were published from 1991 to 2021, with a majority published after 2010 (Appendix S2). We identified an increasing interest in this question over time, although this tendency also reflects an overall increase in the number of papers published during the same period. Of the 91 papers, 48 directly relied on empirical datasets, 20 were reviews, 19 were methodological papers and 4 were reports that we added from grey literature.

Out of the 44 papers assessing temporal trends in biodiversity changes, 57% (n=25) concluded that biodiversity is globally in decline. More than a third of the papers concluded that trends are mixed or factor-dependent (36%, n=16). Only 3 of the reviewed papers showed evidence of increasing biodiversity trends. Out of the 34 studies focusing on drivers, 65% (n=22) concluded negative effects on biodiversity, 26% (n=9) concluded that the effects were factor-dependent, and only 3 papers concluded that there was no significant effect or that the effect was positive (the latter referring to the effect of conservation plans only).

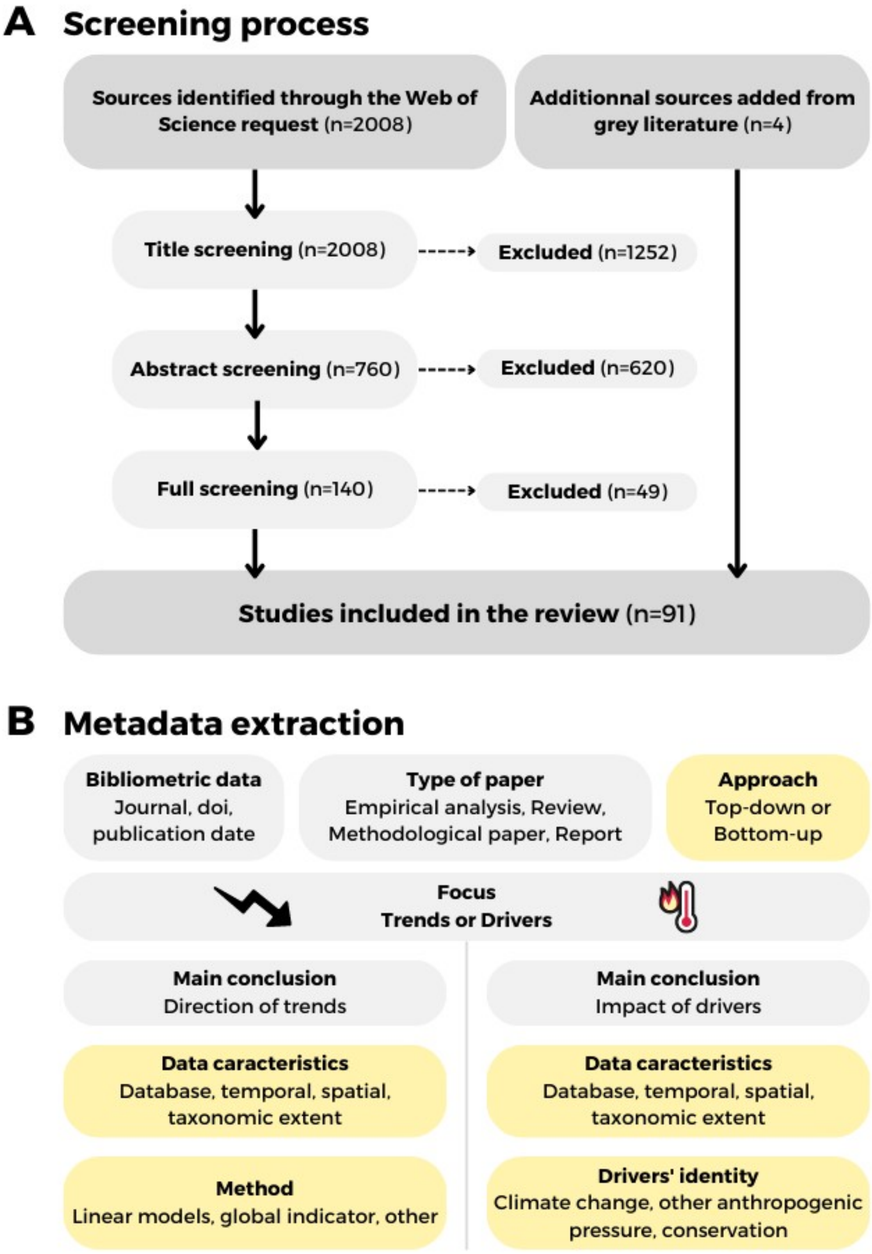

Figure 1. Summary of the sampled literature and extracted metadata. (A) Diagram representing the different steps of the screening process. List of studies extracted from the *Web of Science*, including excluded studies with reasons for exclusion are in the Appendix S3. (B) Summary of the metadata collected for the database. The potential sources of heterogeneities we investigate are highlighted in yellow.

Table 1. Overview of the different sources of data identified.

Data source	**Biotime** $(n_{tot}=7)$	**Living Planet Database (LPD)** $(n_{tot}=8)$	**Global Population Dynamics Database (GPDD)** $(n_{tot}=4)$	**Other*** $(n_{tot}=5)$	**Aggregation**** $(n_{tot}=30)$
Content	Time series data of ecological assemblages (mainly used at community *and* species level)	Time series data of individual species' abundance (mainly used at population level)	Time series data of individual species' abundance (mainly used at population level)	Time series data of several biodiversity measures (both species and population level)	Time series data of several biodiversity measures (mainly used at species *or* population level)
Taxa	Vertebrates, invertebrates and plants (8 in total)	Vertebrates (5 in total)	Vertebrates, invertebrates and plants (8 in total)	3 on average	3 on average
Realms	Marine, terrestrial and freshwater	Marine, terrestrial and freshwater	Marine, terrestrial and freshwater	Marine and terrestrial	Marine, terrestrial and freshwater
Average number of species	13,726 $(n_{calc}=6)$	847$(n_{calc}=8)$	424 $(n_{calc}=3)$	30,553 $(n_{calc}=3)$	2,905 $(n_{calc}=21)$

Description of the five types of encountered databases providing time series data on different biodiversity levels. n_{tot} represents the total number of articles considering each of the data source. n_{calc} represents the number of articles used to calculate the averages (without those whose information is unavailable).

* Single non-aggregated but marginal data sets (used in articles only once).

** Aggregation of several locally available data sets in individual studies.

Papers relying on empirical data in majority used aggregations of several data sets from individual studies (62,5%, n=30). Still, we found that three main global databases gathering biodiversity data were used: BioTIME (Dornelas et al., 2018), the Living Planet Database (LPD) (Loh et al., 2005), and the Global Population Dynamics Database (GPDD) (Inchausti & Halley, 2001). The remaining papers relied on other unique but more sporadically used databases that were not open access. Table 1 highlights the characteristics and properties of the different data sources. The overwhelming majority of papers were based on terrestrial data covering all continents (67%, n=32), which is not surprising since our selection process was based in part on the choice to have global studies. Still, we accepted articles covering at least two continents, and we note that the only continents that were studied in pair were America and Europe. The temporal coverage of the data was quite heterogeneous, but mainly covered the last 70 years (Fig. 2A). This also confirms the strength of BioTIME's temporal coverage compared to other databases (Dornelas et al., 2018). The taxonomic coverage shows that the papers in our corpus mainly relied on data referring to several groups (Fig. 2B). As well as for the geographical extent, this is not surprising considering our selection process. Still, there is a preponderance of data on mammals and birds, more generally on terrestrial vertebrates, and an under-representation of insects and invertebrates.

The empirical data were based on different levels of biodiversity (Fig. 2C). Papers relying on biodiversity at the population scale (e.g. abundances, biomass, density) represented 50% of our corpus (n=24), papers relying on biodiversity at the species scale (e.g. species richness, detection rates) represented 31% (n=15). The 19% (n=9) remaining relied on grouped levels, i.e. several levels among population, species, or also community scale (studied through community composition).

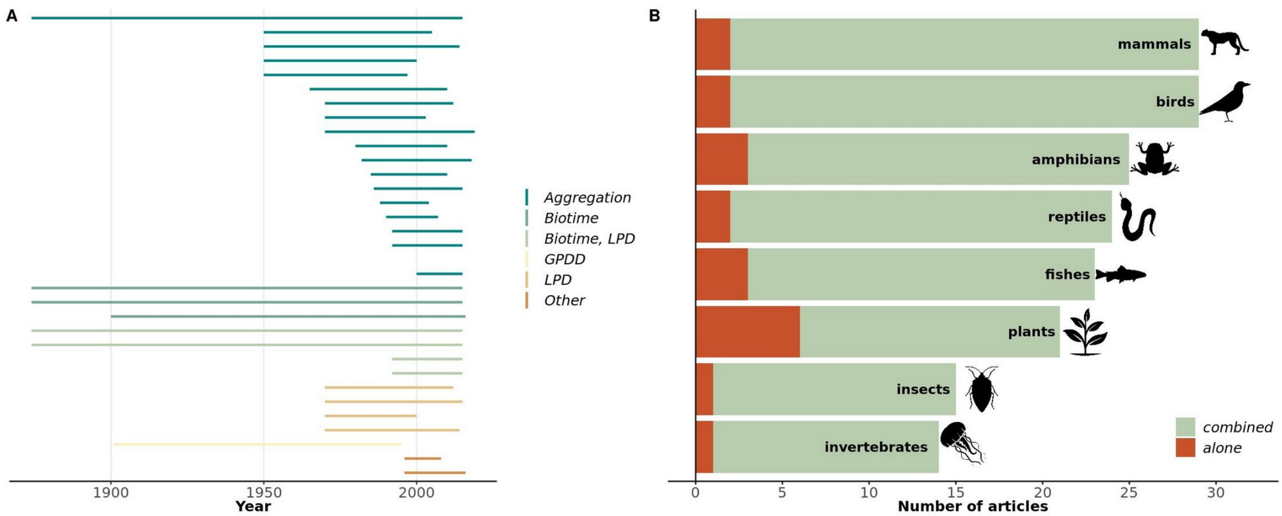

Figure 2. Information on the biodiversity data on which the reviewed papers are based. (A) Temporal extent of the data, colored based on the data source (see Table 1). (B) Taxonomic extent of the data. Number of papers considering each group, wheter considered alone or combined (i.e. when the study does consider several groups at a time). For instance, 2 papers were examining the fate of mammals only and 30 were examining the fate of mammals and other groups at the same time.

In the following, we describe how studies of global biodiversity change are distributed among several criteria. We performed formal statistical analysis using chi square tests to see how papers were distributed among groups. Only two of the tests were significant (the one regarding the impact of the assessment approach on the drivers impacts and the one looking at the identity of the drivers, see appendix S4 for details). However, the low amount of papers available for each single analysis call for cautious interpretations of these tests (see discussion).

Potential sources of heterogeneities in the assessment of biodiversity trends

We investigated three potential sources of heterogeneities. First, we examined the effect of using different assessment approaches. When papers used a bottom-up approach (i.e. aggregating local or regional results with varying methodologies into meta-analyses or reviews), they mostly concluded a decline in global biodiversity (69%, Fig. 3). In contrast, when papers used a top-down approach (i.e. performing analyses through a single methodology on global datasets), their conclusions were much more balanced: a bit more than 50% concluded that biodiversity was decreasing and almost 50% that trends were mixed or increasing (Fig. 3).

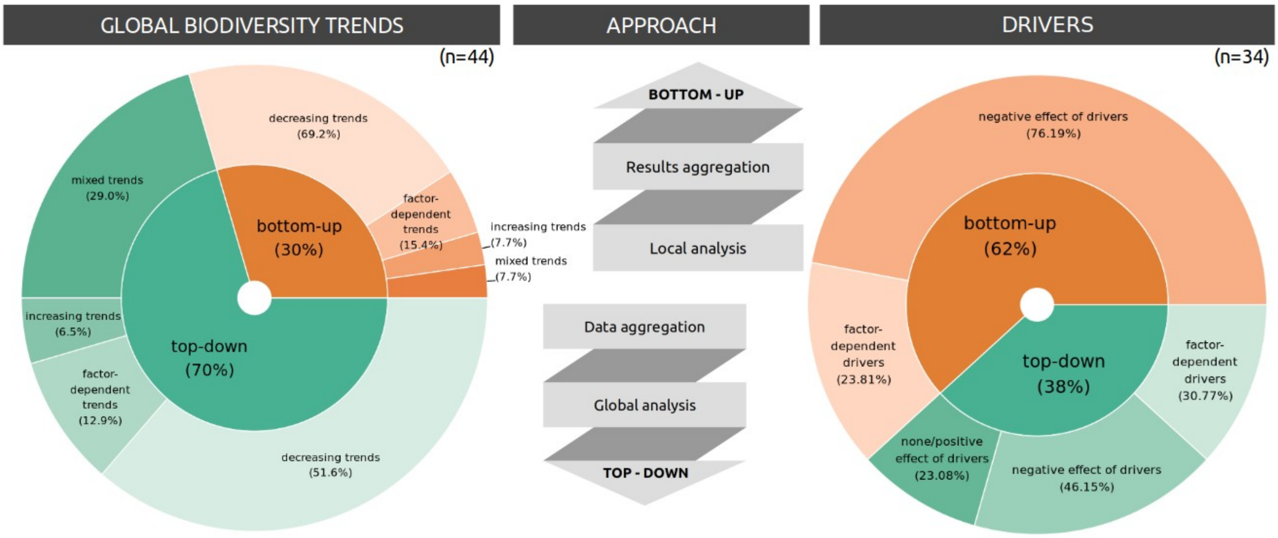

Figure 3. Proportions within conclusions depending on whether global biodiversity trends or drivers were assessed and depending on the assessment approach (i.e. top-down or bottom-up).

Second, we examined the effect of using data with different characteristics. Among the 22 papers using aggregated databases, 45% concluded a decline, 41% mixed or factor-dependent trends and 14% identified increases in biodiversity globally. The LPD and the other individual datasets were mainly associated with a decline in global biodiversity, whereas studies using the BioTIME database mainly concluded that trends were mixed or factor-dependent (Fig. 4A). The conclusions between declining or mixed trends were balanced no matter the number of taxonomic groups considered (Fig. 4A). The time span seemed to be influencing the conclusions however. The longer the data, the more heterogeneous the results were: 78% of articles based on time series of less than 30 years concluded that trends were declining, whereas this percentage dropped to 60% for time series between 30 and 49 years long, and to 22% for time series longer than 50 years.

Third, we examined the effect of using different methods. Among the 12 papers we reviewed that used global indicators to assess biodiversity changes, 9 concluded that biodiversity was declining, and only 3 that trends were more mixed. On the other hand, papers using linear models on individual time series depicted a much more nuanced picture, with 9 papers concluding that trends were mixed, 3 that trends were declining and 2 that trends were increasing. The other methods weren’t much represented but concluded declines in 4 papers out of 6. Papers focusing on the population level showed more declines than the ones focusing on the species level (67 % declines against 44 % declines respectively). The papers relying on several levels of biodiversity only concluded that trends were mixed. However, as Figure 4B illustrates, these conclusions seem to be highly driven by the underlying quantification methods. Indeed, declines identified at both species or population levels are in majority declines that are identified through the use of global indicators.

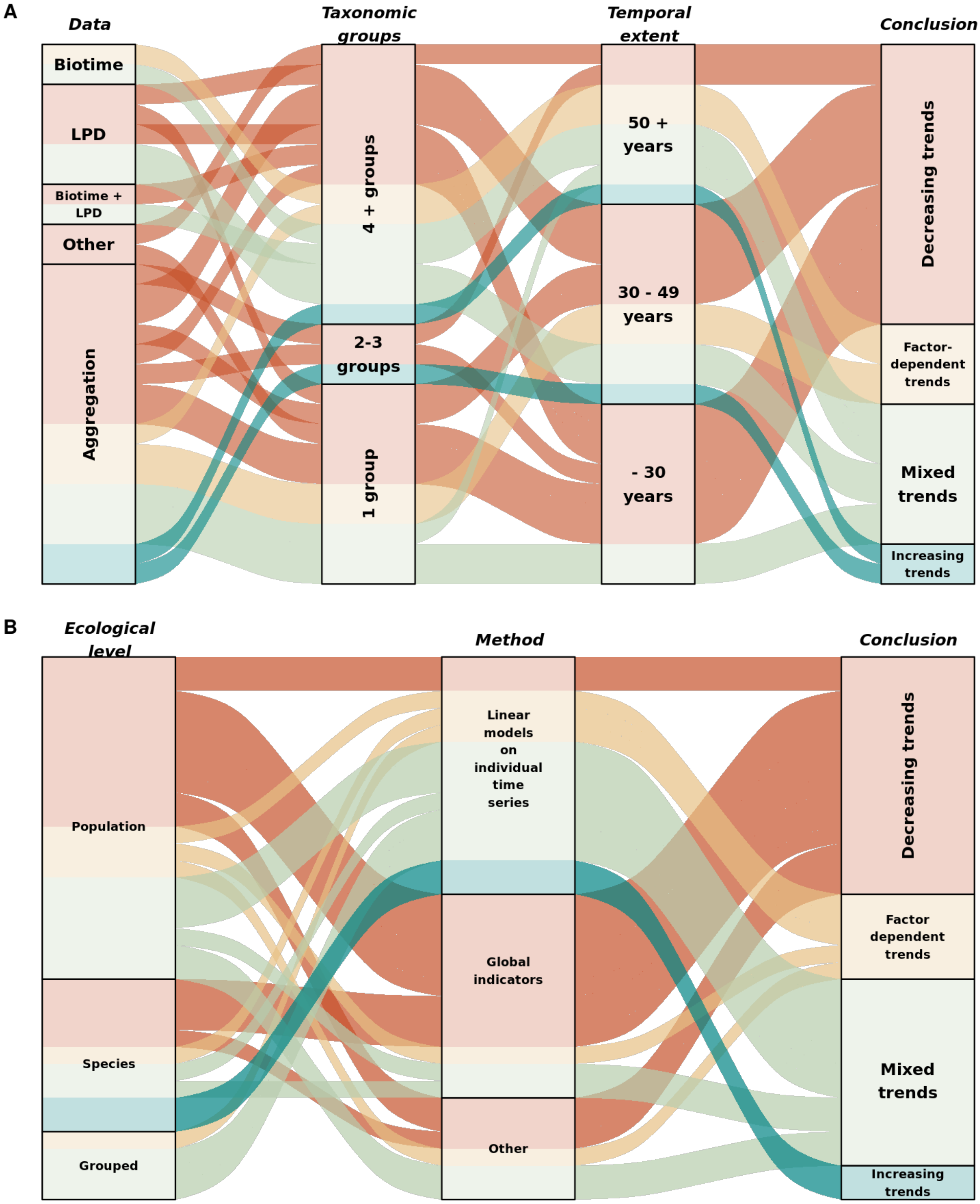

Figure 4. Alluvial plots representing the links between the potential sources of heterogeneity and the conclusions when assessing trends. A (n= 27) highlights the impact of the data characteristics. B (n=32) highlights the impact of the methods and the ecological level. The height of the boxes is proportional to the number of papers. Flow thickness between boxes is proportional to the number of papers. Colours of the flow reflect the conclusions.

Potential sources of heterogeneities in the assessment of biodiversity drivers

We also explored the effect of three potential sources of heterogeneities when assessing biodiversity drivers' impacts. First, we examined the effect of using different assessment approaches. Among the papers using a top-down approach, there was an almost even split between concluding a negative effect of the drivers considered on biodiversity (46%) and a factor-dependent or no effect (54%). In contrast, 76% of the papers using a bottom-up approach concluded that the drivers identified had a negative impact (Fig. 5).

The second source of heterogeneity we explored is related to the characteristics of biodiversity data that were used. Patterns regarding the impact of drivers did not clearly show a data bias (Fig. 5A), probably because of the very low number of papers for which enough information was available (n=9). Only papers using single and rarely used databases or aggregated databases (associated with poor taxonomic and temporal coverage) concluded that drivers did not have an effect on observed changes (n=2). The majority of papers (n=6), regardless of the data used, concluded that drivers had a negative impact on biodiversity.

The third source of heterogeneity we tested was the identity of the assessed drivers. We highlighted that only conservation measures had a positive effect on biodiversity. Climate change affected biodiversity mostly negatively, but conclusions were more nuanced concerning other anthropogenic drivers (Fig. 5B).

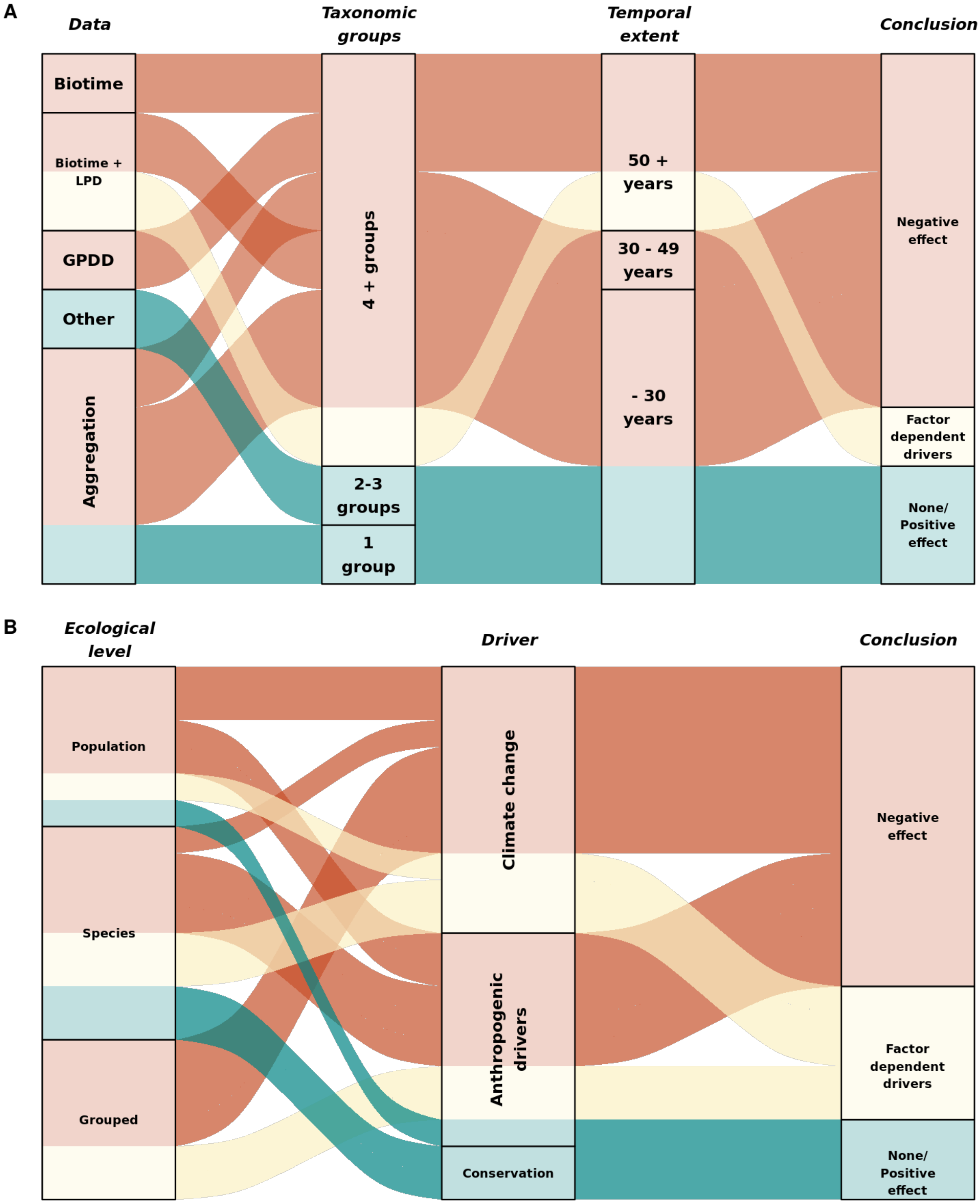

Figure 5. Alluvial plots representing the links between the potential sources of heterogeneity and the conclusions when assessing the impact of the drivers. A (n=9) highlights the impact of the data characteristics. B (n=20) highlights the impact of the biodiversity level and the identity of the drivers. The height of the boxes is proportional to the number of papers. Flow thickness between boxes is proportional to the number of papers. Colours of the flow reflect the conclusions.

Discussion

Quantification of temporal changes in biodiversity at large scales and attribution of drivers of these changes is a daunting task. Studies quantifying global declines are mixed with evidences of more heterogeneous changes, including declines, increases, and no net change at different levels of biological diversity. In a context of accelerated global change, clarifying and addressing these sources of heterogeneity in temporal changes of biodiversity is needed to inform conservation policies. Plus, far from weakening the knowledge on biodiversity loss, working on uncertainty is in fact the best way to consolidate what we know. Here, we explored how different methodological pathways to produce estimates of biodiversity changes likely influence the direction of trends in population abundance, species richness and community composition as well as the effect of the drivers of these trends. As our analysis is not based on a systematic review, we recognize that the coverage of the literature is probably not complete. Moreover, with the explosion of open databases worldwide, articles on this subject are accumulating very quickly (Appendix S2). Therefore, there might be a gap between the conclusions drawn by the corpus considered in this study and what will possibly be reflected by this very active field in the near future. However, the robustness of our methodology to target a broad range of papers within the initial query allows a certain degree of confidence regarding the conclusions we may currently draw in the present paper.

The number of papers found was quite surprisingly low and did not allow any advanced statistical analysis. However, the present review is not meant to be systematic nor to generate quantitative estimates, but is primarily conceptual. Yet, the non-significance of the chi-quared tests confirm the absence of dominating type of studies addressing global biodiversity changes (although the low sample sizes deserve cautious interpretation for some of the comparisons). But beyond figures and tests, we demonstrate that part of the confusion revolving around global biodiversity changes is to find in the diversity of definitions, methods and approaches adopted to address this issue.

Bottom-up approaches amplify publication bias

Producing biodiversity syntheses requires gathering empirical evidence of biodiversity changes distributed on a broad scale. We have identified two major ways of estimating global changes in biodiversity: either by synthesizing already available information (“bottom-up”) or by producing estimates from raw global data (“top-down”). Our findings show that the bottom-up syntheses from reviews or meta-analyses most often conclude a decline in biodiversity. This could be due to biases in the selected studies when performing such bottom-up assessment. The political intent of governments or conservationists to monitor more endangered species results in a selection bias if the trend of those species is interpreted as an average trend for the entire taxonomic group considered (Boakes et al., 2010). Such selection bias might be further amplified due to a publication bias: as studies generally hypothesize a decline, any study showing neutral or positive change would fail to prove the hypothesis, which may encourage authors to select more results on declining trends (Haddaway et al., 2020; Mlinarić et al., 2017). Studies showing biodiversity declines are thus over-represented compared to studies showing neutral or positive changes. This tendency is exacerbated by bottom-up assessments as they rely on already published materials. We do not imply that reviews or meta-analyses should not be conducted, but rather that biodiversity syntheses should make sure publication bias is taken into account (see Haddaway et al., 2020 for recommendations).

Biodiversity syntheses are challenged by data characteristics

Quantification of trends is also based on empirical biodiversity data that are biased in terms of spatial coverage and taxa considered. Plus, these data often represent monitoring of populations or communities through short sampling periods, hence the challenges around the use and collection of these data. Our findings confirm the major geographical and taxonomic drawbacks when estimates are generated from empirical data, namely geographical and taxonomic ones. Europe and North America are the most assessed continents (Boakes et al., 2010; Manes et al., 2021; Saha et al., 2018), whereas information is least available in the tropics (Feeley & Silman, 2011; Saha et al., 2018) and in regions that are currently under pressure (Pereira et al., 2012). Regarding taxonomic groups, terrestrial organisms, and especially vertebrates (Davison et al., 2021; Pereira et al., 2012; Theobald et al., 2015), are more studied than marine ones (Manes et al., 2021). Overall, there is an over-representation of endangered species (Boakes et al., 2010; Saha et al., 2018). In addition to these already well-documented taxonomic and geographical biases, we show that the length of the period considered is influencing the conclusions: the reviewed studies that are based on short time series identify more declines. If species historically monitored are recovering, short time series may miss their recovery. Selecting longer time-series should buffer the decline in this scenario. These results contradict other findings though. For instance, Vellend et al. (2013) found that the length of the time series had no effect on the assessment of biodiversity change. On the contrary, Gonzalez et al. (2016) showed that the percentage of decline increased with the length of the time series.

Thus, the heterogeneity in the conclusions is probably related to heterogeneity in the data characteristics. Beyond being a simple source of heterogeneity, this indicates a lack of representativeness that may represent a bias and therefore influence the reliability of the estimated trends. The lack of representativity in certain groups or regions does not ensure the reliability of the trends, but recent studies highlighted that accounting for these biases (e.g. through weighting processes (McRae et al., 2017)) is not sufficient to correctly assess the trends (Dove et al., 2023). They showed that not only short time series are less reliable than longer ones (Wauchope et al., 2019), but also that the assessment of temporal changes in biodiversity at the global scale depends more on the number of time series (considered here at population scale) than on the representativeness of the number of species present within each taxonomic group in the data (Dove et al., 2023).

To overcome these issues, a short-term solution would be to merge existing aggregated databases that are complimentary in order to increase the amount of data; although it should be noted that such synthesis requires caution regarding possible scale mismatches among datasets (temporal and/or spatial) and diversity in the metrics used (Record et al., 2021). Additionally, sensitivity analyses regarding the length of the time series used should be implemented systematically. The long-term solution is obviously to invest in maintaining monitoring schemes for collecting data in the long term and to make a special effort on covering overlooked taxa and areas.

Beyond linear trends

Another part of the observed heterogeneities arise from methodological issues. In particular, we identify two main methodological approaches. The first is the use of global indicators, and most notably in the papers reviewed here the use of the LPI as well as the RLI. The second approach is the use of individual models, very often linear, in order to characterize trends in time series evaluating population abundances or species richness.

We highlight the fact that the ecological level considered is not as important in the heterogeneities as might be thought, but that the aggregation of trends into single metrics masks the heterogeneities, providing an abundant proportion of declining results. Such indicators have already been criticized for this reason, but also because of their sensitivity to random fluctuations and data gaps (Buschke et al., 2021; Leung et al., 2020).

Our results show that linear models applied to individual time series seem to be a less biased modelling strategy compared to global indicators. Linear models are often used to estimate the rate of change of a variable (Christensen et al., 2014; Donald et al., 2001; Sánchez-Bayo & Wyckhuys, 2019), the most widely used variable being species richness (Hillebrand et al., 2018). However, species richness may not be the most appropriate variable to measure biodiversity change. Indeed, beyond being widely used, changes in species richness remain poorly informative. It has been proven to be insensitive to other form of biodiversity change (Hillebrand et al., 2018; Santini et al., 2017) and unreliable to detect direction in trends despite the relative simplicity to calculate it (Valdez et al., 2023).

Plus, focusing on linear trends may hide other relevant components. First, there are many examples of non-linear dynamics in nature, both in pressures (Steffen et al., 2015) and in responses (McGill et al., 2015). Linear trends are also more likely to miss different periods within time series (e.g. the recent recovery of a given species monitored for a long time). For these reasons, describing non-linear patterns should be even more straightforward than using simplistic linear approaches. Some complex methods like generalised linear models with polynomial regression splines (Cunningham & Olsen, 2009) or generalised additive models (GAM) (Buckland et al., 2005; Fewster et al., 2000) are already being used to describe non-linear dynamics. However, we suggest here to use simpler workflows, like the one described by Rigal et al. (2020) for instance, to avoid overfitting and allow comparisons between different species.

Also, most attention is given on trends while other characteristics in the pattern of biodiversity changes are most often ignored. Variability (and changes thereof) is a proxy of stability in ecological systems (Donohue et al., 2016). Yet, the variability in biodiversity dynamics is largely overlooked: variability is often studied at the scale of ecosystems or communities to characterize their stability (Hughes et al., 2013; Scheffer et al., 2009), but very little at the scale of populations in the context of a global analysis. In the studies we reviewed, stability has only been investigated once (Marsh, 2001), and the few examples of studies that have assessed population stability at the global scale involve taxonomically and spatially biased data (Leung et al., 2017; Williams et al., 2022). Instead, most studies focus on the extinction of species (Bellard et al., 2012) and ignore fluctuations in populations, although fluctuations can indicate high vulnerability to extinction (Clements et al., 2015).

Integrating interacting drivers into biodiversity monitoring and changes assessments

Understanding the biodiversity crisis also requires to understand how global change drivers impact biodiversity across spatial and temporal scales. There are many local or regional examples in which pressure-response links have been established, especially with habitat destruction or land-use practices (Donald et al., 2001; Kohsaka et al., 2013; Liu et al., 2013; Nowakowski et al., 2017), but our work reveals that the way in which pressures aggregate on a global scale and impact the spatio-temporal dynamics of biodiversity remains poorly understood. We also highlight that while links to climate change can be established (Comte & Lenoir, 2020; Knape & de Valpine, 2012; Parmesan & Yohe, 2003), the difficulty of making links between other anthropogenic pressures *and* biodiversity changes at the same time remains (only few examples, e.g. Mantyka-pringle et al., 2012; Nunez & Alkemade, 2021; Oliver & Morecroft, 2014). This observation confirms Mazor et al.(2018): they found that 40,3% of the research effort on drivers of biodiversity loss focus on climate change, while only 5,4% focus on pollution and 5% on overexploitation. However, many studies have suggested that climate change and other threats to biodiversity may interact to lead to even greater consequences (Bowler et al., 2020; Brook et al., 2008; Oliver & Morecroft, 2014; Sala et al., 2000). Such lack of global scale integration jeopardises our understanding of the human induced drivers of biodiversity changes at large scale, leading to inappropriate management strategies and missed conservation opportunities (Sirami et al., 2017).

Conservation perspectives

Although some of the biases we report here potentially lead to over or under estimate the overall decline in biodiversity, we do not question the magnitude of the biodiversity crisis. We are now moving forward with the post-2020 Global Biodiversity Framework and all the Aichi Targets for 2020 have been only partially achieved or not achieved at all. New goals have been set within the Kunming-Montreal Global Biodiversity Framework, many of which rely on the way biodiversity is percieved to be changing. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) has published a very alarming global biodiversity assessment report in 2019. In this context, characterizing the state of biodiversity, the impact of drivers and responses is a key step to take action and “bend the curve of biodiversity loss” (Tekwa et al., 2023). While we urgently need reliable assessments to quantify temporal changes in biodiversity and their links to global drivers, we call for more attention to overlooked and yet informative components of biodiversity changes.

For instance, the Group on Earth Observations Biodiversity Observation Network (GEO BON) initiative emerged in 2013 with the concept of “Essential Biodiversity Variables” defined as “measurement required for study, reporting, and management of biodiversity change”, focusing on the status and trend of biodiversity components (Pereira et al., 2013). These metrics transform data from a variety of sources into indicators that provide a synthetic description of different levels of biodiversity organization, thus facilitating the translation of biodiversity data into policy information.

We suggest that conservation actions should be based not only on Essential Biodiversity Variables but more globally on Essential Biodiversity Data, with requirements on taxonomic, geographic and temporal coverage ensuring the reliability of estimated trends and thus being able to guide strategies based on the least biased observations possible. Similarly, the implementation of a framework such as Essential Biodiversity Assessment Methods, including the need to systematically take into account different levels of biodiversity, as well as the measurement not only of linear dynamics, should be considered collectively and on a large scale.

Eventually, examining the drivers of temporal changes of biodiversity also provides evidence for conservation decision-making (Ehrlén & Morris, 2015; Hefley et al., 2016). Conservation can only be considered in conjunction with an examination of the drivers of these trends, which are of course complex and heterogeneous. Our results plead for an urgent need to develop guidance on the necessary quality required for drivers data, their spatial and temporal coverage, the number of drivers to be considered, and their identity. Methods establishing links also need to be considered, and perspectives are to be explored in terms of not only correlative but also causal links (Rigal et al., 2023).

The results of our review confirm the idea that a multifaceted view of biodiversity is needed to capture all trajectories and the risk of relying solely on global indicators. Empirical evidence for the ongoing biodiversity crisis will never reduce to a silver bullet and univocal metric of global biodiversity change. Eventually, denialism and inaction can be encouraged by the fiction that the state and fate of global biodiversity can be encapsulated in a given metric. A pernicious effect of relying on global metrics would be to consider that the situation is satisfactory providing that a given metric is stable if declining populations are “compensated” or “balanced” by increasing ones. But declines and increases in specific components of biodiversity caused by human activities are by no means cancelling out each other. Any decline of a population or an extinction of a species caused by human activities is a conservation and ethical concern. By quantifying the nuance and full distribution of the impacts of drivers on temporal changes of biodiversity, we should better understand ongoing changes in biodiversity and make sure that conservation actions are making differences.

Data, scripts, code, and supplementary information availability

The R code for metadata manipulation and visualization is available on GitHub (https://github.com/MaelysBoennec/Sources-of-confusion-in-global-biodiversity-trends).

Conflict of interest disclosure

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

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