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 being 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. 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 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 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 in February 2022 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* 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). 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. Figure 1A summaries 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 that were studying both trends and drivers 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 and spatial scope, taxonomic scope, and number of species.

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 declined the drivers between climate change, other anthropogenic pressures (mainly land use change) and conservation policies (protected areas).

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).

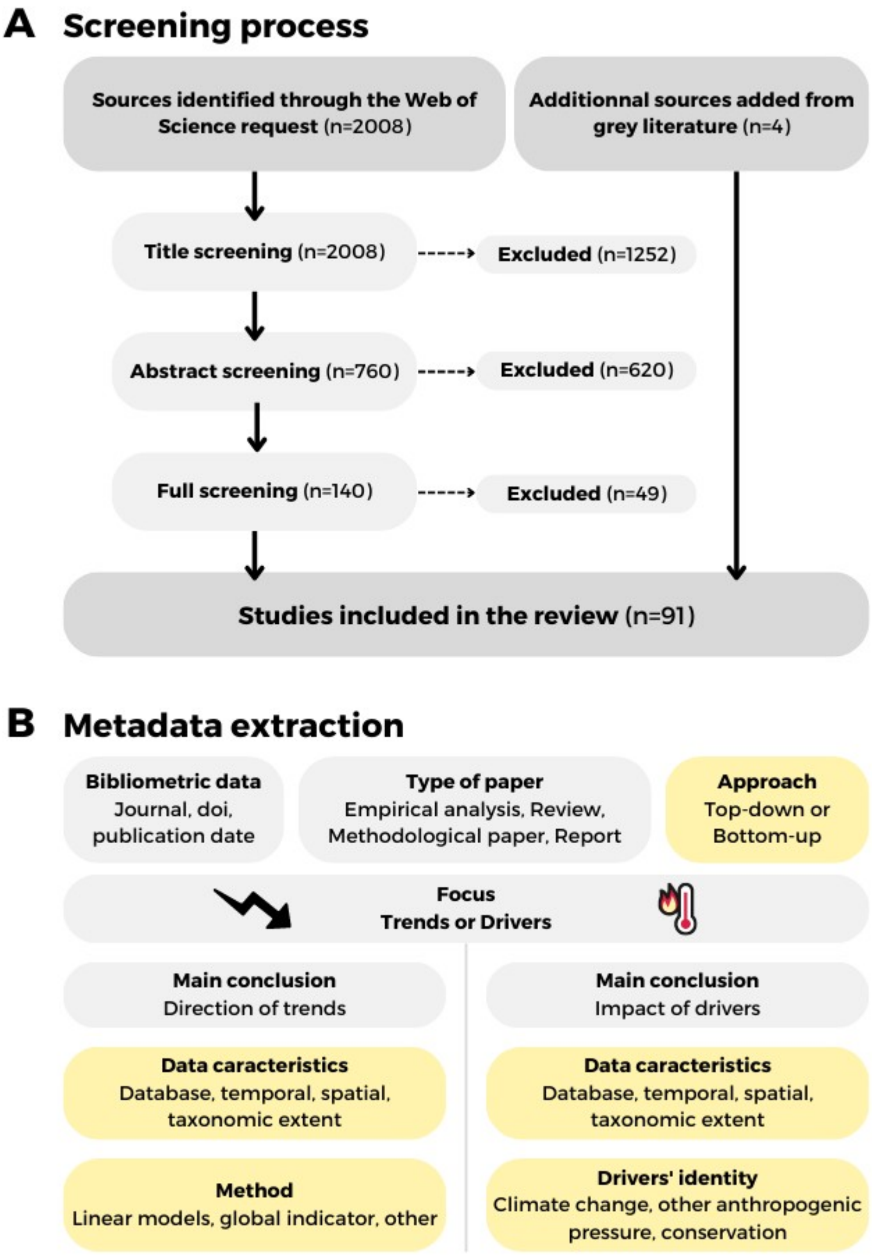

Figure 1. Summary of the sampled literature and extracted metadata. (A) Diagram representing the different steps of the screening process. List of studies extracted from the *Web of Science*, including excluded studies with reasons for exclusion are in the Appendix S3. (B) Summary of the metadata collected 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**** ($n_{tot}=30$)
Contant	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 used in majority 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% remaining relied on grouped levels, i.e. several levels among population, species, or also community scale (studied through community composition).

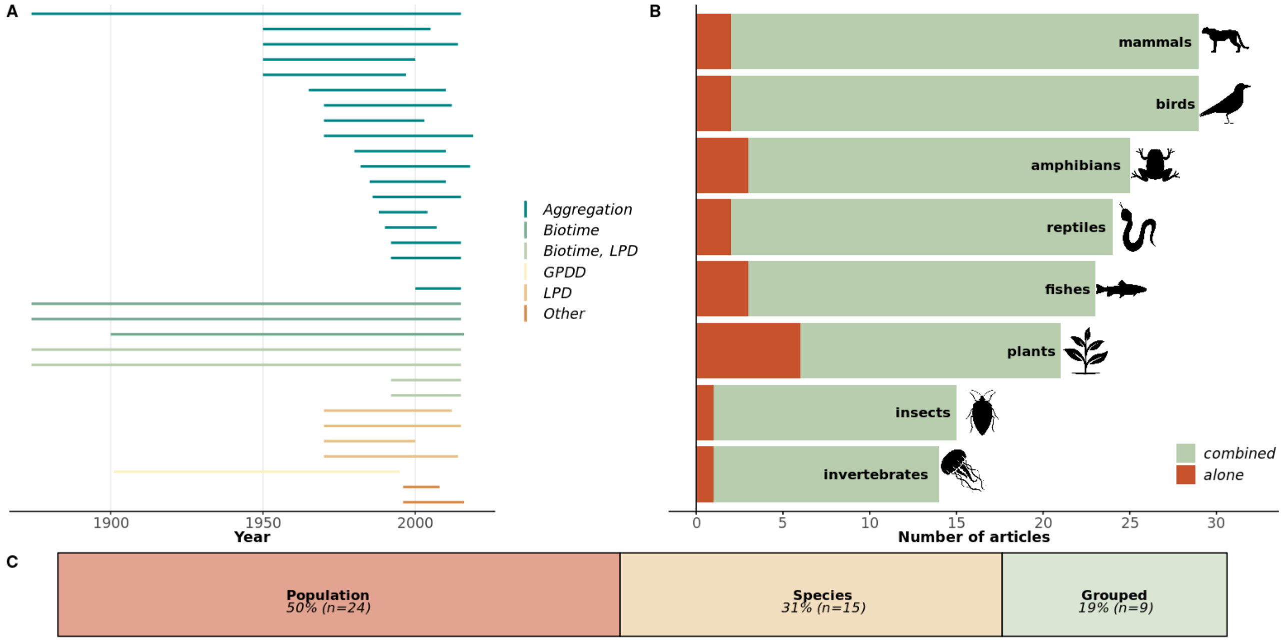

Figure 2. Information on the biodiversity data on which the reviewed papers are based. (A) Temporal extent of the data, colored based on the data source (see Table 1). (B) Taxonomic extent of the data. Number of papers considering each group, wheter considered alone or combined (i.e. when the study does 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. (C) Ecological level representation. Number of papers and percentages are indicated. « Grouped » category reprensent papers examining several ecological levels within the same paper.

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).

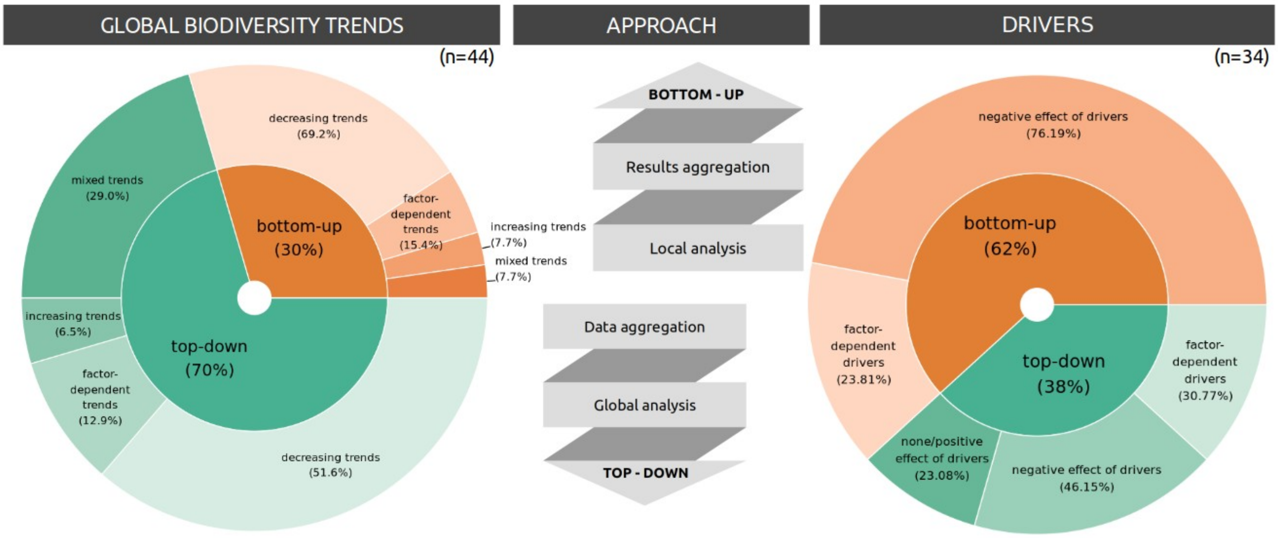

Figure 3. Proportions within conclusions depending on whether global biodiversity trends or drivers were assessed and depending on the assessment approach (i.e. top-down or bottom-up).

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 did influence 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.

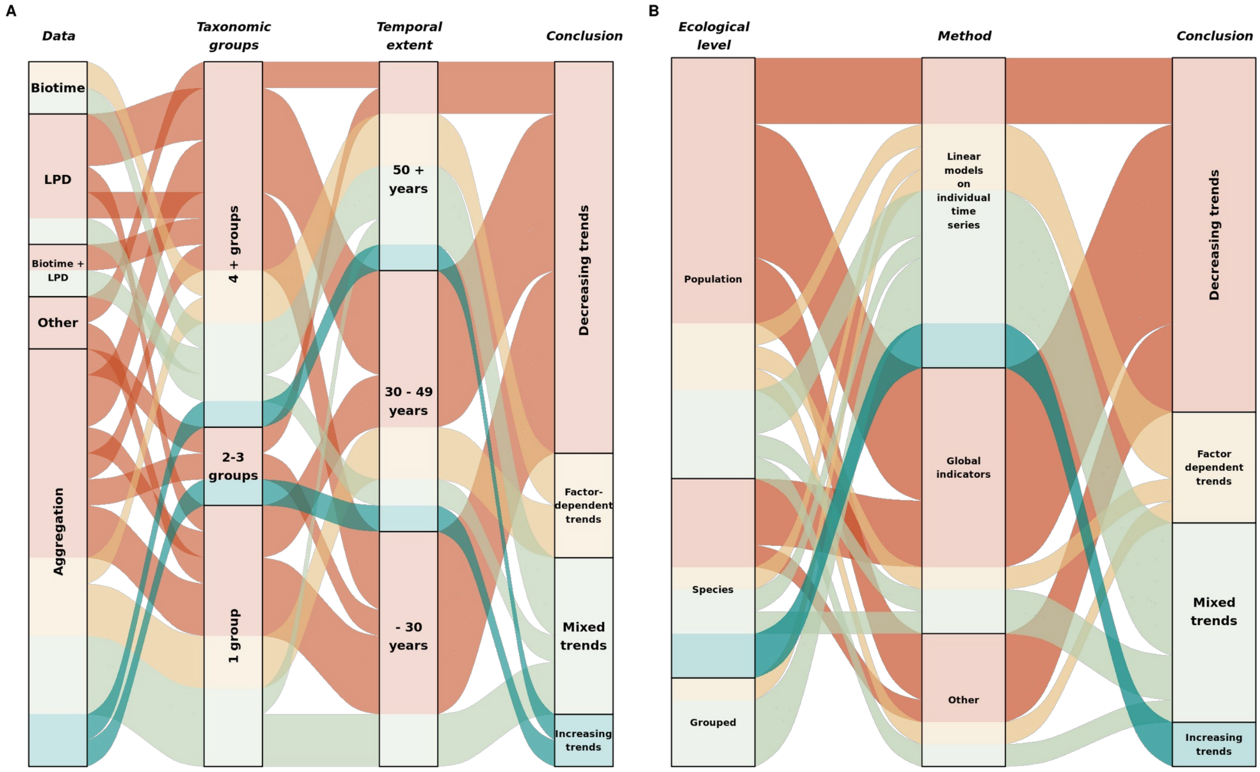

Figure 4. Alluvial plots representing the links between the potential sources of heterogeneity and the conclusions when assessing trends. A (n= 27) highlights the impact of the data characteristics. B (n=32) highlights the impact of the methods and the ecological level. The height of the boxes is proportional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

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. Surprisingly, 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.

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).

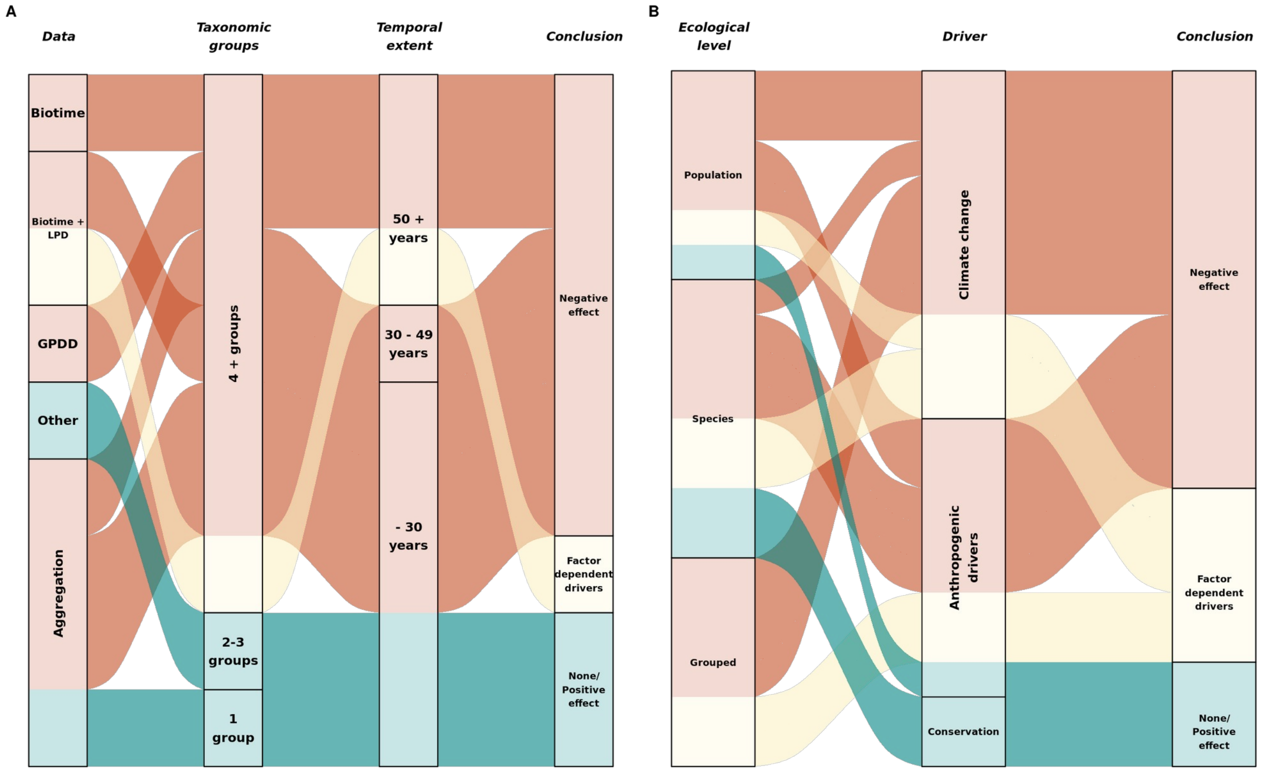

Figure 5. Alluvial plots representing the links between the potential sources of heterogeneity and the conclusions when assessing the impact of the drivers. A (n=9) highlights the impact of the data characteristics. B (n=20) highlights the impact of the biodiversity level and the identity of the drivers. 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.

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).

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 based on a single bibliographic database and additions from the grey literature, we recognize that the coverage of the literature is certainly not complete. Moreover, with the explosion of open databases worldwide, the literature on this subject is flourishing and articles are accumulating very quickly (Appendix S2). There is therefore a gap between the representativity of the current knowledge compared to the one from the established corpus. 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 approximations we may draw in the present paper.

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. 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.

References

Agardy, T. (2005). Global marine conservation policy versus site-level implementation : The mismatch of scale and its implications. *Marine Ecology-progress Series - MAR ECOL-PROGR SER*, *300*, 242-248. https://doi.org/10.3354/meps300242

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, *15*(4), 365-377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Blowes, S. A., Supp, S. R., Antão, L. H., Bates, A., Bruelheide, H., Chase, J. M., Moyes, F., Magurran, A., McGill, B., Myers-Smith, I. H., Winter, M., Bjorkman, A. D., Bowler, D. E., Byrnes, J. E. K., Gonzalez, A., Hines, J., Isbell, F., Jones, H. P., Navarro, L. M., … Dornelas, M. (2019). The geography of biodiversity change in marine and terrestrial assemblages. *Science*, *366*(6463), 339-345. https://doi.org/10.1126/science.aaw1620

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 Biology*, *8*(6), e1000385. https://doi.org/10.1371/journal.pbio.1000385

Bowler, D. E., Bjorkman, A. D., Dornelas, M., Myers-Smith, I. H., Navarro, L. M., Niamir, A., Supp, S. R., Waldock, C., Winter, M., Vellend, M., Blowes, S. A., Böhning-Gaese, K., Bruelheide, H., Elahi, R., Antão, L. H., Hines, J., Isbell, F., Jones, H. P., Magurran, A. E., … Bates, A. E. (2020). Mapping human pressures on biodiversity across the planet uncovers anthropogenic threat complexes. *People and Nature*, *2*(2), 380-394. https://doi.org/10.1002/pan3.10071

Brook, B., Sodhi, N., & Bradshaw, C. (2008). Synergies among extinction drivers under global change. *Trends in ecology & evolution*, *23*, 453-460. https://doi.org/10.1016/j.tree.2008.03.011

Brooke, M. de L., Butchart, S. H. M., Garnett, S. T., Crowley, G. M., Mantilla-Beniers, N. B., & Stattersfield, A. J. (2008). Rates of movement of threatened bird species between IUCN red list categories and toward extinction. *Conservation Biology: The Journal of the Society for Conservation Biology*, *22*(2), 417-427. https://doi.org/10.1111/j.1523-1739.2008.00905.x

Buckland, S. t, Magurran, A. e, Green, R. e, & Fewster, R. m. (2005). Monitoring change in biodiversity through composite indices. *Philosophical Transactions of the Royal Society B: Biological Sciences, 360*(1454), 243-254. https://doi.org/10.1098/rstb.2004.1589

Buschke, F., Hagan, J., Santini, L., & Coetzee, B. (2021). Random population fluctuations bias the Living Planet Index. *Nature Ecology & Evolution, 5*. https://doi.org/10.1038/s41559-021-01494-0

Capdevila, P., Noviello, N., McRae, L., Freeman, R., & Clements, C. F. (2022). Global patterns of resilience decline in vertebrate populations. *Ecology Letters*, *25*(1), 240-251. https://doi.org/10.1111/ele.13927

Cardinale, B. (2014). Overlooked local biodiversity loss. *Science*, *344*(6188), 1098-1098. https://doi.org/10.1126/science.344.6188.1098-a

Cardinale, B. J., Gonzalez, A., Allington, G. R. H., & Loreau, M. (2018). Is local biodiversity declining or not? A summary of the debate over analysis of species richness time trends. *Biological Conservation*, *219*, 175-183. https://doi.org/10.1016/j.biocon.2017.12.021

Ceballos, G., Ehrlich, P. R., Barnosky, A. D., García, A., Pringle, R. M., & Palmer, T. M. (2015). Accelerated modern human–induced species losses : Entering the sixth mass extinction. *Science Advances*, *1*(5), e1400253. https://doi.org/10.1126/sciadv.1400253

Christensen, V., Coll, M., Piroddi, C., Steenbeek, J., Buszowski, J., & Pauly, D. (2014). A century of fish biomass decline in the ocean. *Marine Ecology Progress Series*, *512*. https://doi.org/10.3354/meps10946

Clements, C. F., Drake, J. M., Griffiths, J. I., & Ozgul, A. (2015). Factors Influencing the Detectability of Early Warning Signals of Population Collapse. *The American Naturalist*, *186*(1), 50-58. https://doi.org/10.1086/681573

Comte, L., & Lenoir, J. (2020). Decoupled land–sea biodiversity trends. *Nature Ecology & Evolution*, *4*(7), Article 7. https://doi.org/10.1038/s41559-020-1191-9

Cunningham, R., & Olsen, P. (2009). A statistical methodology for tracking long-term change in reporting rates of birds from volunteer-collected presence–absence data. *Biodiversity and Conservation*, *18*(5), 1305-1327. https://doi.org/10.1007/s10531-008-9509-y

Daskalova, G. N., Myers-Smith, I. H., Bjorkman, A. D., Blowes, S. A., Supp, S. R., Magurran, A. E., & Dornelas, M. (2020). Landscape-scale forest loss as a catalyst of population and biodiversity change. *Science*, *368*(6497), 1341-1347. https://doi.org/10.1126/science.aba1289

Davison, C. W., Rahbek, C., & Morueta-Holme, N. (2021). Land-use change and biodiversity : Challenges for assembling evidence on the greatest threat to nature. *Global Change Biology*, *27*(21), 5414-5429. https://doi.org/10.1111/gcb.15846

Donald, P. F., Green, R., & Heath, M. F. (2001). Agricultural intensification and the collapse of Europe's farmland bird populations. *Proceedings of the Royal Society, Series B, 155,* 39-43.

Donohue, I., Hillebrand, H., Montoya, J. M., Petchey, O. L., Pimm, S. L., Fowler, M. S., Healy, K., Jackson, A. L., Lurgi, M., McClean, D., O'Connor, N. E., O'Gorman, E. J., & Yang, Q. (2016). Navigating the complexity of ecological stability. *Ecology Letters*, *19*(9), 1172-1185. https://doi.org/10.1111/ele.12648

Dornelas, M., Antão, L. H., Moyes, F., Bates, A. E., Magurran, A. E., Adam, D., Akhmetzhanova, A. A., Appeltans, W., Arcos, J. M., Arnold, H., Ayyappan, N., Badihi, G., Baird, A. H., Barbosa, M., Barreto, T. E., Bässler, C., Bellgrove, A., Belmaker, J., Benedetti-Cecchi, L., … Zettler, M. L. (2018). BioTIME : A database of biodiversity time series for the Anthropocene. *Global Ecology and Biogeography*, *27*(7), 760-786. https://doi.org/10.1111/geb.12729

Dornelas, M., Gotelli, N. J., McGill, B., Shimadzu, H., Moyes, F., Sievers, C., & Magurran, A. E. (2014). Assemblage Time Series Reveal Biodiversity Change but Not Systematic Loss. *Science*, *344*(6181), 296-299. https://doi.org/10.1126/science.1248484

Dornelas, M., Gotelli, N. J., Shimadzu, H., Moyes, F., Magurran, A. E., & McGill, B. J. (2019). A balance of winners and losers in the Anthropocene. *Ecology Letters*, *22*(5), 847-854. https://doi.org/10.1111/ele.13242

Dove, S., Böhm, M., Freeman, R., McRae, L., & Murrell, D. J. (2023). *How much data do we need? Reliability and data deficiency in global vertebrate biodiversity trends* (p. 2023.03.18.532273). bioRxiv. https://doi.org/10.1101/2023.03.18.532273

Du, Y., Yang, B., Chen, S.-C., & Ma, K. (2019). Diverging shifts in spring phenology in response to biodiversity loss in a subtropical forest. *Journal of Vegetation Science*, *30*(6), 1175-1183. https://doi.org/10.1111/jvs.12806

Duchenne, F., Porcher, E., Mihoub, J.-B., Loïs, G., & Fontaine, C. (2022). Controversy over the decline of arthropods : A matter of temporal baseline? *Peer Community Journal, 2*. https://doi.org/10.24072/pcjournal.131

Ehrlén, J., & Morris, W. F. (2015). Predicting changes in the distribution and abundance of species under environmental change. *Ecology Letters*, *18*(3), 303-314. https://doi.org/10.1111/ele.12410

Erauskin-Extramiana, M., Arrizabalaga, H., Cabré, A., Coelho, R., Rosa, D., Ibaibarriaga, L., & Chust, G. (2020). Are shifts in species distribution triggered by climate change? A swordfish case study. *Deep Sea Research Part II: Topical Studies in Oceanography*, *175*, 104666. https://doi.org/10.1016/j.dsr2.2019.104666

Fahrig, L. (2017). Forty years of bias in habitat fragmentation research. In *Effective Conservation Science*. Oxford University Press. https://doi.org/10.1093/oso/9780198808978.003.0005

Feeley, K. J., & Silman, M. R. (2011). The data void in modeling current and future distributions of tropical species. *Global Change Biology*, *17*(1), 626-630. https://doi.org/10.1111/j.1365-2486.2010.02239.x

Fewster, R. M., Buckland, S. T., Siriwardena, G. M., Baillie, S. R., & Wilson, J. D. (2000). Analysis of Population Trends for Farmland Birds Using Generalized Additive Models. *Ecology*, *81*(7), 1970-1984. https://doi.org/10.2307/177286

Geldmann, J., Manica, A., Burgess, N. D., Coad, L., & Balmford, A. (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *Proceedings of the National Academy of Sciences*, *116*(46), 23209-23215. https://doi.org/10.1073/pnas.1908221116

Gilman, S. E., Urban, M. C., Tewksbury, J., Gilchrist, G. W., & Holt, R. D. (2010). A framework for community interactions under climate change. *Trends in Ecology & Evolution*, *25*(6), 325-331. https://doi.org/10.1016/j.tree.2010.03.002

Gonzalez, A., Cardinale, B. J., Allington, G. R. H., Byrnes, J., Arthur Endsley, K., Brown, D. G., Hooper, D. U., Isbell, F., O’Connor, M. I., & Loreau, M. (2016). Estimating local biodiversity change : A critique of papers claiming no net loss of local diversity. *Ecology*, *97*(8), 1949-1960. https://doi.org/10.1890/15-1759.1

Haddad, N. M., Gonzalez, A., Brudvig, L. A., Burt, M. A., Levey, D. J., & Damschen, E. I. (2017). Experimental evidence does not support the Habitat Amount Hypothesis. *Ecography, 40*(1), 48-55. https://doi.org/10.1111/ecog.02535

Haddaway, N. R., Bethel, A., Dicks, L. V., Koricheva, J., Macura, B., Petrokofsky, G., Pullin, A. S., Savilaakso, S., & Stewart, G. B. (2020). Eight problems with literature reviews and how to fix them. *Nature Ecology & Evolution*, *4*(12), Article 12. https://doi.org/10.1038/s41559-020-01295-x

He, F., Zarfl, C., Bremerich, V., David, J. N. W., Hogan, Z., Kalinkat, G., Tockner, K., & Jähnig, S. C. (2019). The global decline of freshwater megafauna. *Global Change Biology*, *25*(11), 3883-3892. https://doi.org/10.1111/gcb.14753

Hefley, T. J., Hooten, M. B., Drake, J. M., Russell, R. E., & Walsh, D. P. (2016). When can the cause of a population decline be determined? *Ecology Letters*, *19*(11), 1353-1362. https://doi.org/10.1111/ele.12671

Hillebrand, H., Blasius, B., Borer, E. T., Chase, J. M., Downing, J. A., Eriksson, B. K., Filstrup, C. T., Harpole, W. S., Hodapp, D., Larsen, S., Lewandowska, A. M., Seabloom, E. W., Van de Waal, D. B., & Ryabov, A. B. (2018). Biodiversity change is uncoupled from species richness trends : Consequences for conservation and monitoring. *Journal of Applied Ecology*, *55*(1), 169-184. https://doi.org/10.1111/1365-2664.12959

Houlahan, J. E., Findlay, C. S., Schmidt, B. R., Meyer, A. H., & Kuzmin, S. L. (2000). Quantitative evidence for global amphibian population declines. *Nature*, *404*(6779), 752-755. https://doi.org/10.1038/35008052

Howe, L. C., MacInnis, B., Krosnick, J. A., Markowitz, E. M., & Socolow, R. (2019). Acknowledging uncertainty impacts public acceptance of climate scientists’ predictions. *Nature Climate Change*, *9*(11), Article 11. https://doi.org/10.1038/s41558-019-0587-5

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., & Walker, B. (2013). Multiscale regime shifts and planetary boundaries. *Trends in Ecology & Evolution*, *28*(7), 389-395. https://doi.org/10.1016/j.tree.2013.05.019

Inchausti, P., & Halley, J. (2001). Investigating Long-Term Ecological Variability Using the Global Population Dynamics Database. *Science*, *293*(5530), 655-657. https://doi.org/10.1126/science.293.5530.655

IPBES. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. https://doi.org/10.5281/zenodo.3553458

IPCC. (2021). Summary for Policymakers. In : Climate Change 2021 : The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32,. doi:10.1017/9781009157896.001.

IUCN 2022. The IUCN Red List of Threatened Species. Version 2021-3. (s. d.). IUCN Red List of Threatened Species. Consulté 16 mai 2022, à l’adresse https://www.iucnredlist.org

Joslyn, S. L., & LeClerc, J. E. (2016). Climate Projections and Uncertainty Communication. *Topics in Cognitive Science*, *8*(1), 222-241. https://doi.org/10.1111/tops.12177

Keith, D., Akçakaya, H. R., Butchart, S. H. M., Collen, B., Dulvy, N. K., Holmes, E. E., Hutchings, J. A., Keinath, D., Schwartz, M. K., Shelton, A. O., & Waples, R. S. (2015). Temporal correlations in population trends : Conservation implications from time-series analysis of diverse animal taxa. *Biological Conservation*, *192*, 247-257. https://doi.org/10.1016/j.biocon.2015.09.021

Knape, J., & de Valpine, P. (2012). Are patterns of density dependence in the Global Population Dynamics Database driven by uncertainty about population abundance? *Ecology Letters*, *15*(1), 17-23. https://doi.org/10.1111/j.1461-0248.2011.01702.x

Kohsaka, R., Shih, W., Saito, O., & Sadohara, S. (2013). Local Assessment of Tokyo : Satoyama and Satoumi – Traditional Landscapes and Management Practices in a Contemporary Urban Environment. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parnell, M. Schewenius, M. Sendstad, K. C. Seto, & C. Wilkinson (Éds.), *Urbanization, Biodiversity and Ecosystem Services : Challenges and Opportunities : A Global Assessment* (p. 93-105). Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1_8

Koleček, J., Reif, J., Šálek, M., Hanzelka, J., Sottas, C., & Kubelka, V. (2021). Global population trends in shorebirds : Migratory behaviour makes species at risk. *The Science of Nature*, *108*. https://doi.org/10.1007/s00114-021-01717-1

Laurance, W. F. (2007). Have we overstated the tropical biodiversity crisis? *Trends in Ecology & Evolution*, *22*(2), 65-70. https://doi.org/10.1016/j.tree.2006.09.014

Leiserowitz, A., Maibach, E. W., Roser-Renouf, C., Feinberg, G., & Howe, P. (2013). *Climate Change in the American Mind : Americans' Global Warming Beliefs and Attitudes in April 2013* (SSRN Scholarly Paper Nº 2298705). https://doi.org/10.2139/ssrn.2298705

Leung, B., Greenberg, D. A., & Green, D. M. (2017). Trends in mean growth and stability in temperate vertebrate populations. *Diversity and Distributions*, *23*(12), 1372-1380. https://doi.org/10.1111/ddi.12636

Leung, B., Hargreaves, A. L., Greenberg, D. A., McGill, B., Dornelas, M., & Freeman, R. (2020). Clustered versus catastrophic global vertebrate declines. *Nature*, *588*(7837), 267-271. https://doi.org/10.1038/s41586-020-2920-6

Liu, W., Chen, X., & Wang, Q. (2013). Local Assessment of Shanghai : Effects of Urbanization on the Diversity of Macrobenthic Invertebrates. In T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P. J. Marcotullio, R. I. McDonald, S. Parnell, M. Schewenius, M. Sendstad, K. C. Seto, & C. Wilkinson (Éds.), *Urbanization, Biodiversity and Ecosystem Services :*

Challenges and Opportunities : A Global Assessment (p. 107-122). Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1_9

Loh, J., Green, R., Ricketts, T., Lamoreux, J., Jenkins, M., Kapos, V., & Randers, J. (2005). The Living Planet Index : Using species population time series to track trends in biodiversity. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *360*, 289-295. https://doi.org/10.1098/rstb.2004.1584

Manes, S., Costello, M. J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey, K.-A., Jenkins, R., Khan, T. M., Kiessling, W., Krause, C., Maharaj, S. S., Midgley, G. F., Price, J., Talukdar, G., & Vale, M. M. (2021). Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, *257*, 109070. https://doi.org/10.1016/j.biocon.2021.109070

Mantyka-pringle, C. S., Martin, T. G., & Rhodes, J. R. (2012). Interactions between climate and habitat loss effects on biodiversity : A systematic review and meta-analysis. *Global Change Biology*, *18*(4), 1239-1252. https://doi.org/10.1111/j.1365-2486.2011.02593.x

Marsh, D. M. (2001). Fluctuations in amphibian populations : A meta-analysis. *Biological Conservation*, *101*(3), 327-335. https://doi.org/10.1016/S0006-3207(01)00076-3

Mazor, T., Doropoulos, C., Schwarzmueller, F., Gladish, D. W., Kumaran, N., Merkel, K., Di Marco, M., & Gagic, V. (2018). Global mismatch of policy and research on drivers of biodiversity loss. *Nature Ecology & Evolution*, *2*(7), Article 7. https://doi.org/10.1038/s41559-018-0563-x

McGill, B. J., Dornelas, M., Gotelli, N. J., & Magurran, A. E. (2015). Fifteen forms of biodiversity trend in the Anthropocene. *Trends in Ecology & Evolution*, *30*(2), 104-113. https://doi.org/10.1016/j.tree.2014.11.006

Mckinney, M., & Lockwood, J. (1999). Biotic Homogenization : A Few Winners Replacing Many Losers in the Next Mass Extinction. *Trends in Ecology & Evolution*, *14*, 450-453. https://doi.org/10.1016/S0169-5347(99)01679-1

McRae, L., Deinet, S., & Freeman, R. (2017). The Diversity-Weighted Living Planet Index : Controlling for Taxonomic Bias in a Global Biodiversity Indicator. *PLOS ONE*, *12*(1), e0169156. https://doi.org/10.1371/journal.pone.0169156

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. *Scientific Reports*, *7*(1), Article 1. https://doi.org/10.1038/srep41591

Mlinarić, A., Mlinarić, A., Horvat, M., Horvat, M., Smolčić, V. Š., Smolčić, V. Š., & Smolčić, V. Š. (2017). Dealing with the positive publication bias : Why you should really publish your negative results. *Biochemia Medica*, *27*(3), 0-0. https://doi.org/10.11613/BM.2017.030201

Mora, C., & Sale, P. F. (2011). Ongoing global biodiversity loss and the need to move beyond protected areas : A review of the technical and practical shortcomings of protected areas on land and sea. *Marine Ecology Progress Series*, *434*, 251-266. https://doi.org/10.3354/meps09214

Nowakowski, A. J., Thompson, M. E., Donnelly, M. A., & Todd, B. D. (2017). Amphibian sensitivity to habitat modification is associated with population trends and species traits. *Global Ecology and Biogeography*, *26*(6), 700-712. https://doi.org/10.1111/geb.12571

Nunez, S., & Alkemade, R. (2021). Exploring interaction effects from mechanisms between climate and land-use changes and the projected consequences on biodiversity. *Biodiversity and Conservation*, *30*(12), 3685-3696. https://doi.org/10.1007/s10531-021-02271-y

Olden, J. D., Leroy Poff, N., Douglas, M. R., Douglas, M. E., & Fausch, K. D. (2004). Ecological and evolutionary consequences of biotic homogenization. *Trends in Ecology & Evolution*, *19*(1), 18-24. https://doi.org/10.1016/j.tree.2003.09.010

Oliver, T. H., & Morecroft, M. D. (2014). Interactions between climate change and land use change on biodiversity : Attribution problems, risks, and opportunities. *WIREs Climate Change*, *5*(3), 317-335. https://doi.org/10.1002/wcc.271

Paprocki, N., Heath, J. A., & Novak, S. J. (2014). Regional distribution shifts help explain local changes in wintering raptor abundance : Implications for interpreting population trends. *PloS One*, *9*(1), e86814. https://doi.org/10.1371/journal.pone.0086814

Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, *421*(6918), Article 6918. https://doi.org/10.1038/nature01286

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., Bruford, M. W., Brummitt, N., Butchart, S. H. M., Cardoso, A. C., Coops, N. C., Dulloo, E., Faith, D. P., Freyhof, J., Gregory, R. D., Heip, C., Höft, R., Hurtt, G., Jetz, W., … Wegmann, M. (2013). Essential Biodiversity Variables. *Science*, *339*(6117), 277-278. https://doi.org/10.1126/science.1229931

Pereira, H. M., Navarro, L. M., & Martins, I. S. (2012). Global Biodiversity Change : The Bad, the Good, and the Unknown. *Annual Review of Environment and Resources*, *37*(1), 25-50. https://doi.org/10.1146/annurev-environ-042911-093511

Pievani, T. (2014). The sixth mass extinction : Anthropocene and the human impact on biodiversity. *Rendiconti Lincei*, *25*(1), 85-93. https://doi.org/10.1007/s12210-013-0258-9

Pimm, S., Raven, P., Peterson, A., Sekercioglu, C. H., & Ehrlich, P. R. (2006). Human impacts on the rates of recent, present, and future bird extinctions. *Proceedings of the National Academy of Sciences of the United States of America, 103*(29), 10941-10946. https://doi.org/10.1073/pnas.0604181103

Pörtner, H.-O., Scholes, R. J., Agard, J., Archer, E., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W. L. (William), Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., … Ngo, H. (2021). *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*. Zenodo. https://doi.org/10.5281/zenodo.5101133

Pressey, R. L., Cabeza, M., Watts, M. E., Cowling, R. M., & Wilson, K. A. (2007). Conservation planning in a changing world. *Trends in Ecology & Evolution, 22*(11), 583-592. https://doi.org/10.1016/j.tree.2007.10.001

Radchuk, V., Reed, T., Teplitsky, C., van de Pol, M., Charmantier, A., Hassall, C., Adamík, P., Adriaensen, F., Ahola, M. P., Arcese, P., Miguel Avilés, J., Balbontin, J., Berg, K. S., Borras, A., Burthe, S., Clobert, J., Dehnhard, N., de Lope, F., Dhondt, A. A., … Kramer-Schadt, S. (2019). Adaptive responses of animals to climate change are most likely insufficient. *Nature Communications*, *10*(1), Article 1. https://doi.org/10.1038/s41467-019-10924-4

Record, S., Voelker, N. M., Zarnetske, P. L., Wisnoski, N. I., Tonkin, J. D., Swan, C., Marazzi, L., Lany, N., Lamy, T., Compagnoni, A., Castorani, M. C. N., Andrade, R., & Sokol, E. R. (2021). Novel Insights to Be Gained From Applying Metacommunity Theory to Long-Term, Spatially Replicated Biodiversity Data. *Frontiers in Ecology and Evolution*, *8*. https://www.frontiersin.org/article/10.3389/fevo.2020.612794

Reilly, J., Stone, P. H., Forest, C. E., Webster, M. D., Jacoby, H. D., & Prinn, R. G. (2001). Uncertainty and Climate Change Assessments. *Science*. https://doi.org/10.1126/science.1062001

Rigal, S., Dakos, V., Alonso, H., Auniņš, A., Benkő, Z., Brotons, L., Chodkiewicz, T., Chylarecki, P., de Carli, E., del Moral, J. C., Domşa, C., Escandell, V., Fontaine, B., Foppen, R., Gregory, R., Harris, S., Herrando, S., Husby, M., Ieronymidou, C., … Devictor, V. (2023). Farmland practices are driving bird population decline across Europe. *Proceedings of the National Academy of Sciences*, *120*(21), e2216573120. https://doi.org/10.1073/pnas.2216573120

Rigal, S., Devictor, V., & Dakos, V. (2020). A method for classifying and comparing non-linear trajectories of ecological variables. *Ecological Indicators*, *112*, 106113. https://doi.org/10.1016/j.ecolind.2020.106113

Saha, A., McRae, L., Dodd Jr, C. K., Gadsden, H., Hare, K. M., Lukoschek, V., & Böhm, M. (2018). Tracking Global Population Trends : Population Time-Series Data and a Living Planet Index for Reptiles. *Journal of Herpetology, 52*(3), Article 3.

Sala, O. E., Stuart Chapin, F., III, Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M., & Wall, D. H. (2000). Global Biodiversity Scenarios for the Year 2100. *Science*, *287*(5459), 1770-1774. https://doi.org/10.1126/science.287.5459.1770

Sánchez-Bayo, F., & Wyckhuys, K. A. G. (2019). Worldwide decline of the entomofauna : A review of its drivers. *Biological Conservation*, *232,* 8-27. https://doi.org/10.1016/j.biocon.2019.01.020

Santini, L., Belmaker, J., Costello, M. J., Pereira, H. M., Rossberg, A. G., Schipper, A. M., Ceaușu, S., Dornelas, M., Hilbers, J. P., Hortal, J., Huijbregts, M. A. J., Navarro, L. M., Schiffers, K. H., Visconti, P., & Rondinini, C. (2017). Assessing the suitability of diversity metrics to detect biodiversity change. *Biological Conservation*, *213*, 341-350. https://doi.org/10.1016/j.biocon.2016.08.024

Sax, D. F., & Gaines, S. D. (2003). Species diversity : From global decreases to local increases. *Trends in Ecology & Evolution*, *18*(11), 561-566. https://doi.org/10.1016/S0169-5347(03)00224-6

Scheffer, M., Bascompte, J., Brock, W., Brovkin, V., Carpenter, S., Dakos, V., Held, H., Nes, E., Rietkerk, M., & Sugihara, G. (2009). Early-Warning Signals for Critical Transitions. *Nature*, *461*, 53-59. https://doi.org/10.1038/nature08227

Sirami, C., Caplat, P., Popy, S., Clamens, A., Arlettaz, R., Jiguet, F., Brotons, L., & Martin, J.-L. (2017). Impacts of global change on species distributions : Obstacles and solutions to integrate climate and land use. *Global Ecology and Biogeography*, *26*(4), 385-394. https://doi.org/10.1111/geb.12555

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene : The Great Acceleration. *The Anthropocene Review*, *2*(1), 81-98. https://doi.org/10.1177/2053019614564785

Tekwa, E., Gonzalez, A., Zurell, D., & O’Connor, M. (2023). Detecting and attributing the causes of biodiversity change : Needs, gaps and solutions. Philosophical Transactions of the Royal Society B: Biological Sciences, 378(1881), 20220181. https://doi.org/10.1098/rstb.2022.0181

Theobald, E. J., Ettinger, A. K., Burgess, H. K., DeBey, L. B., Schmidt, N. R., Froehlich, H. E., Wagner, C., HilleRisLambers, J., Tewksbury, J., Harsch, M. A., & Parrish, J. K. (2015). Global change and local solutions : Tapping the unrealized potential of citizen science for biodiversity research. *Biological Conservation*, *181*, 236-244. https://doi.org/10.1016/j.biocon.2014.10.021

Valdez, J. W., Callaghan, C. T., Junker, J., Purvis, A., Hill, S. L. L., & Pereira, H. M. (2023). The undetectability of global biodiversity trends using local species richness. *Ecography*, *2023*(3), e06604. https://doi.org/10.1111/ecog.06604

Vellend, M., Baeten, L., Myers-Smith, I. H., Elmendorf, S. C., Beauséjour, R., Brown, C. D., Frenne, P. D., Verheyen, K., & Wipf, S. (2013). Global meta-analysis reveals no net change in local-scale plant biodiversity over time. *Proceedings of the National Academy of Sciences*, *110*(48), 19456-19459. https://doi.org/10.1073/pnas.1312779110

Wagner, D. L., Fox, R., Salcido, D. M., & Dyer, L. A. (2021). A window to the world of global insect declines : Moth biodiversity trends are complex and heterogeneous. *Proceedings of the National Academy of Sciences*, *118*(2), e2002549117. https://doi.org/10.1073/pnas.2002549117

Walther, G.-R. (2010). Community and ecosystem responses to recent climate change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1549), 2019-2024. https://doi.org/10.1098/rstb.2010.0021

Wauchope, H. S., Amano, T., Sutherland, W. J., & Johnston, A. (2019). When can we trust population trends? A method for quantifying the effects of sampling interval and duration. *Methods in Ecology and Evolution*, *10*(12), 2067-2078. https://doi.org/10.1111/2041-210X.13302

Williams, J. J., Freeman, R., Spooner, F., & Newbold, T. (2022). Vertebrate population trends are influenced by interactions between land use, climatic position, habitat loss and climate change. *Global Change Biology*, *28*(3), 797-815. https://doi.org/10.1111/gcb.15978

Willis, K. J., & Bhagwat, S. A. (2009). Biodiversity and Climate Change. *Science*, *326*(5954), 806-807. https://doi.org/10.1126/science.1178838

Wilson, R. J., & Fox, R. (2021). Insect responses to global change offer signposts for biodiversity and conservation. *Ecological Entomology*, *46*(4), 699-717. https://doi.org/10.1111/een.12970

Wolf, A. A., Zavaleta, E. S., & Selmants, P. C. (2017). Flowering phenology shifts in response to biodiversity loss. *Proceedings of the National Academy of Sciences*, *114*(13), 3463-3468. https://doi.org/10.1073/pnas.1608357114

WWF. (2020). Living Planet Report 2020—Bending the curve of biodiversity loss. Almond, R.E.A., Grooten M. and Petersen, T. (Eds). WWF, Gland, Switzerland.

WWF. (2022). Living Planet Report 2022 – Building a nature-positive society. Almond, R.E.A., Grooten, M., Juffe Bignoli, D. & Petersen, T. (Eds). WWF, Gland, Switzerland.