How has biodiversity of birds changed in time? A meta-analysis across metrics and spatio-temporal scales

*François Leroy1,\*, Jiri Reif2,3, David Storch4, Petr Keil1*

1 Department of Spatial Sciences, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Praha-Suchdol, Czech Republic

2 Faculty of Science, Institute for Environmental Studies, Charles University, Prague, Czechia

3Department of Zoology and Laboratory of Ornithology, Faculty of Science, Palacky University, Olomouc, Czechia

4 Center for Theoretical Study, Charles University, Jilska´ 1, 110 00-CZ Praha 1, Czech Republic

\* Correspondance : [leroy@fzp.czu.cz](mailto:leroy@fzp.czu.cz)

# Abstract

Biodiversity changes in time due to human impacts and natural processes, and this change affects both ecosystem functioning and human wellbeing. However, empirical quantification of this change remains a challenge even in well surveyed groups such as birds. This may be because the change depends on spatio-temporal scales, specifically on spatial grain (i.e. area of a sampling unit), geographic extent, temporal grain (i.e. duration of a sampling event), and temporal extent. Further, different metrics of biodiversity may exhibit different spatial trends. Here we review global literature assessing the temporal trends of avian biodiversity from ca 1900 AD to present, focusing on studies summarizing trends across many locations (i.e. spatial replicates) within a larger region. From each study we extracted direction of average trend (decreasing, increasing, stable), spatial and temporal grains and extents at which trends have been assessed, metrics of biodiversity (taxonomic and functional richness and diversity, evenness, spatial and temporal beta diversity), and location. That is, we list and discuss the trends of these metrics as a function of the spatial and temporal features they are defined at. We found over 50 trends resulting from averages over spatial replicates. Most studies were from Europe and North America, the rest of the world is represented poorly. There was high heterogeneity in the trends, with increasing, decreasing, and stable trends being all common at all spatial scales. There was no clear tendency of any metric or scale to exhibit a particular direction of the trend. However, our results confirm that biodiversity dynamic can have opposite trends according to the spatial scales considered. Concerning temporal scaling, we point a lack of homogeneity in definitions, and we suggest a common framework to better understand the link between temporal scale and biodiversity dynamic. By bringing all this empirical literature together, we have identified underrepresented regions, times, and metrics that need further attention. We highlight the importance of considering both spatial and temporal scaling jointly in any assessment of biodiversity change. Finally, we provide practical guidelines for how to do this effectively both in birds, and in other taxa, by clearly defining spatio-temporal features in ecology.

**Keywords:** macroecology, species richness, temporal trend, biodiversity dynamics, resolution, XXX

# Introduction

We have reasons to suspect that the global alteration of biodiversity due to anthropogenic stressors is unprecedented, and political goals have been declared in order to limit it (e.g. (Secretariat of the Convention on Biological Diversity & UNEP World Conservation Monitoring Centre, 2006). However, data-driven basis for these policies remains a challenge, mainly due to severe gaps and biases in empirical biodiversity data (Meyer et al., 2015). To complicate matters further, current scientific literature has shown that temporal trends of local biodiversity can be opposite to trends at larger spatial scales (*e.g.* Chase et al., 2019; Keil et al., 2011, 2018). Thus, we should expect changes in biodiversity to be far more complex than a simple global decrease. Finally, biodiversity can be measured by many metrics, and these can differ in their temporal trends (McGill et al., 2015): for instance, while there may be small average net change in local species richness, ecosystems can still undergo significant changes in species composition (Blowes et al., 2019; Dornelas et al., 2013; Vaidyanathan, 2021).

**Scale.** Particularly the scale is critical (Levin, 1992) yet lacks standardized analyses. Since Arrhenius (1921) and Grinnell (1922), we know that spatial and temporal scaling of biodiversity affects macroecological patterns. Even though particularly the static spatial scaling of biodiversity has been of great interest (*e.g.* Storch et al., 2007), wonders persist about how temporal trends of biodiversity are linked to the spatial and temporal scales. In other words: does the observed biodiversity trends differ if we zoom out from local communities to regions, countries or continents? Here, the term “spatial grain” is also used to refer to the spatial scale of biodiversity, *i.e.* the area at which the metric of biodiversity is assessed. One should be careful to not confuse spatial grain with the spatial extent of a study, i.e. the total area of the ecosystem which is observed or analyzed (Dungan et al., 2002). The same terminology is applied for the temporal scale: temporal grain refers to the temporal unit of the measured biodiversity (Adler & Lauenroth, 2003). In contrast to spatial scaling, temporal scaling is much less studied. This is mostly due to the lack of temporally replicated data.

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| --- | --- |
| **(a)** | **(b)** |
| Timeline  Description automatically generated | Spatial grain and extent illustration |

***Figure 1****: Illustration of the concepts of spatial (a) and temporal (b) scales used in this review.*

**Metrics.** Studying biodiversity can be confusing as there are many ways to measure it. The different metrics and indicators have diverse features, and one should consider which one is the most suited to its study. First, the type of biodiversity studied must be chosen (*e.g.* taxonomic, functional, phylogenetic diversity). Only then, one must choose the metric(s). Several standardized metrics have been created to assess their populations. Fraixedas et al. (2020) reviewed this wide spectrum of bird biodiversity indicators, without considerations to their link with spatial and temporal grains.

Measures of static biodiversity are commonly used such as local species richness (α diversity), regional richness (ɣ diversity, Whittaker, 1960), by indices that consider abundances (*e.g.* Shannon, 1948; Simpson, 1949), or by Hill numbers (M. O. Hill, 1973). On the other hand, change of species composition in space and time can be expressed as (Whittaker, 1972), or by pairwise dissimilarity among locations or time periods (Koleff et al., 2003). All these metrics assess species-based metrics, *i.e.* they use the species as a unit. However, it has also been shown that functional and phylogenetic diversity can provide supplementary information on the community structure and its dynamic (*e.g.* McGill et al., 2006; Mouquet et al., 2012; Webb et al., 2002).

**What is lacking? (me brainstorming)**

* There have been numerous empirical studies that report systematic biodiversity trends (REF examples from the table).
* However, we currently lack a review/synthesis of all this published empirical literature.
* Is there an overall trend that holds across all of the different studies? Where do they come from? Which biodiversity metrics they use? Which scales do they cover.
* This review will, in part, show how the definition of temporal grain has still no consensus in the scientific literature.

**Objectives.** Here, to address these issues, we review articles assessing the temporal trends of avian biodiversity, with species focus on the variety of metrics that they use, and spatial and temporal scales at which temporal trends have been assessed. We consider the most common macroecological indicators used to assess biodiversity at the community level and higher, such as diversity indexes (*e.g.* species richness, functional diversity etc, McGill et al., 2015). We highlight a lack of consensus about specifications and definitions of both spatial and temporal grains (respectively) of trends, we demonstrate that the scaling of trends is seldom considered, leading to confused messages about overall trends. Moreover, we show that **1)** studies lack spatial replication that would make reported trends robust and general and that **2)** the studies assessing biodiversity trends with spatial replicates are from North America and Europe only. We believe that this review will improve the current knowledge on spatio-temporal scaling of trends biodiversity, and thus be useful for the ornithological field community and the conservation decision making.

We focus our review on birds, as they represent perhaps the most surveyed taxon. Thanks to the many ornithological monitoring initiatives and surveys, we have a large number of high-quality time series on bird populations (Bejček & Stastný, 2016; Kamp et al., 2021; Sauer et al., 2013…). This is because birds are easy to observe, easy to identify and thus many volunteers are motivated to participate on citizen-science projects (Sullivan et al., 2009, https://www.inaturalist.org/) or to conduct standardized sampling (*e.g.* most of the breeding bird surveys are conducted by volunteers).

# Material and Methods

For this review, we focused on articles assessing temporal trends of the most common metrics of avian biodiversity and specifying spatial and temporal scales, which are at the same time consistent with broader macroecological scaling and theory (Storch et al., 2007; Storch & Gaston, 2004), and thus can be compared across studies and scales. Namely, these were: *Species richness (SR), Functional richness, Evenness, Diversity, Functional diversity, Temporal beta-diversity, Spatial beta-diversity, Functional beta-diversity, Gamma-diversity, Functional Gamma-diversity*. Some of these classes contain several different indexes. For instance, the class *Diversity*, which contains either the Shannon or Simpson index (see Supplementary Material Table 1 for the notes).

We only considered articles for which there were spatial replicates, *i.e.* where the trend of the metric was assessed at several locations at a given spatial grain. With these replications, the trend reported at one spatial grain is more reliable and general. However, at larger spatial grains (*i.e.* national, continental or global scales), spatial replicates are rare. Thus, we considered these trends from a single location only when based on a large set of observations from smaller spatial scales.

We used our collective knowledge about scientific literature on the topic, and we also used a more exact and quantitative “advanced search” tool of the ISI Web of Science Core collection database with these following queries:

1. ALL=(birds AND species richness AND temporal trend) which resulted in 88 references.
2. ALL=(birds AND diversity AND temporal trend) which resulted in 156 references.

For each query, the title and abstract of these articles were reviewed. In addition, we scanned the references of these articles for other potentially relevant literature. When the temporal trend was explicitly reported (either in a graph or text), we extracted from the material and methods the type of metric, the spatial grain of the trend (*i.e.* the area at which the metric trend is assessed), its temporal grain (*i.e.* the temporal unit of the sampling plan), the spatial extent (*i.e.* the entire area on which the study applies), the temporal extent and the beginning and ending years of the study as well as the general trend of the metric (Table 1). The temporal lag of the trend, *i.e.* the time-span between two time steps, was also reported (Dungan et al., 2002). We discretized spatial grain sizes discretized into four levels: *local ≤ 25 Km², regional > 25 Km², national* when entire countries are considered, and *global* at the worldwide scale (grain = extent = the entire Earth’s mainland).

Concerning the trend assessment, different papers contain the *p-value*, confidence interval or directly specify the significance of a trend of a metric. However, some papers give only graphical representations of the trend. Moreover, the final trend retained (*i.e.* either *Increase, Stable* or *Decrease*) doesn’t reflect all the fluctuations of the metric through time but rather the difference between the starting and ending points.

# Results and Discussion

We found 32 references in which authors were both determining the temporal trend of a metric and explicitly defining the spatial grain size of their analyses. We removed all studies which reported trends for only a single spatial location. We ended up with XXX trends of YYY metrics from 19 studies in total (Table 1).

The median spatial extent of the 19 articles is NA *Km²*, with the smallest area of NA *Km²* and the greatest representing the global emerged surface (*i.e.* NA *Km²*). These articles reported 20 combinations of scales and metrics.

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| **(a)** | **(b)** | **(c)** |
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***Figure 2*** *Temporal extents (a) and geographic extents (b) of studies that we reviewed.*

# Trends across spatial scales

**Overall trends.** Overall, there were 10 *Decrease*, 38 *Increase* and 7 *Stable* reliable trends (*i.e.* spatially replicated) across the literature. In our case, local scales are more represented than the others and the number of articles decreases with the increasing spatial scale (Figure 3.a.). This is expected, as the spatial replications get more demanding in organization and resources as the grain size enlarges. The *Increase* of the metrics seems to be dominating at smaller scales. On the other hand, the proportion of *Decrease* is larger at regional scales than at local scales. At the global scale, no *Increase* was found.

**Trends by metric.** Among the different metrics, most of the examined studies deal with temporal trends of species richness (Figure 3.b.). The use of the other metrics was rare. The less common trend of abundance is *Increase*, whilst *Decrease* and *Stable* trends are almost as common. In general, all the diversity indexes (*i.e.* taxonomic and functional richness, evenness and diversity) are mostly found increasing.

**Trends by spatial grain.** In the studies that we reviewed, at local grains, taxonomic and functional richness mostly increased (Figure 3.c.). Evenness indices, *i.e.* taxonomic and functional evenness, were also mostly increasing. Concerning the abundance indices, we found mostly no trend, or increases. At regional grains, abundance metrics always decreased, temporal β-diversity always increased, and species richness mostly increased. At national and global grains, studies analyzing multiple locations are rare, and most trends reported here for these two spatial scales are not replicated. Exceptions are Bowler *et al.* (2021) and Donald *et al.* (2001). The former showed negative trends in abundance indices for Denmark and Germany, and positive trends for Switzerland and Czech Republic, *i.e.* no clear direction of the trend (here referred as *Stable*). However, for Donald (2001), trends of mean population size were computed for 30 European countries and the majority was negative. Global trends only come from Jarzyna and Jetz (2018), who report a global decrease of species richness, functional diversity and a stable trend of temporal β-diversity.

Concerning species richness, we can see that the decrease is global, but that this decrease is rare at finer spatial scales. In fact, we observe more often increases, confirming the high perturbations that biodiversity is undergoing (Dornelas et al., 2014; Vaidyanathan, 2021). This analysis goes along with the temporal β-diversity which is always observed either stable or increasing. Indeed, increasing turnover through time is a sign of an increasing perturbation of the ecosystems.

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| **(a)** | **(b)** |
| Figure 4.1: Proportion of Increase, Decrease or Stable trends for each spatial scale | Figure 4.2: Proportion of Increase, Decrease or Stable trends for each of the metric |
| **(c)** |  |
| Figure 4.3: Proportion of Increase, Decrease or Stable trends for each metric. Each panel represent one spatial scale | |

***Figure 3***

# Trends across temporal scales

The oldest study started in 1911 and the median duration is 28 years, with a minimum timespan of 6 years and a maximum of 99 years. Many studies are based on the same datasets (*e.g.* the US Breeding Bird Survey), only three different temporal grains were found (2.5, 3.4, 0.09 hours).

We found longest temporal lags in studies with large spatial extent. This is because data used in the selected articles are mainly structured data, *i.e.* data following a well established sampling plan. This type of survey is sparse since it needs resources and organization. Increasing the spatial extent thus increases both the temporal extent and the time to sample all the sampling units. This explains this positive correlation between spatial extent and temporal lag. This limitation can be overcome thanks to citizen science data, which have increasingly been used (*e.g.* Bowler et al., 2021; Isaac et al., 2014, 2020). The opportunistic nature of these data allows for short census times, even over a large area. These data, with high temporal grain resolution for large spatial scales, could in future be used to explore in more details the temporal scaling of biodiversity trends, especially for low temporal lags.

Determination of the temporal grain in the studies in Table 1 was complicated. Usually, the temporal grain of the sampling was specified, but sometimes with inaccuracies (*e.g.* *“The sites are visited twice a year (April to early May and late May to June), during which volunteers walk two parallel 1-km-long transect lines”*, Harrison et al., 2014). Moreover, the temporal grain of the sampling doesn’t represent the temporal grain of the metric. For instance, some metrics are summed over a certain area (*e.g.* summing the species richness over an atlas square, such as in Van Turnhout et al., 2007) and sometimes over both an area and a period of time (*e.g.* Chase et al., 2019). Analogically, the temporal grain should have also been summed over all the sampling censuses englobed in this area/time span, but this was never specified. Moreover, when the trend is computed, usually the lag (*i.e.* the time between two computation of the metric, Dungan et al., 2002) is clearly specified, but the temporal grain is not. For the cases where the metric of biodiversity is determined out of model (*e.g.* Harrison et al. 2014), it is easier to assess the temporal grain, since predictions are based on the sampling temporal grain. Thus, for these cases, the final temporal grain was most of the time explicitly given.

In short, temporal grain of the sampling plan is sometimes specified. However, when the metric and its trend are computed, temporal grains are occasionally merged. In this case, the value wasn’t specified.

# Spatial replication

Articles reporting trends from more than a single location are uncommon (we only found 19 of them), either due to a lack of data, or because the trend was assessed for the spatial extent of the data. For instance, the US Breeding Bird Survey (*e.g.* Schipper et al., 2016) follows a standardized sampling plan with spatial replications (*i.e.* multiple census plots). However, not all the trends reported for the BBS are summarized at their specific grain, and were sometimes aggregated over their respective national scales, reducing spatial replication. For instance, a common method encountered is to learn a predictive model from the data, predict the target feature (*e.g.* species richness, abundance) and then compute the trend from the output of the model at the national spatial extent (*e.g.* Doxa et al., 2010; Eglington & Pearce-Higgins, 2012; Jiguet et al., 2005, 2012; Sauer et al., 2017). These analyses are practically useful for conservation, and are common (Fraixedas et al., 2020): they give inform about ecosystem health at national extent, and are thus useful for decision-makers.

Another common type of study uses the space-for-time substitution (Walker et al., 2010) to assess the trend of a metric (one of the best example is J. K. Hill & Hamer, 2004). This method consists in considering sampling in different places as representing a temporal trend. One could think that using these studies could increase significantly the spatial replicates. However, the space-for-time substitution is mainly used to assess the impact of a processes (*e.g.* before/after logging, before/after urbanization etc) meaning that the trend computed is highly biased, which we try to avoid for our topic.

Even fewer articles computed the trends of metrics with spatial replicates across more than one spatial grain. So far this was the case for only Chase et al. (2019) and Jarzyna and Jetz (2018). Importantly, Jarzyna et al. (2015) did spatial replicates of temporal change community metrics (*i.e.* temporal dissimilarity, temporal turnover, extinction and colonization) at several spatial scales. However, the temporal trends of these metrics weren’t considered and are therefore not reported in Table 1.

# Future directions

A striking but expected result (see Meyer et al., 2015), was the lack of studies form outside of the high-income global North. Out of 17 papers, 5 were located in North America and 12 in Europe. This is gap was also reported by Fraixedas *et al.* (2020). Yet, biodiversity dynamic in Europe may not be representative of global dynamic, and studies of biodiversity trends at several spatio-temporal scales are needed outside of Europe. These studies are needed on local grains, as well as at the spatial grain of continents (*e.g.* see Alroy, 2015 for amphibians and reptiles).

The spatial grain of biodiversity trends is critical, yet this has not always been specified in the articles. One should consider the way a metric was computed, *e.g.* if it was summed, modelled, averaged over the sampling units. According to the method, the spatial grain can vary from the sampling unit to the sampling extent. Given the importance of spatial scaling of biodiversity patterns (Storch & Gaston, 2004), one has to expect that it will be also important for its dynamic (*e.g.* Chase et al., 2019). We thus argue that authors should pay extra attention to specifying the spatial grain for every metric of biodiversity trends.

The importance of temporal scaling of biodiversity is known since Grinnell (1922), who used California birds to demonstrate the species-time relationship, which has since been proven to be common with other bird populations (White, 2004). Thus, as spatial grain, temporal grain is known to be important to explicit. However, there is no consensus on the definition of temporal grain and is thus specified in various ways: sometimes very precised (*e.g.* time of each census point, as in Schipper et al., 2016) and sometimes without explicit information (*“All sites were visited six times in 1994 and five times in 2004 during early morning”*, Wretenberg et al., 2010). As for the spatial grain, the temporal grain can vary according to the way the metric is assessed (*e.g.* if the data is aggregated over an area and/or a period of time). However, when temporal trend of a metric is assessed, the temporal lag of the trend is often only specified (*i.e.* time-span between *t* and *t+1*). In other words, when computing a trend, one usually uses a single point either every day, every month or every year. However, this temporal lag doesn’t represent the temporal grain that interests us. If one wants to study the temporal scaling of biodiversity trends, a clear assessment of the temporal grain needs to be done systematically.

# Conclusion

Reviewing the scientific literature on avian biodiversity trends give us a glimpse of what needs to be done to better understand the scaling of biodiversity dynamic. The first challenge is to find a common definition of spatial and temporal grain when computing the trend. We showed that these definitions vary according to the way the metric is computed. Whilst spatial grain of a trend is intuitively important for biodiversity, temporal grain is less often considered, especially when the temporal trend is computed. Finally, as birds are one of the most data-rich taxa of vertebrates, the challenges highlighted here will be even more severe for other groups.

# Some text that we removed but could be useful

**Composite and multi-species indicators.** The composite indicators are made to summarize several ecosystem information into one informative index. The most known ones are the Red List Index ([Stuart H. M. Butchart et al. 2007](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.1ci93xb); [Stuart H. M. Butchart et al. 2004](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.3whwml4); [S. h. m. Butchart et al. 2005](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.2xcytpi)), the Living Planet Index ([Loh et al. 2005](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit" \l "bookmark=id.sqyw64)) or the Biodiversity Change Index ([Normander et al. 2012](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit" \l "bookmark=id.25b2l0r)). In these composite indicators, metrics of great interest are the abundance-based or population-based metrics. As individuals react to stress or disturbances, the population trends reflect ecosystems health. The population decline that a species undergoes before going locally extinct is not captured by species-based metrics. Thus, population trends are usually efficient at assessing finer biodiversity declines. Although overall abundance is often hard to assess, the abundance of few indicator species can reflect processes in an entire ecosystem ([Richard D. Gregory et al. 2005](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.2grqrue)). This has led to a proposition of a family of metrics called the multi-species indicators (MSI, [Landres, Verner, and Thomas 1988](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.3ygebqi)). Examples are the farmland bird indicator, woodland bird indicator or Wildland Bird Indicator which summarizes the latter two ([Richard D. Gregory et al. 1999](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.41mghml); [Richard D. Gregory and Strien 2010](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.1hmsyys)). These metrics compute the geometric mean of abundance of few key species over time.

**Bird stuff.** Some of these functions, such as seed dispersal, control of pests, scavenging, or pollination, depend on birds and their diversity. Birds also have a significant esthetical value, with most countries having numerous iconic/charismatic species of conservation interest (<https://www.iucnredlist.org/>). Moreover, given their ability to quickly move between locations, their presence is also a good indicator for ecosystem health. Unfortunately, anthropogenic stressors like habitat loss, over-exploitation, pollution, or introduction of invasive species are a threat to birds and their biodiversity ([Donald, Green, and Heath 2001](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.49x2ik5); [Frédéric Jiguet et al. 2010](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.46r0co2)), with concerns that they could face a sixth mass extinction ([Barnosky et al. 2011](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit" \l "bookmark=id.z337ya)).

**Metric heterogeneity.** In contrast to macroecology, applied ecology has offered multiparametric indices that aim to reflect multiple components of an ecosystem, the so-called *composite indicators*. For birds, these indices have been widely used (see review by [Fraixedas et al. 2020](https://docs.google.com/document/d/1iLaKCgOToG2z3n7-jCZhLGTiK-xjQKeRlAqjQfd_1bQ/edit#bookmark=id.32hioqz)) and have proven to be effective for conservation policies. Some of these metrics either reduce (*e.g.* MSI which use a limited number of species) or increase (*e.g.* the Biodiversity change index which takes into account habitat features) the complexity of the metric. In order to study the link between biodiversity trends and spatio-temporal grains, we need to use the common macroecology metrics, such as species richness, diversity or abundance indices.

***Table 1:*** Trends of different metrics of biodiversity at various spatial and temporal scales

| Reference | Metric | Spatial grain (Km²) | Spatial extent (Km²) | Temporal lag (year) | Temporal grain (hour) | Temporal extent (year) | Years | Country | Trend |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Barnagaud et al. (2017) | Functional richness | Local | 9,834,000 | 1 | 2.50 | 41 | 1970-2011 | USA | Increase |
|  | Functional evenness | Local | 9,834,000 | 1 | 2.50 | 41 | 1970-2011 | USA | Increase |
|  | Evenness | Local | 9,834,000 | 1 | 2.50 | 41 | 1970-2011 | USA | Increase |
|  | SR | Local | 9,834,000 | 1 | 2.50 | 41 | 1970-2011 | USA | Increase |
| Chase et al. (2019) | SR | Local | 2,800,000 | 5 | 2.50 | 30 | 1982-2011 | USA, Canada | Stable |
|  | SR | Regional | 2,800,000 | 5 | 2.50 | 30 | 1982-2011 | USA, Canada | Stable |
|  | SR | Regional | 2,800,000 | 5 | 2.50 | 30 | 1982-2011 | USA, Canada | Stable |
|  | SR | Local | 2,800,000 | 5 | 2.50 | 30 | 1982-2011 | USA, Canada | Increase |
|  | SR | Local | 2,800,000 | 5 | 2.50 | 30 | 1982-2011 | USA, Canada | Increase |
| Davey et al. (2012) | Diversity | Local | 242,495 | 1 |  | 13 | 1994-2006 | UK | Increase |
|  | Evenness | Local | 242,495 | 1 |  | 13 | 1994-2006 | UK | Increase |
|  | SR | Local | 242,495 | 1 |  | 13 | 1994-2006 | UK | Increase |
| Jarzyna and Jetz (2018) | SR | Regional | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | SR | Regional | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | SR | Regional | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | SR | National | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | SR | Global | 148,940,000 |  |  | 45 | 1969-2013 | World | Decrease |
|  | Temporal beta-diversity | Regional | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | Temporal beta-diversity | Regional | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | Temporal beta-diversity | Regional | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | Temporal beta-diversity | National | 9,834,000 |  | 2.50 | 45 | 1969-2013 | USA | Increase |
|  | Temporal beta-diversity | Global | 148,940,000 |  |  | 45 | 1969-2013 | World | Stable |
| Pilotto et al. (2020) | Diversity | Local | 10,180,000 |  |  |  | NA | Europe | Increase |
|  | SR | Local | 10,180,000 |  |  |  | NA | Europe | Increase |
|  | Temporal beta-diversity | Local | 10,180,000 |  |  |  | NA | Europe | Stable |
| Ram et al. (2017) | SR | Regional | 350,000 | 1 |  | 18 | 1998-2015 | Sweden | Increase |
| Reif et al. (2013) | Spatial beta-diversity | Local | 79,000 | 1 | 3.40 | 23 | 1982-2004 | Czech Rep. | Stable |
|  | SR | Local | 79,000 | 1 | 3.40 | 23 | 1982-2004 | Czech Rep. | Stable |
| Schipper et al. (2016) | Diversity | Local | 24,710,000 | 5 | 2.50 | 40 | 1971-2010 | Canada, USA, Mexico | Increase |
|  | Diversity | Local | 24,710,000 | 5 | 2.50 | 40 | 1971-2010 | Canada, USA, Mexico | Increase |
|  | Functional diversity | Local | 24,710,000 | 5 | 2.50 | 40 | 1971-2010 | Canada, USA, Mexico | Decrease |
|  | Functional evenness | Local | 24,710,000 | 5 | 2.50 | 40 | 1971-2010 | Canada, USA, Mexico | Increase |
|  | Functional richness | Local | 24,710,000 | 5 | 2.50 | 40 | 1971-2010 | Canada, USA, Mexico | Increase |
|  | SR | Local | 24,710,000 | 5 | 2.50 | 40 | 1971-2010 | Canada, USA, Mexico | Increase |
| Sorte and Boecklen (2005) | Evenness | Local | 9,834,000 | 1 | 2.50 | 36 | 1968-2003 | USA | Decrease |
|  | SR | Local | 9,834,000 | 1 | 2.50 | 36 | 1968-2003 | USA | Increase |
| Van Turnhout et al. (2007) | SR | Regional | 41,543 | 4 |  | 28 | 1973-2000 | Netherlands | Increase |
|  | SR | Local | 41,543 | 4 |  | 28 | 1973-2000 | Netherlands | Increase |
| Wretenberg, Pärt, and Berg (2010) | SR | Local | 1,800 | 1 |  | 11 | 1994-2004 | Sweden | Decrease |
| Keller et al. (2020) | SR | Regional | 11,075,000 | 30 |  | 45 | 1972-2017 | Europe | Increase |
| Monnet et al. (2014) | SR | Local | 551,695 | 1 | 0.09 | 22 | 1989-2012 | France | Increase |
|  | Spatial beta-diversity | Local | 551,695 | 1 | 0.09 | 22 | 1989-2012 | France | Decrease |
|  | Functional beta-diversity | Local | 551,695 | 1 | 0.09 | 22 | 1989-2012 | France | Decrease |
|  | Gamma-diversity | Regional | 551,695 | 1 | 0.09 | 22 | 1989-2012 | France | Increase |
|  | Functional Gamma-diversity | Regional | 551,695 | 1 | 0.09 | 22 | 1989-2012 | France | Decrease |
| Spasov et al. (2017) | SR | Local | 110,994 | 1 |  | 6 | 2005-2006 | Bulgaria | Stable |
| Jarzyna and Jetz (2017) | SR | Local | 9,834,000 | 1 | 2.50 | 42 | 1969-2010 | USA | Increase |
|  | Functional diversity | Local | 9,834,000 | 1 | 2.50 | 42 | 1969-2010 | USA | Increase |
| Tingley and Beissinger (2013) | SR | Local |  |  |  | 99 | 1911-2009 | USA | Decrease |
| La Sorte et al. (2009) | SR | Local | 9,834,000 | 1 | 2.50 | 27 | 1975-2001 | USA | Increase |
| La Sorte (2006) | SR | Local | 9,834,000 | 1 | 2.50 | 36 | 1968-2003 | USA | Increase |
| Ma et al. (2012) | SR | Local | 125,384 | 20 |  | 26 | 1965-2005 | USA | Increase |

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