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Effects of climate change on biodiversity in Austria

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Abstract

Climate change alters the abiotic conditions in our environment and therefore affects organisms and ecosystems. This review summarizes the available research for Austria and neighbouring Central European countries on already observed and predicted consequences of climate change for biodiversity. I found that species richness is the most common biodiversity metric assessed, whereas functional diversity, range size and extinction risk are barely considered. Flora and fauna are equally well represented in literature, but mammals, reptiles and fish are missing entirely or are only considered in studies on single species or species groups that were not considered here. Other organismal groups (e.g. microorganisms, lichens, fungi) are studied less often but affected more frequently. Biodiversity metrics change more frequently in forests compared to rivers and in response to rising temperatures compared to decreasing water availability. Temperature occurs in almost every publication as a proxy for climate change, whereas water availability is measured more infrequently and considered rather in simulations than in empirical studies. Most communities and ecosystems in Austria already react to climate change, and while some biodiversity metrics increase, this might come at the cost of others. Aquatic ecosystems are assessed less frequently than terrestrial ones, with natural grassland and forests being the best studied ecosystems. The Alps and mountainous ecosystems are overstudied, whereas there is a lack of research in other regions. A broader view on ecosystems and taxonomic groups and on interactions with land use would benefit an integrated understanding of the effects of climate change on biodiversity.

Zusammenfassung

Der Klimawandel verändert die abiotischen Bedingungen in der Umwelt und beeinflusst darüber Organismen und Ökosysteme. Diese Review fasst die für Österreich und benachbarte mitteleuropäische Länder verfügbare Literatur über bereits beobachtete sowie vorhergesagte Auswirkungen des Klimawandels auf die Biodiversität zusammen. Ich habe herausgefunden, dass Artenreichtum das am häufigsten angewendete Biodiversitätsmaß ist, wohingegen funktionelle Diversität, Arealgröße und Aussterberisiko kaum berücksichtigt werden. Flora und Fauna sind in der Literatur gleich gut repräsen-

tiert, aber Säugetiere, Reptilien und Fische fehlen völlig oder wurden nur in Studien über einzelne Arten bzw. Artengruppen untersucht, welche hier nicht miteinbezogen wurden. Andere Organismengruppen (z.B. Mikroorganismen, Flechten, Pilze) wurden zwar seltener untersucht, waren aber häufiger von Klimawandelfolgen betroffen. Steigerungen der Biodiversität treten in Wäldern häufiger auf als in Flüssen, und als Antwort auf steigende Temperaturen verglichen mit sinkender Wasserverfügbarkeit. Temperatur wurde in fast jeder Publikation als Proxy für den Klimawandel verwendet, wohingegen Wasserverfügbarkeit deutlich seltener herangezogen wurde und das häufiger in Simulationsstudien als in empirischen Studien. Die meisten Artengemeinschaften und Ökosysteme in Österreich reagieren bereits auf den Klimawandel, und während die Biodiversität in mancher Hinsicht ansteigt, könnte dies auf Kosten anderer Bereiche geschehen. Aquatische Ökosysteme wurden seltener betrachtet als terrestrische, wobei natürliches Grasland und Wälder am häufigsten untersucht wurden. Die Alpen und Bergökosysteme wurden übermäßig erforscht, wohingegen es in anderen Regionen an Forschung mangelt. Neben mehr Forschung zu den Interaktionen mit Landnutzung braucht es einen breiteren Blick auf Ökosysteme und taxonomische Gruppen, um ein besseres und vollständigeres Verständnis der Auswirkungen des Klimawandels auf die Biodiversität zu fördern.

Introduction

Climate change is one of the central research topics of our time. It affects humanity with rising temperatures, droughts, sudden floods, changing precipitation patterns, thawing permafrost, etc. (IPCC 2022), one more worrisome than the other. Fighting the climate crisis has become a major concern for many governments and organizations worldwide, not least because its direct and indirect effects cause social and economic problems. However, there is a second crisis, whose effects are equally grave and in many parts even more difficult to predict, because its course is intertwined with climate change, land use change, nutrient cycles, socio-economic development and political decisions. Nevertheless, the biodiversity crisis deserves just as much attention as it is reaching a temporary maximum with the sixth mass extinction in our planet's history (Cowie et al. 2019, IPBES 2019).

Lai et al. (2022) identified many hotspots of climate change in the part of Central Europe treated in this study. Indeed, Gobiet et al. (2014) state in their review that temperature increases of + 0,25 °C per decade have to be expected in the Alpine region, and even + 0,36 °C per decade after the middle of the 21st century (assuming the A1B emission scenario of the then-actual third IPCC report). This said, they point out that the observed warming has exceeded the one expected in the past, reaching 0,5 °C per decade (Gobiet et al. 2014). Apart from this, they report predicted changes in the seasonality of precipitation, radiation and relative humidity, as well as more intense floods and droughts (Gobiet et al. 2014). The question is: Will organisms and ecosystems be able to keep pace with these tremendously fast changes?

Over the last decades and with an increasing awareness for the importance of the topic, a lot of research on the effects of climate change on biodiversity has been conducted all over the world and accumulated to a considerable amount of knowledge. However, if one is interested in a certain region or country, it is not always straightforward to access the right information, which makes meta-analyses and reviews a necessary and helpful starting point for many researchers. Additionally, there are certain shortcomings in the distribution of research: even in the rather well-studied Europe, there are biases towards certain regions which host popular study sites (Brighenti et al. 2019). In Central Europe, reviews exist for the Alps and Switzerland, such as for example Vitasse et al. (2021), Brighenti et al. (2019) or Vittoz et al. (2013), but not for other countries such as Austria, or for (bio-)geographically defined regions of the continent. In addition to that, it can be difficult to distinguish between the effects of direct human action such as land-use change or habitat fragmentation and those of human-induced climate change, which often also interact with each other (Mantyka-Pringle et al. 2012). Compiling the relevant information is nevertheless crucial for transforming it effectively into scientific advice and policies.

As Vittoz et al. (2013) emphasize, assessing the impacts of climate change on a national scale is important because decisions are made at this level rather than on a global or continental scale. Here, I reviewed publications from Austria and its immediate surroundings to provide an overview on the consequences of climate change for biodiversity and to assess the state of research on this topic in Austria and Central Europe. I included studies from beyond the Austrian borders, since although Austria is a rather small country, it has very different habitats and a considerable climatic variability due to its geographical location between climatically more homogenous regions. As a consequence, it had to be assumed that certain habitats with only minor distribution in Austria would be underrepresented in publications from Austria, but could rather be found in those from neighbouring countries where they are more common.

The Austrian Panel on Climate Change (APCC) is currently working on the second Austrian Assessment Report on Climate Change. The first Austrian Assessment Report on Climate Change (APCC 2014) summarized the extent of climate change in Austria, its consequences for the environment and society, as well as possible strategies for adaptation and mitigation. It shows that there is growing evidence for changes that have already taken place and growing certainty for those which are predicted to occur in Austria: retreating glaciers and thawing permafrost, rising temperatures, changing precipitation patterns, drying of running and standing waters (e.g. Lake Neusiedl) and increased risk for extreme events such as floods and wildfires (APCC 2014). Currently, the southeastern part of Austria is receiving 10 - 15 % less precipitation than 150 years ago, whereas the western part gets the same amount additionally (APCC 2014). Large parts of Austria are located within the Alps, where temperatures are rising 1.6 to 2.5 times faster than in the rest of the Northern hemisphere (Foster & Rahmstorf 2011; APCC 2014; Vitasse et al. 2021). This means that in Austria, the average temperature rose by 1 °C between 1980 and 2014 and it will have risen by 1.4 °C more by 2050 (APCC 2014). Still, those climate change effects which could be observed in the past 250 years will even be exceeded by those to come by the end of the 21st century (APCC 2014). Gobiet et al. (2014) state that 40 - 60 % of snow cover will get lost in the alpine zone, and snow will vanish almost completely below 1500 m a.s.l., which will have serious consequences not only for the organisms and ecosystems there, but also for hydrological regimes in a much larger region and for humans in terms of natural hazards in the touristically attractive Alps. Extreme events have considerable impacts on the Austrian economy, and the intensification of geographical and seasonal differences generates additional costs (APCC 2014). Drier summers and wetter winters can also impact the vegetation period and the performance of plants and the organisms which depend on them (APCC 2014).

This master thesis is aiming to contribute to the second Austrian Assessment Report on Climate Change by providing a compilation of the relevant literature on the effects of climate change on biodiversity in Austria (and neighbouring regions). Initially, the aim was to gather enough data to perform a meta analysis for at least one of the research questions or biodiversity response categories. However, this could not be realized due to a lack of adequate documentation of effect sizes and statistical details in the research articles. As a consequence, this work cannot provide any insight on the extent of the specific effects of climate change on biodiversity. Instead, it examines and quantifies the different dimensions of biodiversity research on climate change, identifies research gaps and shows general patterns of beneficial, neutral or disadvantageous climate change effects. The following research questions were addressed in my study:

1. Which metrics of biodiversity (e.g. species richness, species turnover, functional diversity) are used in the literature to assess the effects of climate change on biodiversity in Austria and neighbouring Central European regions? Which taxonomic groups are assessed? Which aspects of climate change (e.g. temperature, drought) are considered?

2. How does climate change affect biodiversity in Austria and neighbouring regions? Are there taxonomic groups or ecosystems which are affected more or less than others? Are the consequences beneficial or disadvantageous for biodiversity in terms of species richness and diversity, population and range dynamics, functional diversity, community composition, biotic interactions and extinction risk?
3. Are there any predictions on how the biodiversity in Austria and neighbouring regions will be influenced by climate change in the future? Which time frames are addressed and what kind of scenarios are used?
4. Are there any taxonomic groups, ecosystems or regions which are addressed less in research on climate change effects than others? Are there any other literature gaps in research concerning the effects of climate change on biodiversity in Austria and Central Europe?

Methods

Literature search and selection

The first step was to develop a search string (see appendix for exact wording) that would on the one hand include the whole breadth of biodiversity research and on the other hand focus only on those studies looking at climate change effects which were conducted in Austria and its neighbouring countries. This was achieved by combining three parts: a) search terms concerning climate change; b) terms describing biodiversity and major organismal groups and c) terms defining the countries or regions in which the studies should have taken place. As two thirds of Austria are located within the Alps, which therefore constitute an important factor for Austria's biodiversity, the French Alps were included additionally. Concerning Germany, only the southern parts were included as the higher latitudes' climate and habitats differ too much from Austria's. For similar reasons, the Italian Alps were the only part of Italy included. These restrictions for France, Germany and Italy were applied by not including the countries' names in the search string but finding studies from these nations via the term "Alps".

The literature search was conducted in Scopus without any additional filters on February 23rd, 2023 and yielded 9313 results. These were sorted by title in a first step, resulting in a list of 768 publications which made allusions to climate change effects on biodiversity in their title, and whose abstracts were scanned in a second step (Fig. 1). Those of the 768 articles that appeared to be potentially relevant in terms of their study focus on climate change effects on biodiversity as well as their geographical extent and location were coded into categories describing the studied biological and climatic aspects. Subsequently, studies focussing only on changes in biomass, vegetation cover, phenology, physiology, tree-line location, ecosystem functions and behaviour as response variables or increasing CO_2 and nitrogen concentrations as explanatory variables were excluded from further analysis due to the limited amount of time and labour capacity for this work. Another reason for exclusion was a focus on single species or genera, because this work is supposed to give an overview of climate change effects on biodiversity as a whole rather than summarize the effects on particular species which were chosen either for them being rare or easy or convenient to study. Reviews were also excluded but taken into account for the

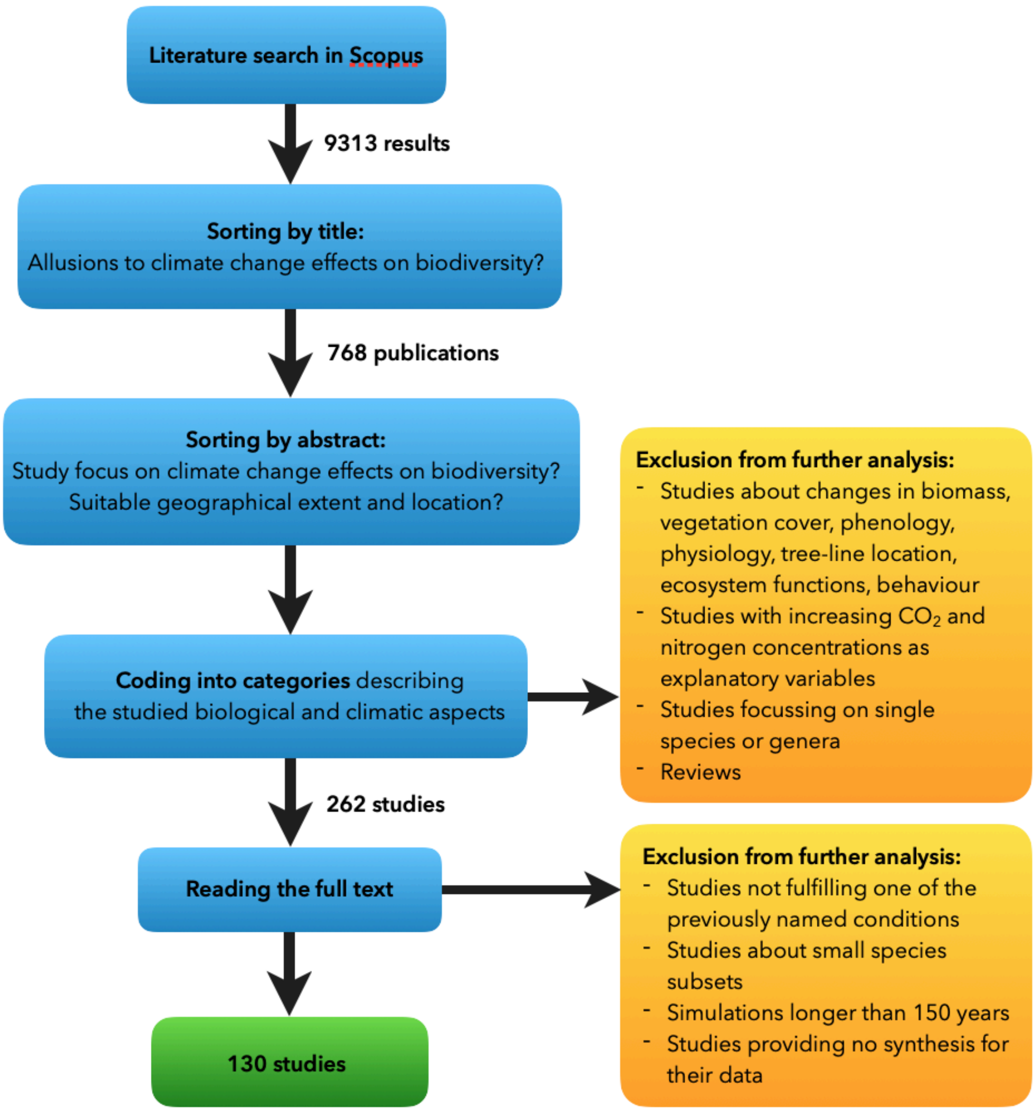

Figure 1: Flowchart describing the process of literature selection.

discussion later. One study (Habel et al. 2023) which was published after the search had been conducted was added subsequently after indication by Stefan Dullinger.

This process resulted in 262 research articles which were then read thoroughly. However, during closer examination, it became clear for half of them that they did not fit the purpose of this study for one of the following reasons:

- Many studies looked at a very small subset of species (e.g. three bird species) and were rather similar to the already excluded single species studies.
- Some abstracts had been misleading and it became obvious in the methods section that the study belonged to an excluded category.
- The geographical extent of the study was either not located within the defined area (see above) or too large (e.g. all of Europe).
- It was a mere documentation of the present state but had no connection to a change in climatic conditions.

- A few climate simulations were run for more than 150 years. As the precision of predictions decreases the further they reach into the future and as there are no official climate change scenarios for this time frame, they were not taken into consideration.
- Some studies just listed data on single species without providing a synthesis.

Analysis and evaluation

The metadata of the remaining 130 studies, their study design and results were documented in a standardized way (Table 1). If more than one taxonomic group, ecosystem type or climate change variable had been examined, an extra separate entry was made, but only if the respective results were provided separately. A complete list of all publications used for this review can be found in the appendix. An additional CSV table in the online appendix (see enclosed CD for the print version) compiles the information listed in table 1 for each study.

Table 1: Information on the data collected for each research article

Metadata	Title, author(s), year of publication, source, doi
Study design	- Country and region with coordinates - Elevational zone and transect start / end in m a.s.l. - Aquatic / terrestrial; ecosystem according to Corine Landcover categories - Taxonomic group; neobiota - Study over time or space-for-time-substitution; length, start and end year of study period, continuity of sampling - Field or lab study, experiment or observational study; simulation (period start, end, length; climate scenario) - Climate change variables: temperature (and its "unit": °C, elevation, …), water availability, glacier / snow retreat, indirect climate change effects, land use interactions
Results	- Effect direction: positive / no effect / negative - Classification of biodiversity change into nine categories: species richness, species diversity, functional diversity, movement along an elevational gradient, community composition, population dynamics, biotic interactions, land cover, range size and extinction risk - For each result: effect size and unit, statistical information

The studies were published between 2003 and 2023, with a clear trend towards increasing numbers of publications with time (Fig. 2): There were only three publications between 2003 and 2006, then on average six publications per year between 2007 and 2018. From 2019 on, each year more than eleven studies were published on the effects of climate change on biodiversity, which is why 56 of the 130 articles were published within the last five years before the search was conducted.

Figure 3 shows the distribution of study sites within Austria and surrounding countries. The elevation covered ranges between 110 m a.s.l and 4634 m a.s.l., with study areas located between the French Jura Mountains in the West and the High Tatra Mountains in the East as well as between the northern parts of the Czech Republic and the National Park in Mercantour in the southern Alps. The climate in this temperate region is influenced by both the Mediterranean and Atlantic, but there are already some continental tendencies in the East, and the Alps have to be emphasized as playing a major role in it too (Pils 2023).

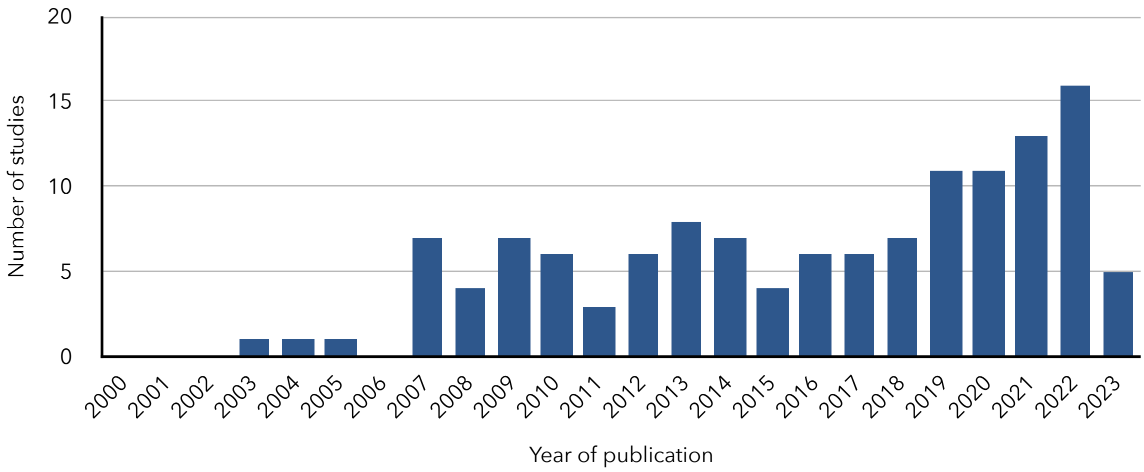

Figure 2: This histogram shows the respective number of reviewed studies published in the years 2000 - 2023. 130 studies were reviewed in total. During the search process, no filter concerning the year of publication was applied.

As the results were sorted into categories, it is important to note that the meaning of the reported effect direction strongly depends on the biodiversity category the entry belongs to and that positive does not necessarily mean beneficial, but indicates an increase. This would be the case for the categories species richness, species diversity, functional diversity, elevational gradient, population dynamics and range size. A positive effect direction says that e.g. the mean distribution of the studied plant community moved upwards along the elevational gradient or that the number / frequency of individuals increased. However, a positive effect direction in the category extinction risk would mean that the risk for extinction increases - although this is a negative message for biodiversity. There are other categories which need to be treated with caution: For example, if an effect of climate change on community composition was reported, this would be documented as a positive effect in the sense that there was a change in community composition. If there was no change, the effect direction would be 0 = no effect. The same applies to changes in land cover and biotic interactions, although a reported increase in competition could be judged to be disadvantageous for biodiversity. An example for a negative effect direction in the category biotic interactions would be a case in which the intensity of a mutualistic relationship decreased due to climate change. These differences in the meaning of seemingly simple classifications show how difficult it is to communicate the whole spectrum of biodiversity research while staying consistent in terminology. Table I in the appendix gives a detailed description of the biodiversity categories.

The climate change variables include factors such as temperature and water availability, which are commonly used to define weather and climate trends. Here, they are used in a broader sense. A temperature increase can be measured in °C, but it can also be recognized by the change of temperature indicator values of the plant community present in the study area. To account for the fact that climate change is part of the much larger range of different changes summarized as "global change", the category land-use interactions was added, although it is no climate factor. Nevertheless, land use does influence the water availability, e.g. by depleting ground water reservoirs, and strongly influences ecosystems via nutrient cycles, which is why it should be considered an environmental variable. Also, land use change and climate change take place simultaneously, probably influencing each other's effects on biodiversity.

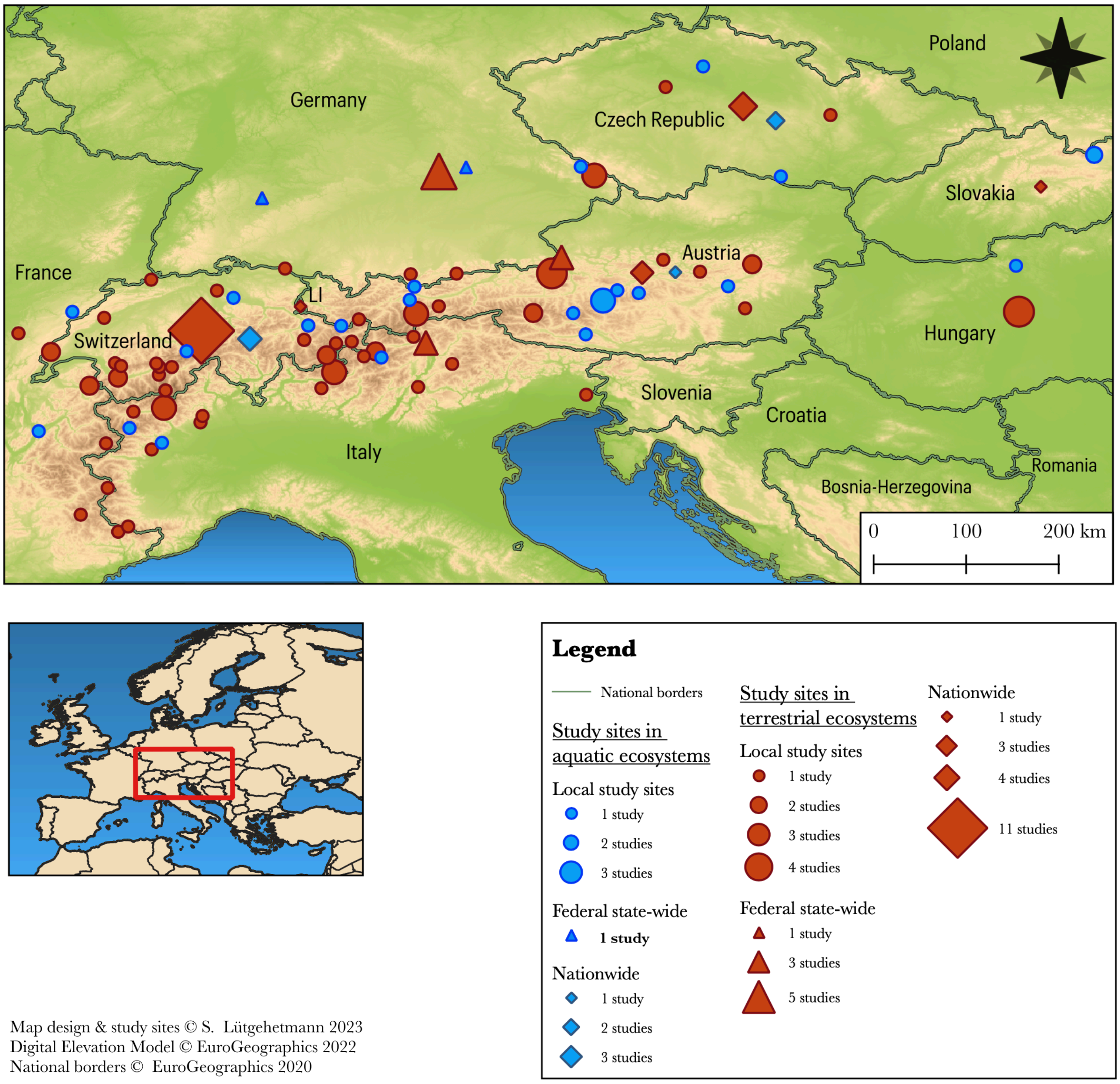

Figure 3: The map of central Europe above shows the location of all study areas from the research articles included in this review (n = 130). In those studies using nationwide data, a reference point was added at the center of the country. Similarly, if studies used data from different sites located less than a hundred kilometers apart and did not separate them in their results, a reference point was set between these sites. Different colours indicate whether the publication treated aquatic (blue) or terrestrial (red) ecosystems. The small map on the left indicates the location of the overall study area in Europe.

Statistical analysis

I used the collected data to, first, analyze whether the taxonomic group (fauna / flora / others), ecosystem type (aquatic / terrestrial), ecosystem (forests / grasslands / lakes / rivers / others), climate change variable (temperature / water availability / snow or glacier cover / interactions with land use / indirect climate change effects) and study length (in years) influence the effect direction (positive / no effect / negative) of the biodiversity response. This was done separately for empirical studies and (future) simulations studies to separate data from models and to allow for the different time frames addressed. I used a generalized linear mixed model for this analysis. In this model, the circumstance that the results stem from different publications was considered by using the study ID as grouping variable and estimating a random intercept term for it. I could not account for random effects of the individual predictor variables because the dataset was too small. The model hence accounts for the fact that the different approaches and other peculiarities of each study may affect the *a priori* likelihood that the study will have detected an effect of climate change on the biodiversity metric considered, but not that they may also change the sensitivity to detect differences among levels of the predictor variable. The number of datasets, i.e. entries for e.g. a certain biodiversity response of a particular group under a particular climate scenario, varied considerably among studies and reached a maximum of 36 (see Figure I in the appendix for a histogram showing the number of result entries per study).

To avoid problems with model fitting that emerged when I assumed a multinomial distribution of the response variable (no / positive / negative effect), I divided model building into two steps: A first model type tested whether there was any influence of the above mentioned predictors on the absence or presence of an effect caused by climate change, independent of whether this effect was positive or negative. A second model type tested whether there was any influence on the effect direction, that is whether the effect on biodiversity was positive or negative. As both model types had too many factor levels when all predictor levels were used simultaneously, I did a series of univariate models instead. In all models, I assumed a binomial distribution of the response variable.

Another generalized mixed effects model of the same type and structure was built to test whether there is any effect of the predictors taxonomic group, ecosystem type and study duration on the probability of having a study looking at drought effects. Additionally, an extra model run was performed with the whole dataset to test whether being an empirical or simulation study had any influence on detecting positive or negative effects of climate change on biodiversity.

A last model searched for the influence of taxonomic group, ecosystem type and climate change variable on the probability of a study being a simulation study (vs. an empirical study). Again, the publication ID was added as a random effect. All of these latter models also had too many factor levels and were hence run run as a series of univariate models as well.

All statistical analyses were performed in R (Version 4.1.2, R Core Team 2021). The R package lme4 (Bates et al. 2015) was used to build mixed models. All graphs were designed in Numbers (Version 13.1, Apple Inc. 2008-2023). Maps were designed with QGIS 3.28.8 Firenze (QGIS Development Team 2019).

Results

Despite the relatively small size of the country, a majority of 34,6 % of the studies found using the search string and selection criteria (n = 130) was conducted in Switzerland (Fig. II in the appendix). Austria and Italy had a share of 26,9 % and 21,5 % respectively. There were no studies from Slovenia and just very few from Slovakia (2,3 %) and Hungary (4,6 %). This observation still holds when considering former names of these nations. Within Austria, a clear focus on the Alps becomes visible (Fig. 3). Just twelve of the 130 publications worked across borders and treated areas in different countries.

Almost all of the 130 studies investigated the effects of changing temperatures on biodiversity, whereas 42 looked at the effects of reduced water availability (Fig. 4). Of these, 32 investigated the joint effects of temperature and water availability. In contrast, only few studies dealt with the effects of a retreating snow or glacier cover and the diverse indirect effects of climate change. Indirect climate change effects taken into account by the studies reviewed here are: the alteration of habitat for birds in terms of forest expansion and loss of grassland due to climate change, the occurrence of wildfires, differing organic matter input for soil microbial communities due to range shifts of species from warmer climates, changes in water transparency and conductivity and the proportion of a pond covered by vegetation. Interactions of climate change effects with land use were considered by 13 studies.

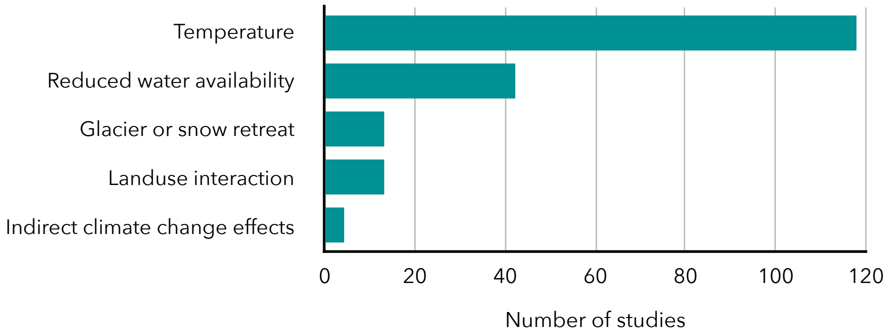

Figure 4: The graph shows how the different variables of global change are represented by the dataset. Temperature and reduced water availability were jointly studied in 32 cases. Glacier / snow retreat was usually combined with temperature, just two studies focused on this variable alone and one combined it with both temperature and water availability. Land use interactions were studied for temperature and temperature + water availability, just once for water alone. Indirect climate change effects were studied alone or with the other variables except for glacier / snow retreat.

Most of the simulation studies were conducted based on official IPCC climate change scenarios (Fig. 5), usually comparing an optimistic with a pessimistic scenario. None of the simulations used the new shared socioeconomic pathways (SSPs) scenarios from the latest IPCC reports. Instead, the representative concentration pathways (RCPs) or even older scenarios were applied. Research on changes in ran-

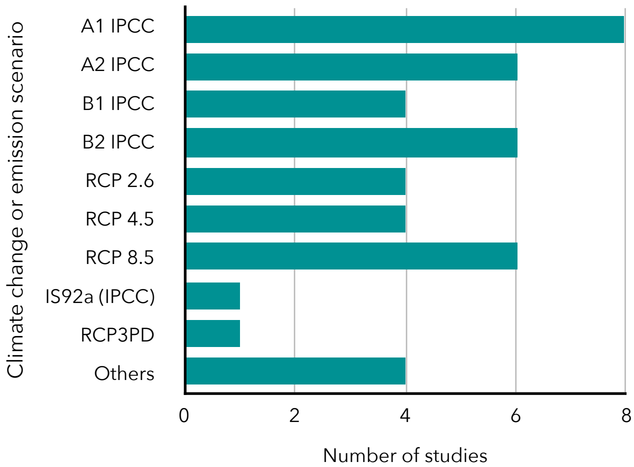

Figure 5: Number of times certain climate change or emission scenarios were used in the simulation studies (n = 24). Multiple counts are possible because many publications compared simulation results among emission scenarios. The category “others“ comprises research articles based on (local) climate change scenarios which were not assigned to any official scenario.

ge size, land cover and extinction risk was (almost) exclusively done via simulations, whereas field studies dominated in all other biodiversity categories (appendix, Fig. III). There were very few laboratory studies. Of the field studies, almost all were observational studies and only few experiments (appendix, Fig. IV). Most studies were studies over time, but about one third used space for time substitution. A majority of empirical studies had a time frame below 50 years, whereas most simulation studies covered between 70 and 110 years, usually running until the end of the 21st century (appendix, Fig. V).

The biodiversity metrics studied most frequently are species richness and community composition (Fig. 6). In contrast, only five research articles were about extinction risk. The nine publications dealing with changes in biotic interactions are not depicted in Figure 6 because they could not be assigned to single taxonomic groups. They treated competition, predation, herbivory, pathogeny, parasitism and hybridization (table II, appendix). Studies treating either flora or fauna occur at almost equal numbers and much more frequently than studies about fungi, lichens, mosses or microorganisms. However, microorganisms had a surprisingly big share in some categories, e.g. community composition.

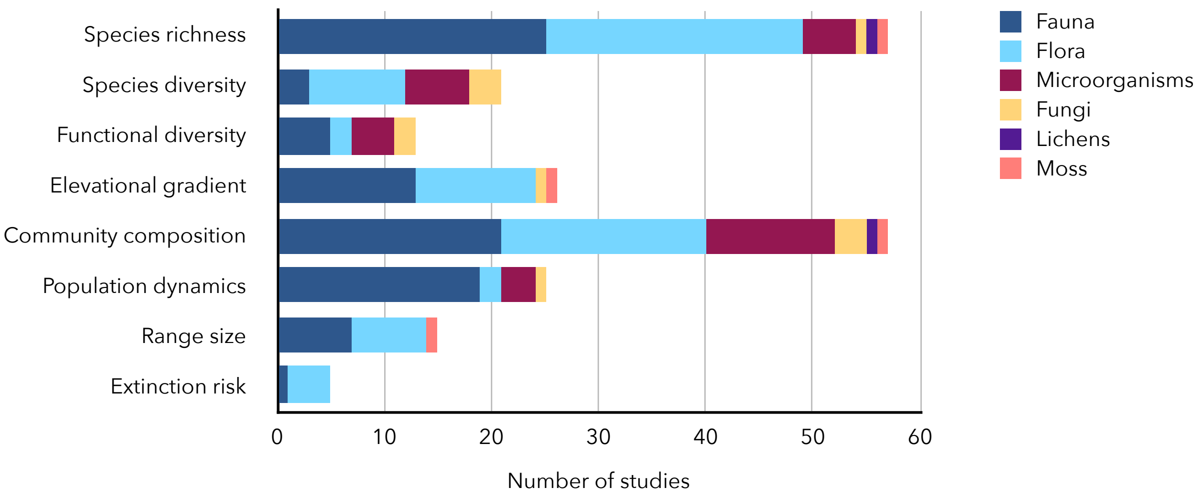

Figure 6: Number of studies per major organism group according to the category of biodiversity variable that was used to measure climate change effects. Both empirical and simulation studies are included (n = 130). Multiple counts are possible due to publications treating more than one organismal group or assessing several biodiversity metrics.

Taking a closer look at the faunal groups (Fig. 7), it becomes obvious that a majority of studies dealt with insects. Mammals, fish and reptiles are entirely missing in the study set, and given the fact that studies about birds and amphibians are comparatively rare as well, it can be summarized that invertebrates were studied a lot more than vertebrates. Also, the share of other organismal groups was surprisingly high (see Table III in the appendix for a list of taxonomic groups included in the two categories “other organisms“ and “other insects“). Only four studies looked at the effects of climate change on endemic species separately and just two at endangered species. Three publications considered neophytes, but just one of them had its main focus on neophytes. No other kind of neobiota were studied separately in any of the other publications.

A majority of 70 studies included several ecosystem types (Fig. 8). Of those focussing on a single ecosystem, most were located in natural grasslands, followed by forests. There were also many studies in aquatic habitats such as alpine lakes and streams. However, vulnerable ecosystems such as inland wetlands and peat bogs were treated by just one and two studies, respectively. The majority of publications did not focus on certain ecosystem types but included several in their analysis. Nevertheless, aquatic and terrestrial habitats never occurred in the same publication.

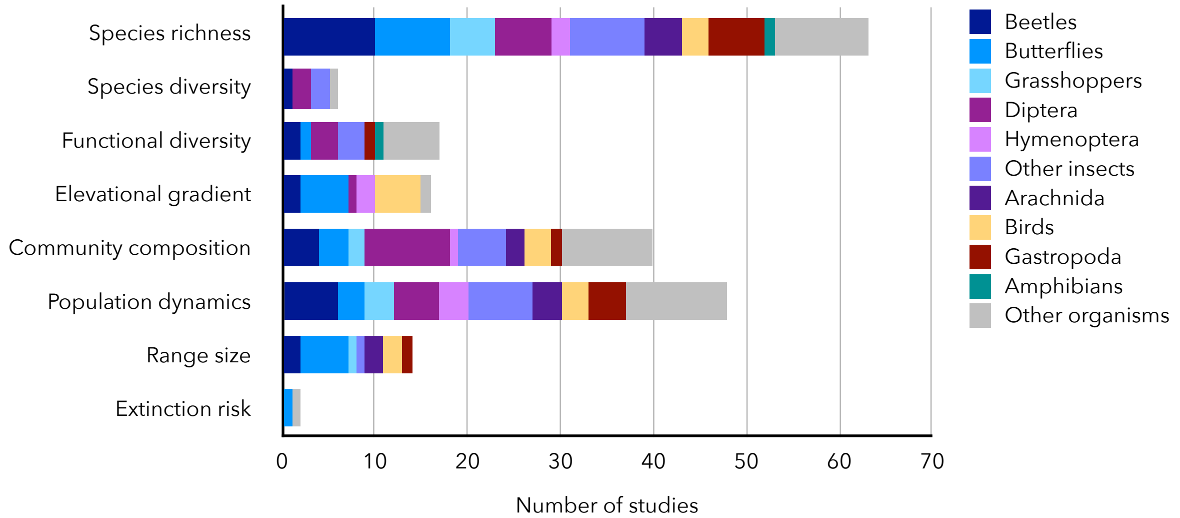

Figure 7: Number of studies on animals per category of biodiversity variable used to measure climate change effects according to faunal group. Both empirical and simulation studies are included (n = 130). Multiple counts are possible due to publications treating more than one organismal group or assessing several biodiversity metrics.

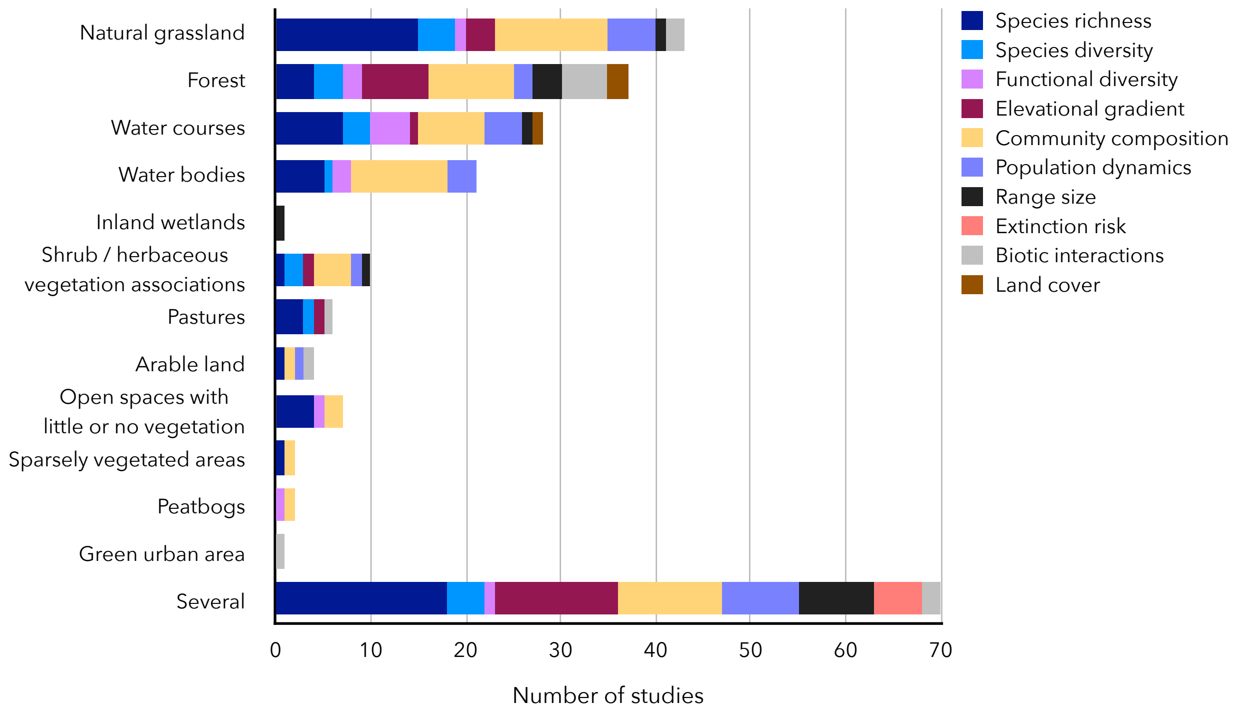

Figure 8: Number of studies per Corine Landcover category according to the category of biodiversity variable that was used to measure climate change effects. Both empirical and simulation studies are included (n = 130). Multiple counts are possible due to publications treating more than one ecosystem or assessing several biodiversity metrics.

The presence of significant effects of climate change on biodiversity was reported by more than two thirds of the publications concerning flora and fauna, and in both aquatic and terrestrial ecosystems (Fig. 9). The general trend of the effect direction differs though between the biodiversity metrics assessed, and in some cases, increases and decreases occurred in equal numbers. Species richness and the intensity of biotic interactions increased in a majority of studies, and there are more examples of increasing than of declining or stagnating functional diversity measures as well. There is no clear picture for species diversity and population dynamics. A majority of the studied faunal and floral communities shifted upwards along the elevational gradient in both aquatic and terrestrial habitats. However, in the latter, about one third of the communities within the studies showed no significant movement uphill, and a small part even moved downwards. About three quarters of all communities were significantly altered by climate change and although there were only few studies about changes in land cover, they all predict significant changes. Range size was predicted to decrease for most organisms. This corresponds to the predicted increase in extinction risk for all studied species. There were no studies about the effects of climate change on the extinction risk and biotic interactions of aquatic organisms.

The research reviewed here shows that climate change already affects biodiversity in Austria: Independently of the ecosystem and the climate change variable, at least two thirds of all results from empirical studies documented the presence of a significant effect (Fig. 10: c, e, g). More than two thirds of all effects present constituted an increase in the respective biodiversity category (Fig. 11: a, c, e, g). Concerning effect absence or presence, the picture is even clearer for the simulation studies, in which the predicted absence of an effect was a rare exception (Fig. 10: b, d, f and h). However, they predicted negative effects more frequently (Fig. 11: b, d, f, h).

Figures 10 and 11 further depict the results from the generalized mixed effects models (see tables IV to X in the appendix for statistical details). The first model type showed that for the empirical studies, it was more likely to see an effect of climate change on biodiversity in a publication about other taxonomic groups than in one about fauna ($p = 0.0531$) or flora ($p = 0.0555$). Neither the ecosystem type (aquatic / terrestrial) nor the ecosystem had any significant influence on the presence of an effect. Likewise, none of the global change variables had a significant influence on it. The study duration had a tendency for a positive influence on the probability to see an effect on biodiversity ($p = 0.0557$) in the empirical studies, but not in the simulations. As almost all of the simulation studies documented the presence of an effect, it was not possible to build a model testing for the influence of taxonomic group, ecosystem type, ecosystem and climate variable on the probability of effect presence or absence in simulation studies. The second model found no significant influence of the studied taxonomic group and the ecosystem type (aquatic / terrestrial) on the effect direction (Fig. 11: a - h). For the empirical studies, there was also no significant effect for ecosystems, but in simulation studies, the effect direction showed a trend to be more likely positive in studies about forest than those about rivers ($p = 0.063$). A longer study duration meant a higher probability of seeing a positive instead of a negative effect ($p = 0.0061$) only in the empirical studies. The probability for a positive effect was higher in empirical studies about increasing temperatures than in those about decreasing water availability ($p = 0.0515$). There was no such difference for the other climate variables and the simulation studies.

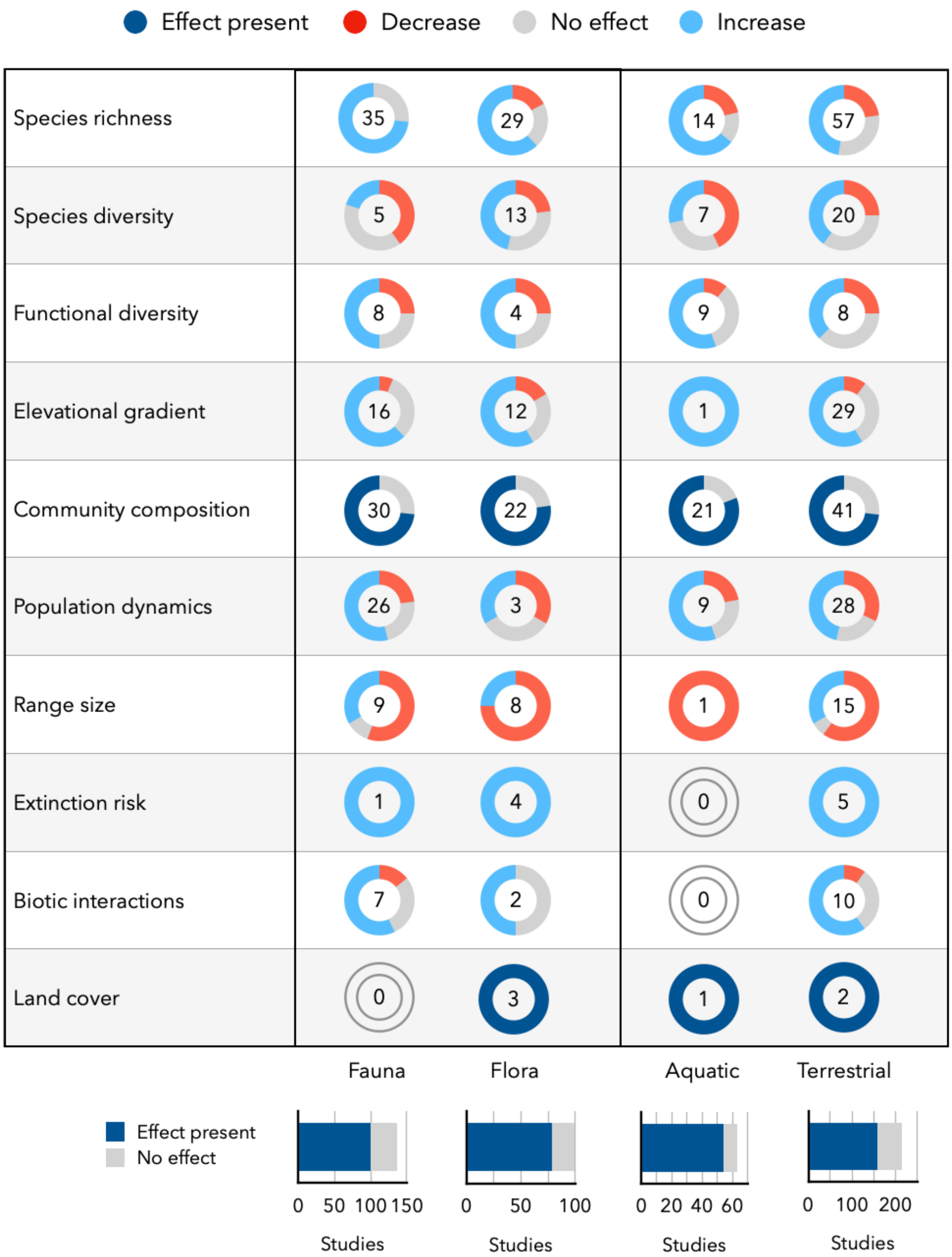

Figure 9: The colours of the circle segments indicate the direction of the measured climate change effect on the biodiversity variable (on the left) for studies about fauna or flora and in aquatic or terrestrial ecosystems. The numbers within the circles give the number of research articles within the respective category. Please note that sums for aquatic and terrestrial studies may exceed those for fauna and flora as they also include other organism groups. It is important to consider each category on its own and to allow for different meanings of the effect directions: An increase in the elevational gradient simply means that the community shifted its distribution upwards along an elevational gradient. A positive sign for species richness indicates an increase in the number of species. Likewise, an increase in extinction risk is represented by the same colour although it is disadvantageous for biodiversity. An increase in the intensity of a biotic interaction such as herbivory would be documented as positive in the sense that it increased. For community composition and land cover, there are only two effect directions: "positive" means that a change took place, "no effect" means that the community or land cover type stayed the same. As a consequence, the effect directions of the different biodiversity categories cannot be summarized by simply adding them up. This is why the small bar charts in the lower part of the figure just distinguish between the presence or absence of an effect.

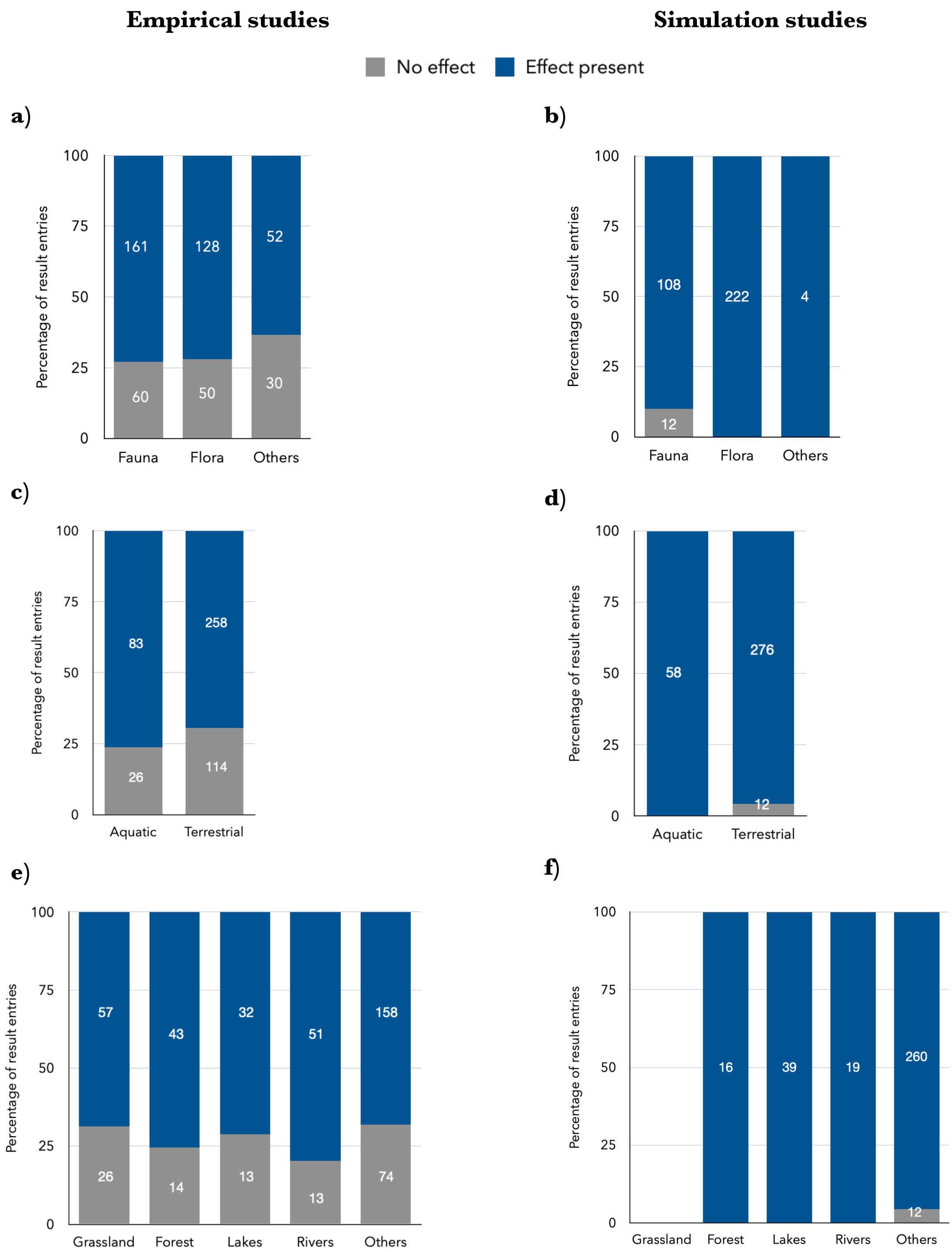

Figure 10: The diagrams show the percentage of result entries documenting either the presence or absence of an effect of climate change on biodiversity. All diagrams on the left (a, c, e, g) represent data from empirical studies, whereas all diagrams on the right (b, d, f, h) represent data from simulation studies. The numbers inside the bars indicate the corresponding number of entries. The predictors were tested for significance with generalized mixed effects models. All of the pairs showed non-significant differences ($p > 0.05$). For the simulation studies, no statistical test could be performed for the question whether the predictors had any influence on the presence of an effect due to the fact that almost all studies documented an effect, so there was no comparison.

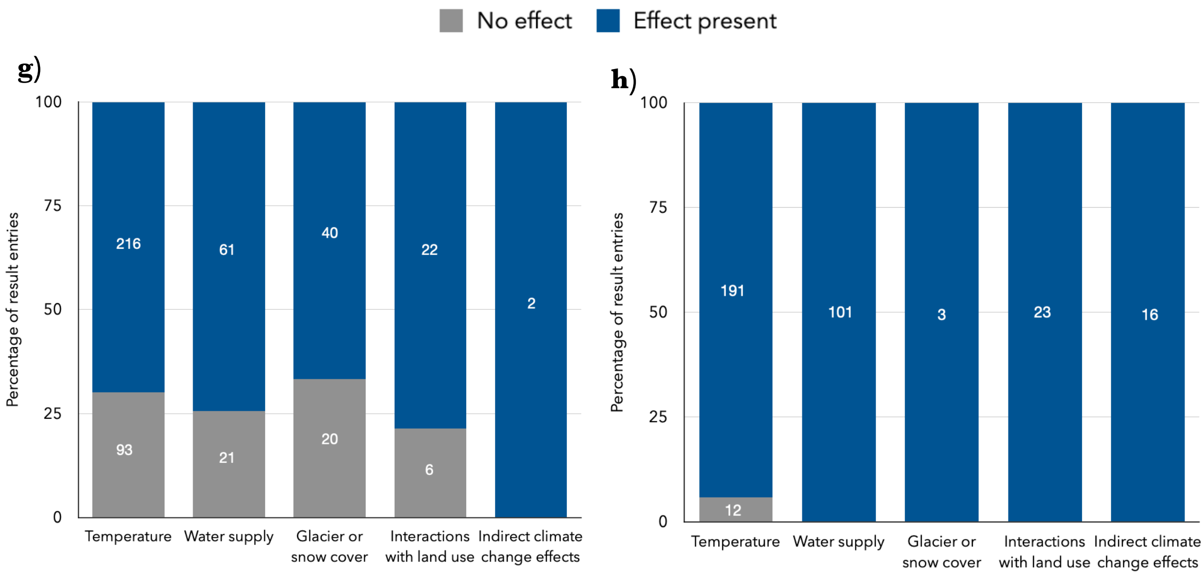

Figure 10: Continued.

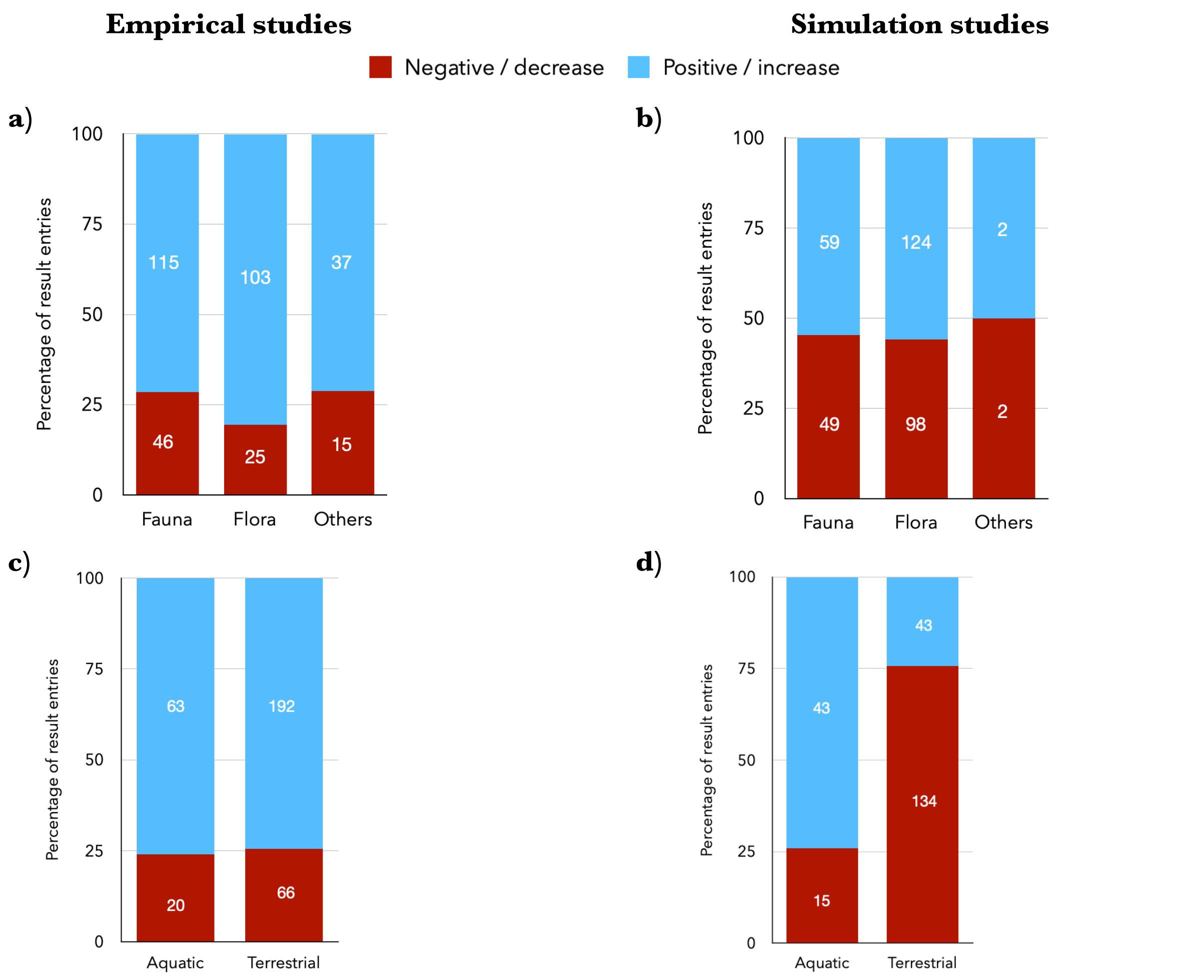

Figure 11: The diagrams show the percentage of result entries documenting either a positive or negative effect. All diagrams on the left (a, c, e, g) represent data from empirical studies, whereas all diagrams on the right (b, d, f, h) represent data from simulation studies. The numbers inside the bars indicate the corresponding number of entries. The predictors were tested for significance with generalized mixed effects models. All of the pairs showed non-significant differences ($p > 0.05$).

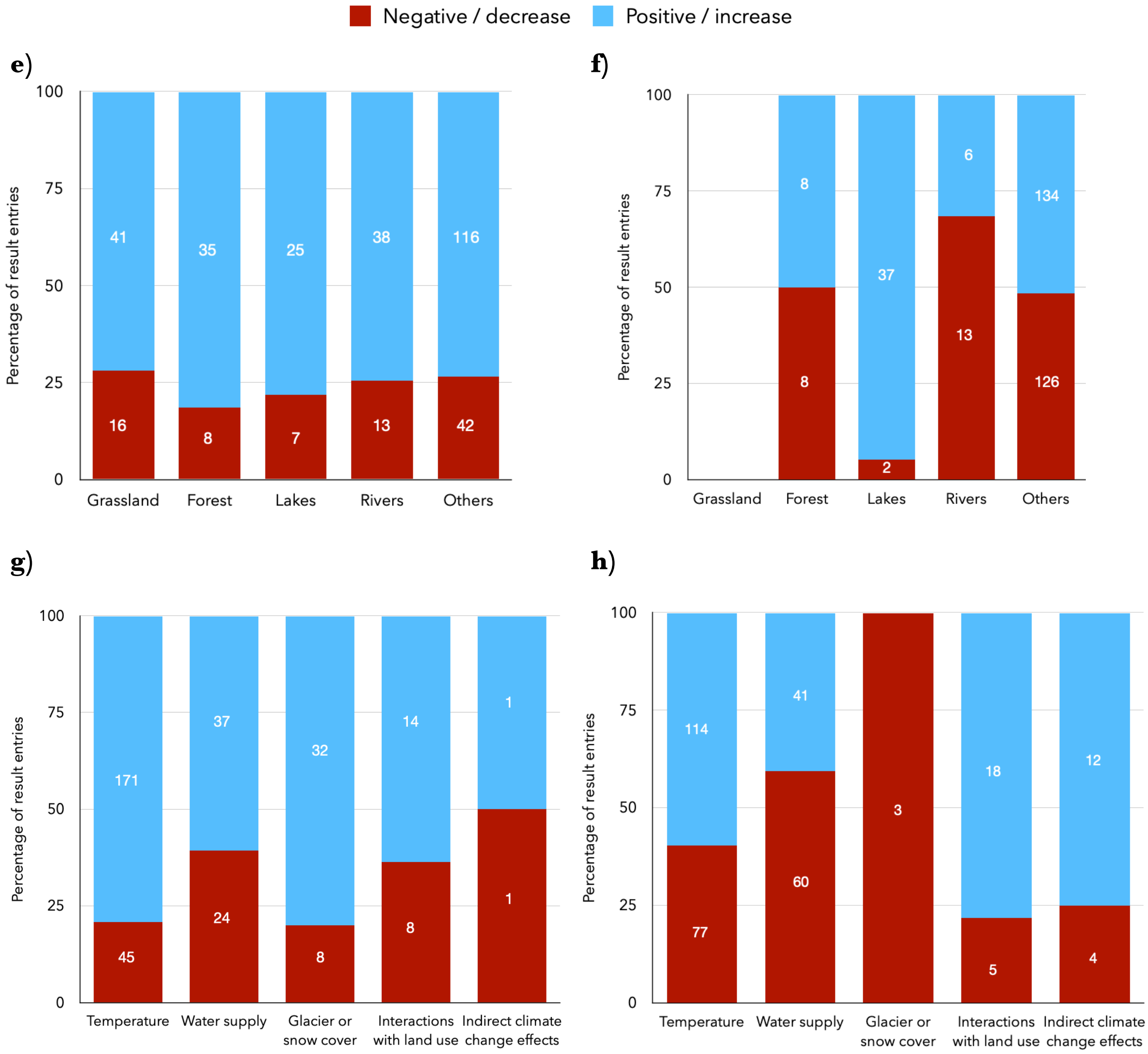

Figure 11: Continued.

The models also showed that there is no significant effect of the ecosystem type (aquatic / terrestrial), the studied climate change variable or the taxonomic group on whether the study was an empirical or simulated one (see tables XI - XII in the appendix for statistical details). Also, there is no influence of taxonomic group, ecosystem type or study length on whether the study was about the consequences of drought, precipitation reduction or any other form of water shortage (see tables XIII - XVII in the appendix for statistical details). However, simulation studies treated this topic significantly ($p < 0.001$) more often than empirical studies.

As indicated in the introduction, the documentation of effect sizes and statistical information was insufficient in many publications (see Figure VI in the appendix), so that a meta analysis could not be performed.

Discussion

The 130 articles show that research on climate change in Austria and Central Europe covers a long time period and many different taxonomic groups and ecosystems. They assessed the consequences for many aspects of biodiversity, ranging from species richness and community composition to biotic interactions, showing that significant climate change effects are already observable and will further occur in the century to come. Although some topics could receive more attention, the current state of research provides an impressive and surprisingly broad knowledge base on the effects of climate change on biodiversity.

<u>Which aspects of climate change have been assessed and where?</u>

Almost every study used temperature to quantify climate change. This might be because on the one hand, data on temperature are available for long time periods and easier to predict than e.g. precipitation patterns. On the other hand, most studies took place in the Alps, where temperatures are rising faster than in the rest of the Northern hemisphere (Foster & Rahmstorf 2011; Vitasse et al. 2021), meaning that temperature seems to be at the top of the list of quickly changing environmental parameters. Also, many other environmental parameters are influenced by temperature, e.g. the cover and duration of snow, thawing of permafrost, precipitation and radiation. Only few studies included indirect climate change effects in their analyses. Apart from this, only 13 publications considered interactions with land use. This might be because Austria and Central Europe are highly urbanized and there exist only few regions which still escape strong impacts from humans. Nevertheless, if interactions between land use and climate change exist, they would concern large parts of Austria and need to be understood before comprehensible mitigation plans can be made. Both land use interactions and indirect climate change effects may alter the results significantly as Rosset et al. (2010) show for aquatic organisms in Swiss lakes: Their different predictions for species richness of Gastropoda, Coleoptera, Odonata, amphibians and plants are based on the A2 IPCC emission scenario. They show that by the end of the 21st century, species richness will increase for all taxonomic groups, but for the flora, the magnitude of this effect is strongly influenced by the degree of land use change (e.g. nutrient enrichment in high alpine ponds) and the strength of a set of indirect climate change effects (Rosset et al. 2010).

Relatively few studies included water availability or the retreat of glaciers and snow in their assessment of climate change effects on biodiversity. Of those who did, most were about aquatic organisms in alpine streams, e.g. Niedrist & Füreder (2021) who found that increasing water temperatures and glacier retreat lead to an increase in species richness of + 1,8 taxa per 1 °C in Hohe Tauern National Park in Austria. Indeed, a majority of the studies reviewed here documented the presence of significant climate change effects on biodiversity, which meant an increase of the biodiversity metric in most cases. The predicted decreases in snow cover and duration will make room for new competitors from lower elevations previously detained by snow cover and duration (Gobiet et al. 2014). However, Rosbakh et al. (2014) show that not all alpine plant communities respond in the same way: Their data from Berchtesgaden National Park covering 50 years show that whereas species richness in the subalpine zone was unaffected by climate change, it increased by 41 % in the low alpine zone, but decreased by 24 % in the high alpine zone (Rosbakh et al. 2014). This emphasizes the conclusion by Gobiet et al. (2014) that the climate in the Alps is strongly influenced by local features between the deeply carved valleys and high summits, making it very difficult to predict. According to the authors, trends for precipitation can vary strongly both locally and regionally within the Alps, but also depend on elevation and season (Gobiet et al. 2014).

Although there were a few studies on extreme events in the dataset, the general picture is that there is only relatively little consideration of the topic, given the fact that they will increase drastically in frequency and strength. However, there is awareness for the topic, as calls for more short-term studies on the consequences of extreme events (Rogora et al. 2018) or references to the extreme drought in Switzerland 2003 as an example for the diverse consequences of climate change show (Gobiet et al. 2014).

Research in the most frequently studied ecosystems (natural grasslands, forests, lakes and rivers) concentrated on the Alps. I found that negative effects are to be expected more frequently in rivers than in forests. It may be hypothesized that this may be due to the fact that in addition to rising temperatures and changes in precipitation, which affect forests too, rivers are also subject to major changes in their hydrological regime if glaciers retreat and snow cover decreases. However, this predicted difference between the two ecosystems does not show in the observed data. The high share of studies investigating several ecosystems can be explained by the fact that transect studies usually did not distinguish in their results between the ecosystems the transect crossed. Nevertheless, aquatic and terrestrial ecosystems never occurred in the same study. Brighenti et al. (2019) criticize that research often takes place at the same locations, e. g. at Val Rosegg in Switzerland or Hohe Tauern in Austria, whereas other regions such as the Western Alps receive relatively little attention. Although this review can confirm that certain places such as the Hohe Tauern and other national parks are quite popular sites when it comes to studying the effects of climate change on biodiversity, there is no bias towards any part of the Alps. There is a strong bias though between the alpine region and lower elevations: in Austria, research focuses almost exclusively on the Alps. In contrast, the Danube river (Austria's largest stream and an important vital line for south-eastern Europe) and associated ecosystems were completely missing from the studies reviewed here, although there is a well known national park in the riverside forest right next to the Austrian capital Vienna. Given that especially the East of Austria and ecosystems outside the Alps are underrepresented, more research should be done there, but also in more diverse places and with regard to the actual shares the respective ecosystems have. This means to consider that the cultural landscape has enhanced biodiversity in Central Europe for the past few thousand years, and should therefore be addressed by research on the impacts of climate change on biodiversity. Simultaneously, certain ecosystems which only have a relatively low share in Austria and Central Europe may be threatened by climate change: Bogs and fens for example are under pressure from rising temperatures, decreasing water supply and land use, but have a high importance for climate change mitigation because they are important carbon stocks (Essl et al. 2012). It follows that focussing too much on certain ecosystems and regions might lead to a biased perception. This should not be understood as a general disapproval of detailed studies for certain sites, but for some organisms such as fungi, microorganisms or lichens, it does not seem possible (or sensible) to focus research on a single region, as data on these organisms is generally scarce and not matching their real diversity and distribution.

Simulation studies demonstrate that it is sometimes necessary to work on a larger scale. Of the eight simulations for Austria, only two used nationwide models. In contrast, most of the twelve simulations for Switzerland did. One example for Switzerland is Nobis et al. (2009) who simulated an invasion of neophytes under different climate change and urban sprawl scenarios, showing the close connection between land use and biodiversity. In that sense, the nationwide research in Switzerland can be seen as a good example, also with respect to their impressive collection of long-term data on various biodiversity metrics (e.g. Bergamini et al. 2009, Gilgado et al. 2020).

Which taxonomic groups have been assessed?

In relation to their ecological importance, we know relatively little about how fungi are affected by climate change. Fungi usually stand at the end of the trophic chain as they decompose wood and other organic materials. They therefore influence the nutrient availability in ecosystems and prepare the ground for other organisms to live on. Vittoz et al. (2013) could say very little about this topic in their review for Switzerland and in the literature reviewed here, only few publications assessed changes in species richness or elevational shifts of fungi and none treated their range size and extinction risk. Given that they represent an entire kingdom, this represents a major research gap. It remains unclear why the probability of finding an effect of climate change is smaller in other organisms such as microorganisms and fungi than in flora and fauna (Fig. 10 a). It may be hypothesized that microorganisms and fungi are less restricted by dispersal limitations and therefore the occurring communities would always be constituted by those organisms which are adapted best to the current conditions. However, this topic is understudied and it is not clear what biodiversity response is to be expected from them.

Another unsuspected finding in my study was the scarceness of studies on amphibians and fish. They obviously need water and wet habitats, which makes them one of the first to suffer from long enduring droughts. In addition to that, ectotherms depend on suitable temperatures and can only change their behaviour in order to cope with anomalies. Given the fact that amphibian populations are already heavily under pressure from toxic chemicals released into the environment and the pathogenic fungus *Batrachochytrium dendrobatidis* Longcore, they are especially vulnerable to additional threats like climate change. Blaustein et al. (2010) provide a global review on how amphibians are affected by climate change, but we need detailed and up-to-date data so as to guide national protection programs. Aquatic organisms such as fish suffer in several ways from increasing water temperatures, as Vittoz et al. (2013) explain. Unluckily, their escape route upstream is often blocked by anthropogenic obstacles such as dams and hydroelectric power stations. In addition to that, other anthropogenic factors such as the use of water for agricultural irrigation can lower the water level, leading to changed hydrological regimes and higher temperatures (Vittoz et al. 2013).

Vittoz et al. (2013) had to exclude mammals from their review for Switzerland because there was no research on how they are affected by climate change. It was rather surprising to find that ten years later, mammals were still entirely missing from my dataset, especially as they are very popular when it comes to choosing a flagship species for a nature conservation project. Birds and reptiles are common representatives in public communication as well (e.g. the European green lizard *Lacerta viridis* Laurenti), but underrepresented in studies about climate change effects on biodiversity. One reason for this might be that very often, phenology (e.g. concerning breeding and migration timing) is chosen to study this topic in birds, but was excluded in this review. Another reason could be that birds and mammals are rather studied alone instead of embedded in their species community, as their much higher share in those studies about single species, which couldn't be included in this review, shows. However, we should question this habit, because these animals rely on intact food webs and ecosystems just like any other, sometimes even more as they often stand on a high trophic level. Generally, very few studies treated organisms from more than one trophic level and higher taxonomic levels were rather considered in lower trophic levels. This might be because we already know more about animals from higher trophic levels which additionally (and this is especially true for mammals) are biologically closer to us and fewer in numbers, which might tempt researchers to look at them at the species level.

<u>Which biodiversity metrics were used to assess the effects of climate change on biodiversity?</u>

In order to get an overview on whether climate change has rather positive or negative effects on biodiversity, it is necessary to distinguish clearly between the biodiversity metrics used to measure these effects and to consider that such attributes as positive and negative always depend on the context: An increase in the category population dynamics for herbivorous insects may be beneficial for this trophic group and others relying on it, but the contrary is true for organisms which compete with or represent a prey for the populations on the rise. Depending on the ecological preferences, this may as well happen within one taxonomic group: Gallé (2017) studied ant communities in Kiskunság national park in Hungary between 1981 - 2017 and found that, as the site became drier due to the sinking ground water levels, the slightly hygrophilous species vanished and the thermophilous, drought-tolerant species previously found only at the top of the dunes, built 135 % more nests.

Generally, an increase in species richness due to climate change may sometimes lead to a homogenization of the species community and thereby a decrease in species diversity. These opposing trends are mirrored by the studies reviewed here. For example, Matteodo et al. (2016) report a simultaneous decrease in Bray-Curtis-dissimilarity index and increase in alpha-diversity for plant communities on natural grasslands and snowbeds in the Swiss Alps between 1967 and 2014. Apart from species richness, functional diversity increases in many cases due to the immigration of species from warmer realms. The findings of Brighenti et al. (2019) confirm this: They summarize the consequences of glacier retreat and permafrost thawing on Alpine streams, both on hydrological and ecological conditions. Alpha diversity increases whereas beta and gamma diversity decrease due to the loss of cold stenotherms and cryal specialists (Brighenti et al. 2019). In the meantime, biomass and abundance of those taxa who benefit increase just like functional diversity does (Brighenti et al. 2019).

One way to adapt to rising temperatures is to follow the environmental gradient and move uphill. About 60 % of the publications reviewed here found that communities of both flora and fauna significantly shifted their distribution upwards along the elevational gradient. Many studies report astounding range shifts, e.g. Habel et al. (2023) who detected a shift of + 309 m upwards in the distribution of butterflies in the federal state of Salzburg, Austria, between 1950 - 2018, equaling a movement of + 4,5 m per year. Gilgado et al. (2019) compared new data on alpine to nival Diplopoda from the Swiss National Park with historical records and found that although there was no change in their frequencies, species had shifted their distribution + 161 m uphill in the last century. However, not all taxonomic groups can change their distribution so easily, as Vitasse et al. (2021) highlight in their review on climate change effects on the phenology and elevational distribution of animals, plants and fungi in the Alps. Their comprehensive meta-analysis covers the past 40 years and comes to the conclusion that there are large differences in the speed of both range shifts and phenological adaptations between and within fauna and flora, which will lead to changes in species' interactions as their current competitors and partners move at a different rate. Phenological and spatial mismatches would be the consequence (Vitasse et al. 2021). Furthermore, invasive species may become an additional issue, because they usually have traits facilitating their dispersal, enabling them to overtake the natives on the race to the top, as Dainese et al. (2017) report. Their data on plant distribution in the Alps in North Eastern Italy show that neophytes expanded their range upwards almost twice as fast as the native flora (Dainese et al. 2017). They warn against the additional pressure this might have on ecosystems in the Alps (Dainese et al. 2017).

<u>Neobiota, species conservation and new communities</u>

Although neobiota are a hot discussion topic, they were rarely considered by the literature on the effects of climate change on biodiversity that I reviewed, and only in plant communities. A possible reason for this might be that their spread is typically considered in studies about a single invading species or a subset of those and my literature search methodology thus missed them. Furthermore, they would not occur in studies aiming to gather information on species to be protected from climate change effects, but rather in publications on range shifts. There again, research on biotic interactions would be beneficial so as to shed light on possible disadvantages such as competition or benefits such as functional substitution. Also, it would be interesting to see whether distinguishing between native species and neobiota would show any differences in their responses to climate change.

Apart from the ecological consequences of new species, the mean upslope shift of species is still slower than that of the isotherms (Vitasse et al. 2021), so the question arises how to protect species. Lai et al. (2022) call upon concentrating all efforts of conservation measures on Natura2000 sites, arguing that it would be too hard and not realistic to realize new protection sites in densely populated Europe. However, this approach falls short of considering the importance of the surrounding landscape for protected sites. Globally, land use change is the direct driver with the largest relative impact on terrestrial and freshwater ecosystems (IPBES 2019), meaning that it should be considered in future projections for alternative policy and climate change scenarios. In a nationwide study in Germany, Brühl et al. (2020) found a variety of pesticides within the boundaries of protected sites. The number of pesticides correlated to the size of agricultural area within a radius of 2000 m around the protected sites (Brühl et al. 2020). This emphasizes that the so-called matrix should be considered as an important factor for the fitness of organisms within protected areas. It bears a great potential too. Creating corridors to counteract habitat fragmentation is just one necessary step to mitigate the consequences of climate change. Grass et al. (2019) call for a context-specific combination of land sparing and land sharing so as to achieve multifunctional landscapes and counteract extinctions. The problem of changing environmental conditions creates a challenge for the self perception of nature conservationists as well: Should they let the natural processes happen and accept (local) extinctions and major changes in communities and ecosystems? Should they support species in their attempt to adapt? Or should they even actively assist migration and engage or intervene in processes? This decision is not an easy one as it touches basic principles of applied nature conservation and the answer given will have far reaching consequences for species, communities, ecosystems and humans. Probably, future generations will have to define a new "normal state" as natural interactions and habitats change in reaction to climate change.

In some ecosystems, an increase in species richness may be evaluated as "positive", whereas in other, naturally species-poor habitats, the addition of previously absent competitors or predators may have a devastating effect on the current system. In about 60 % of the studies on the effects of climate change on the biodiversity of the flora, species richness increased significantly. This was true for an even higher percentage of the studies on fauna. In this light, it was surprising to find that only four studies looked at the effects of climate change on endemic species separately and only two at endangered species. Concerning vertebrates, it seems likely that endemic and endangered species are rather treated by publications focussing on single species or species subsets, and would therefore not appear in the dataset used here. Nevertheless, this cannot be said about endangered and endemic species from other taxonomic groups, meaning that there is a research gap concerning the effects of climate change on their biodiversity.

Genetic diversity is one important aspect when it comes to protecting endangered species, as it plays a major role in fragmented populations. Increasing urbanization and agricultural development should therefore be considered in future scenarios. As Scriber (2014) comments, invasive genes should not only be seen as a threat to biodiversity as we know it, but hold a positive potential in terms of genetic rescue. However ambivalent the topic, research on climate change impacts on genetic diversity is rare: Just like in Vittoz et al. (2013), the topic cannot be covered here due to a lack of data. There were no studies in the dataset covering the effects of climate change on genetic diversity. Based on publications about extinction risk and population dynamics, what can be said is that local and regional extinctions will occur in Central Europe until the end of the 21st century. Engler et al. (2009) used species distribution models to predict the percentage of plant species losing more than 90 % of their present habitat in the Western Alps. Depending on the emission scenario and the expected dispersal capacity, between 28 % of all plant species considered under scenario B1 and 70 % under scenario A1FI will be concerned (Engler et al. 2009). A smaller percentage of plant species but still many will go extinct (in terms of losing 100 % of their habitat) (Engler et al. 2009).

<u>Call for better documentation and research gaps concerning biodiversity metrics</u>

Besides the taxonomic richness, biotic interactions between the species present considerably shape communities and ecosystems. However, of the 130 studies only ten investigated how climate change affects interactions between species, and all of these studies were about terrestrial ecosystems. More research is needed on the effects of climate change on biotic interactions in general, and especially about those between aquatic organisms. Descombes et al. (2016) show how important changes in behaviour and trophic interactions are when it comes to the survival of species in the face of climate change. They simulated the distribution of butterfly species and their respective host plants under three climate change scenarios. What is special about their study is that they also simulated how species' distributions would develop if the butterflies expanded their diet to other (closely related) plants. The local extinction risk decreased clearly (Descombes et al. 2016). This shows that making the effort of studying complex interactions is worth it as we can gain in-depth knowledge from it. Dyer and Letourneau (2013) state that climate change effects may multiply as they move along trophic cascades. The final outcomes may be a lot stronger than one can tell from the effect observed for a single species. Consequently, it would be advisable to search for synergies and side effects, to prevent ecological systems from collapsing. This means to be precise: It is relatively easy to measure increases or decreases in biomass per square meter as a response to increased temperature and water stress. But the results do not convey information on which plant species' population is affected most, which herbivore species loses its main food resource or which insect might lose habitat due to a loss of open ground. In order to gain knowledge on these questions, complex interactions have to be considered. Vitasse et al. (2021) agree that this field of research deserves greater attention and research on related topics shows how to approach similar thematic complexes, e.g. Buzhdygan & Petermann (2023) who found that land use affects multitrophic diversity and ecosystem functions.

The variety of methods and the varying comprehensiveness of documentation might make it hard to gain a good overview or a sensible conclusion even if there are several studies on climate change effects on the same taxonomic group or ecosystem. This appeal for better documentation cannot be emphasized enough, at least from the point of view of a researcher trying to compile data for a review or meta-analysis. Many results were just given in phrases like "the frequency increased significantly", without any numbers or statistical information to support the statement. Many studies did not even test for significance and some disregarded even basic rules for graphical presentation such as scaled and labeled axes. Even among those who tested for significance and reported it, there were huge differences in the thoroughness of the documentation of statistical parameters and effect sizes. However, one cannot perform a meta-analysis (or more basically: understand the extent of the past, present and future biodiversity crisis) if research articles fail to report the exact numbers. For the biodiversity metrics community composition and population dynamics, this was the case for half of the studies. Other researchers have noticed this problem before. For example, Pold & DeAngelis (2013) studied the consequences of climate change on soil microbes' diversity as well as feedback reactions on the carbon cycle. In their global review they conclude that warming effects seem to be ecosystem-specific, but have to point out that this conclusion may also be due to a lack of consistency between the different studies and diversity measurements (Pold & DeAngelis 2013). This observation was made by Rogora et al. (2018) too, who call for a more common use of standardized methods to improve comparability and to enable a better differentiation between global and local patterns. In this context, one may ask whether it would be better to stick to older emission scenarios (as the publications in this dataset did) or to stay up-to-date and use scenarios from the latest IPCC reports. There are arguments for both sides, but as each IPCC report is based on a deeper understanding of climate change and its consequences than the previous one, it seems like the second is the better option in the long term.

It can be acknowledged that research in Austria and Central Europe covers many different aspects of biodiversity. The metrics of biodiversity used in the literature to assess the influence of climate change on biodiversity were not represented equally in the data though: Only very few publications treated changes in behaviour, range size and extinction risk. Also, there was no study on latitudinal range shifts (category excluded subsequently due to lack of publications), maybe because only few worked internationally or with nationwide data. Of the three studies on land cover change, Zischg et al. (2021)

is the most remarkable: The authors modeled the upward shift of vegetational belts in Switzerland (nationwide) for three different climate scenarios. The scope of these changes illustrates the magnitude of climate change effects on nature. Organisms will either have to find behavioral adaptations, e.g. like the Austrian butterflies seeking protection from the heat in caves (Moog et al. 2021) or change their altitudinal and latitudinal distribution, following the environmental gradient. Those who cannot follow fast enough will depend on their capacity to adapt and evolve or suffer unfavourable conditions. In any case, this and the relative competitive capacity of native and newly arrived species will determine how ecosystems will function in the future.

Conclusion

It can be summarized that we already have a good idea of how climate change affects biodiversity in Austria and Central Europe. Whether these effects are beneficial or disadvantageous depends on the context, but most biodiversity metrics seem to show an increase. Documented observations cover both long and short-term processes and detailed predictions exist for the period until the end of the 21st century. However, there are certain research gaps: Invertebrates were studied a lot more than vertebrates. More research on mammals, birds, reptiles and amphibians is needed, but also on fungi. Lichens and moss species are understudied as well, even though they react highly sensitive to changing environmental conditions. Initial (local) increases in species richness may turn out to be disadvantageous for biodiversity in the long term as they lead to a homogenization of the landscape, decreasing beta and gamma diversity and a replacement of native specialist species by generalists, to which neobiota often belong. Local extinctions will be the result. This trend may affect alpine and montane species stronger than others because their current habitat is limited vertically by the decreasing area towards the mountaintops. For lowland species however, elevational shifts might prove beneficial as human pressures decrease with increasing elevation and topographic complexity (Elsen et al. 2020). In any case, considering the possibility of varying effect sizes and directions due to the vertical zonation along elevational gradients is advisable.

Nevertheless, research should not focus on the Alps alone. There are species-rich habitats of high ecological value in the East of Austria as well which deserve protection. A more even distribution of study effort would provide a more complete picture of the actual situation in the whole country and enable researchers to recognize those areas with a higher need for action. This would in turn help to guide informed policy decisions to minimize the anthropogenic impact and counteract the negative effects of climate change on biodiversity. Insights from other, ecologically similar parts of Central Europe may substitute own national research programs for some time, but local evidence is needed to spark action.

Although a monitoring of changes is important, we need more research on the options that exist for local stakeholders to prevent negative consequences before mitigation of climate change effects is the only option left. Climate change should be recognized as a phenomenon with many faces, meaning that it is not enough to look at the effects of rising temperatures or water shortage. Apart from their intensity, the frequency of droughts and other extreme events will determine the magnitude of their consequences, and the course and direction of possible adaptations by nature will be influenced by anthropogenic factors such as agriculture, urbanization and tourism (Elsen et al. 2020). In addition to providing a comprehensive documentation of all methods and results, researchers should take indirect climate change effects and ecological chain reactions into account and consider more than one taxonomic group or ecosystem when it comes to assessing the effects of climate change on biodiversity. In this context, ecosystem resilience will be a key to successful conservation, and to a good quality of life, as the IPBES reports emphasize with respect to ecosystem services (e.g. IPBES 2019). Economic and political reason, preventive health care and nature conservation provide plentiful of motivation to make an effort to decrease greenhouse gas emissions and mitigate climate change (APCC 2014).

The research projects cited here differed strongly in the ecosystems, taxonomic groups, climatic factors, emission scenarios, places and time periods they assessed. They prove that there is already a good amount of evidence to prove that anthropogenic climate change is already affecting biodiversity in Austria and Central Europe. Some parts of the topic have not been explored enough yet, but the observations and predictions we have until now are enough to derive an urgent need for action.

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Appendix

Search string

The following search string was used to search Scopus on the 23rd February 2023 at 04:50 p.m. It yielded 9313 results.

> Climat* chang* OR warming OR drought AND
>
> biodivers* OR speci* OR composition* OR flora* OR fauna* OR vegetation OR trophic OR richness OR taxonomic* OR taxa OR ecosystem OR forest OR aquatic OR rang* OR population OR community OR distribution OR plant OR animal OR abundan* OR bird OR avi* OR aves OR fung* OR micro* OR reptil* OR insect* OR amphibian OR lichen OR moss OR mammal OR fish OR butterfly OR lepidoptera OR grasshopper OR orthoptera OR spider OR arachnid* OR beetle OR coleoptera AND
>
> Austria* OR Alps OR Switzerland OR Swiss OR Bavaria* OR Sloven* OR Slovak* OR Hungar* OR Czech

Additional figures

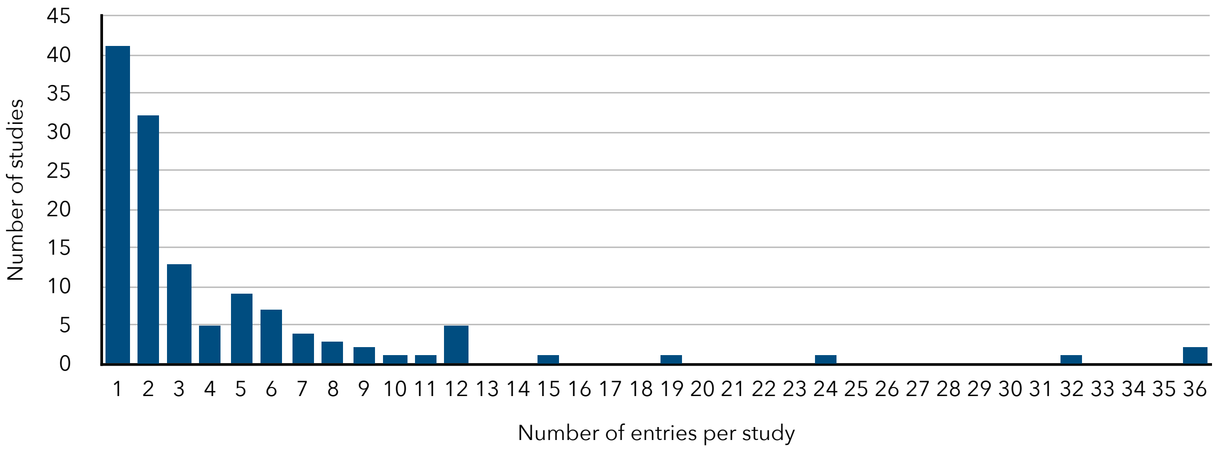

Figure I: This histogram indicates the distribution of result entries of the 130 studies considered in this review.

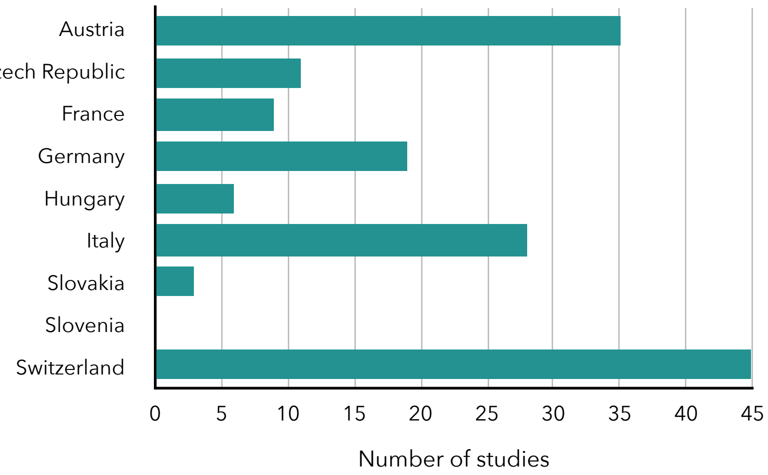

Figure II: Number of studies with study sites in the countries within the study region. Numbers do not add up to the total of 130 studies which were assessed, because some studies had sites in more than one country and were therefore counted more than once for this figure.

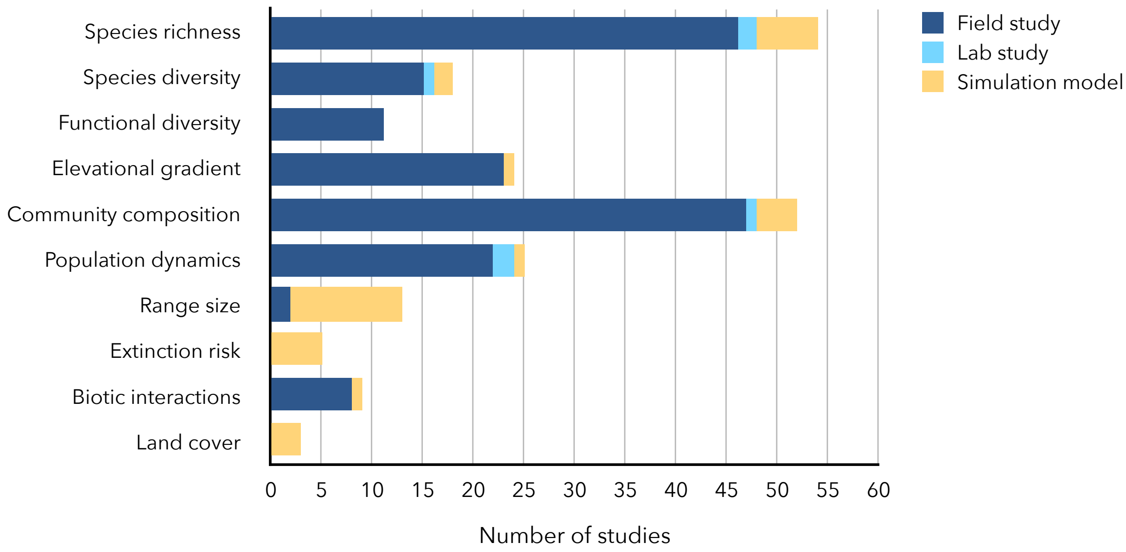

Figure III: Number of studies per biodiversity category belonging to three different types of basic study design (field study, lab study, simulation model). As many publications assessed the effects of climate change on more than one biodiversity category, the sum of all bars exceeds the total of 130 studies which were included in the review. Multiple counts were not possible for the basic types of study design. See Table I (appendix) for a description of the biodiversity categories.

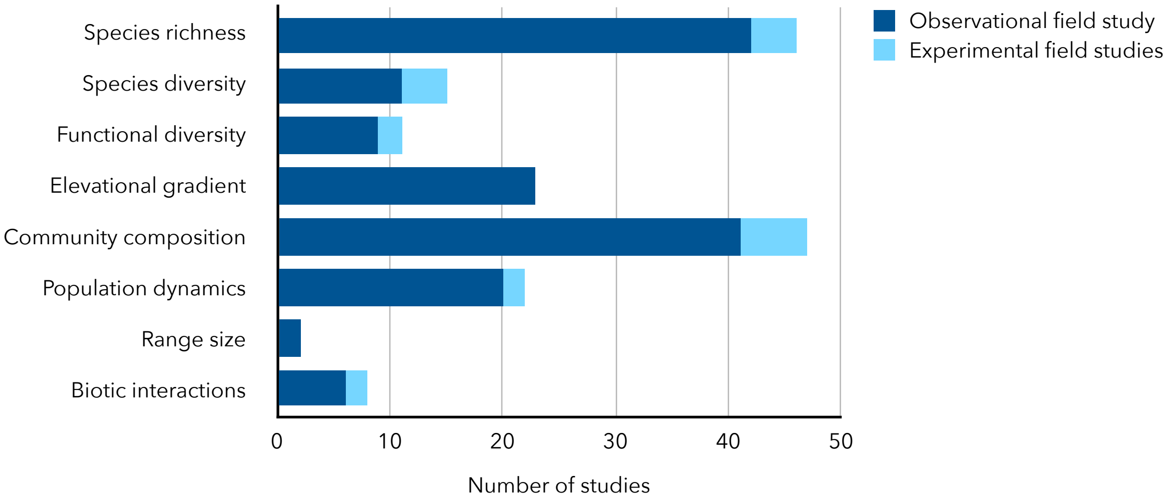

Figure IV: Number of observational and experimental field studies per biodiversity category. Multiple counts are possible for studies which assessed more than one biodiversity category, which is why the sum of all bars exceeds n = 130 publications. See Table I (appendix) for a description of the biodiversity categories.

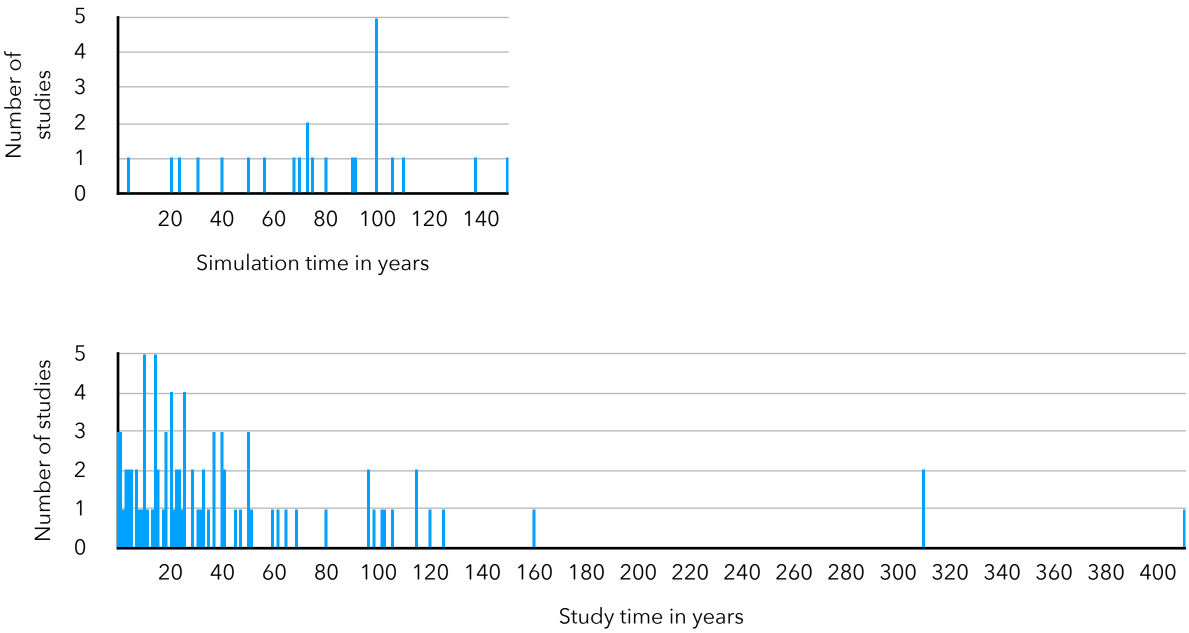

Figure V: The upper diagram shows the number of studies and time period covered for simulations (n = 24), the lower for empirical studies (n = 90). The 16 studies missing to the total of 130 assessed studies are not included in this figure because they used space for time substitution.

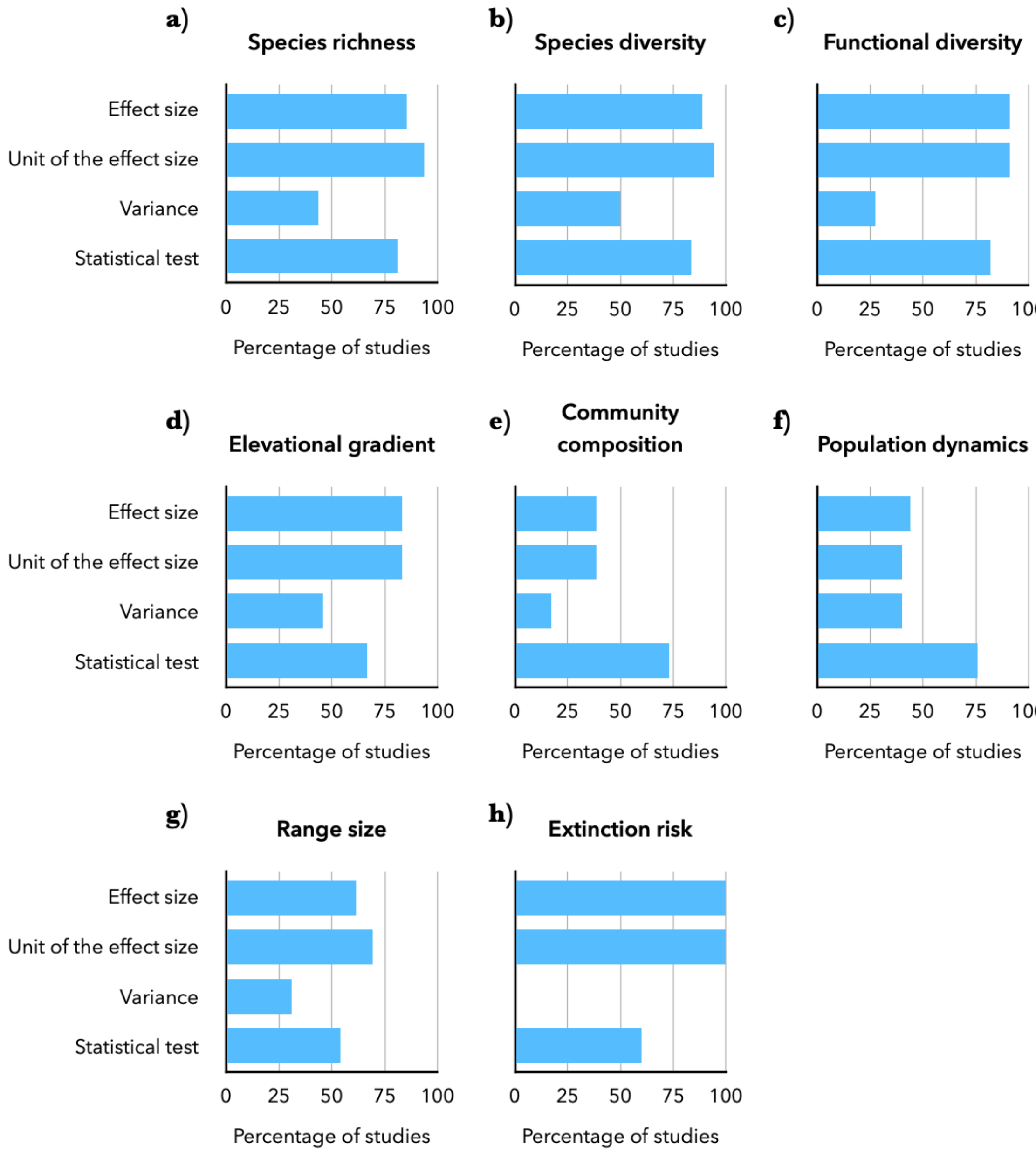

Figure VI: The diagrams indicate the percentage of studies which supplied information on the effect size of a climate change induced biodiversity response, its unit, variance and the statistical test used for significance testing. The diagram titles give the respective biodiversity response category the studies belonged to. Keep in mind that a publication reporting the statistical test in its methods section could still miss out on reporting the effect size, its unit and variance, which is why the distribution of reported information was very patchy.

Literature used for analysis

The following 130 research articles resulted from a systematic search in Scopus and a subsequent selection process. They all treated the effects of climate change on biodiversity in Austria and neighbouring Central European regions. These articles provided the data for all analyses.

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Additional tables

Table I: Description of the categories used to classify the biodiversity response to climate change

In order to document how the literature assessed climate change effects on biodiversity, the studies were sorted into the following categories according to the type of biodiversity responses they had measured. For the statistical analyses, these were coded in columns with 0/1. Additionally, information on the effect size and its unit as well as the statistical test and variance metric were recorded in separate columns.

Biodiversity category	Description
Biotic interactions	Studies about climate change induced changes in biotic interactions such as herbivory, predation, parasitism, competition, …
Community composition	Studies about changes in community composition, e.g. measured via Bray-Curtis-dissimilarity, correspondence analysis, mean indicator values, relative abundance, …
Elevational gradient	Studies dealing with the elevational shift of communities' range and abundance
Extinction risk	Studies predicting the percentage of species facing extinction under a changing climate
Functional diversity	Studies focussing on changes in the number and relative abundance of functional groups, functional evenness or Reynold's group richness
Land cover	Studies predicting changes in the major vegetation types, e.g. from grassland to forest or shifts in the process of succession
Population dynamics	Studies about climate change induced population trends, e.g. measured via increases or decreases in the abundance of individuals per square meter
Range size	Studies looking at the effects of climate change on species' potential distribution, e.g. by calculating the percentage of suitable habitat area under future conditions compared with current distributions
Species diversity	Studies about changes in diversity, e.g. measured via Shannon diversity index or other diversity indices
Species richness	Studies about changes in the number of species or taxonomic groups

Table II: Overview on the publications treating biotic interactions

Publication	Biotic interaction
Adamík & Král 2008)	Predation of the dormice *Glis glis* on hole-breeding birds
Alexander et al. (2015)	Competition between plants
Anselmo & Rizzioli (2022)	Competition and hybridization in beetles
Dobbertin et al. (2007)	Herbivory by several bark beetles on *Pinus sylvestris*
Fricke et al. (2022) (1)	Herbivory of invertebrates
Fricke et al. (2022) (2)	Predation of Arachnida
Kerner et al. (2023)	Herbivory of butterflies on plants
Scala et al. (2019)	Pathogeny of fungi on plants
Wermelinger et al. (2021)	Herbivory, predation and parasitism: Trophic interactions between bark beetles, Scots pine, predator Diptera and parasitoid Hymenoptera

Table III: List of taxonomic groups included in the categories “other insects“ and “other organisms“

Category	Taxonomic groups
Other insects	Plecoptera, Trichoptera, Ephemeroptera, Heteroptera, Odonata, Hemiptera
Other organisms	Nematoda, Acarina, Oligochaeta, Tricladida, Bivalvia, Diplopoda, Cladocera, Cnidaria, Hirudinea, Sphaeriidae, Crustaceae, Platyhelminthes, Rotifera, phy-toplancton, Lycopoda, Pteridophyta, Collembola, Charophyta, Turbellaria,

Table IV: Statistical information on the models used to test for the influence of different predictors on the presence vs. absence of an effect of climate change on biodiversity

Model type	**Generalized linear mixed model fit by maximum likelihood (Laplace Approximation); family: binomial (logit); random effect: (1| study_ID)**					
Data	Simulation studies	Observational studies	Observational studies	Observational studies	Observational studies	Observational studies
Predictor	Study duration	Taxonomic group	Climate (global) change variable	Ecosystem	Ecosystem type	Study duration
Predictor levels		Fauna / flora / others	Indirect climate change effects / interactions with land use / snow and glacier cover decrease / temperature increase / decreased water availability	Forest / Grassland / Lakes / Rivers / others	Aquatic / terrestrial	
Response	Effect presence / absence	Effect presence / absence	Effect presence / absence	Effect presence / absence	Effect presence / absence	Effect presence / absence
Akaike information criteri-	54.9	560.2	567.7	567.5	562.0	558.1
BIC	66.4	576.9	592.7	592.6	574.6	570.7
Log-likelihood	-24.4	- 276.1	- 277.8	- 277.7	- 278.0	- 276.1
Deviance	48.9	552.2	555.7	555.5	556.0	552.1
Residual degrees of freedom	343	477	475	475	478	478

Table V: Model output of the GLMM (see Table IV) used to test for the influence of the study duration on the likelihood to see an effect of climate change on biodiversity in simulation studies

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Study duration	**Intercept**	8.473e -01	3.450e - 01	2.456	0.0141
	Duration in years	7.959e + 00	4.155e + 04	0	0.9998

Table VI: Model output of the GLMMs (see Table IV) used to test for the influence of different predictors on the likelihood to see an effect of climate change on biodiversity in the observational studies

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Taxonomic group	**Intercept (Fauna)**	1.64473	0.35388	4.648	3.36e - 06
	Flora	0.09005	0.43505	0.207	0.8360
	Other organisms	- 0.96813	0.50057	- 1.934	0.0531
Climate (global) change variable	**Intercept (temperature)**	1.360e+00	1.990e-01	6.834	8.28e - 12
	Indirect climate change effects	2.621e+01	7.168e+05	0	1.0
	Interactions with land use	3.242e-01	6.005e-01	0.540	0.589
	Snow and glacier cover decrease	5.428e-02	3.775e-01	0.144	0.886
	Decreased water availability	2.710e-01	3.946e-01	0.687	0.492
Ecosystem	**Intercept (forest)**	1.46231	0.50294	2.908	0.00364
	Grassland	- 0.36148	0.62888	- 0.575	0.56542
	Lakes	0.26192	0.76885	0.341	0.73336
	Other ecosystems	- 0.06269	0.56524	- 0.111	0.91168
	Rivers	0.48844	0.75661	0.646	0.51856
Ecosystem type	**Intercept (aquatic)**	1.8507	0.4761	3.887	0.000101
	Terrestrial	- 0.5086	0.4689	- 1.085	0.278141
Study duration	**Intercept**	1.092364	0.271402	4.025	5.7e-05
	Duration in years	0.012828	0.006704	1.914	0.0557

Table VII: Statistical information on the models used to test for the influence of different predictors on the direction of climate change effects on biodiversity in simulation studies

Model type	**Generalized linear mixed model fit by maximum likelihood (Laplace Approximation); family: binomial (logit); random effect: (1| study_ID)**				
Data	Simulation studies	Simulation studies	Simulation studies	Simulation studies	Simulation studies
Predictor	Taxonomic group	Climate (global) change variable	Ecosystem	Ecosystem type	Study duration
Predictor levels	Fauna / flora / others	Indirect climate change effects / interactions with land use / snow and glacier cover decrease / temperature increase / decreased water availability	Forest / Grassland / Lakes / Rivers / others	Aquatic / terrestrial	
Response	Effect direction (positive / negative effect on biodiversity metrics)	Effect direction (positive / negative effect on biodiversity metrics)	Effect direction (positive / negative effect on biodiversity metrics)	Effect direction (positive / negative effect on biodiversity metrics)	Effect direction (positive / negative effect on biodiversity metrics)
Akaike information criterion	152.2	160.3	158	154.5	154.5
BIC	167.5	183.2	177	165.9	165.9
Log-likelihood	-72.1	-74.2	-74	-74.3	- 74.2
Deviance	144.2	148.3	148	148.5	148.5
Residual degrees of freedom	330	328	329	331	331

Table VIII: Model output of the GLMMs (see Table VII) used to test for the influence of different predictors on the likelihood to see a positive (vs. negative) effect of climate change on biodiversity in simulation studies

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Taxonomic group	**Intercept (Fauna)**	11.599	3.550	3.267	0.00109
	Flora	-2.710	1.788	-1.515	0.12974
	Other organisms	-11.599	18.639	-622	0.53374
Climate (global) change variable	**Intercept (indirect climate change effects)**	8.226e + 00	4.188e + 00	1.964	0.0495
	Interactions with land use	2.914e - 01	1.150e + 00	0.253	0.7999
	Snow and glacier cover decrease	- 9.995e + 02	3.875e + 07	0.00	1.0
	Temperature increase	3.747e - 01	1.105e + 00	0.339	0.7346
	Decreased water availability	3.095e - 01	1.458e + 00	0.212	0.8319
Ecosystem	**Intercept (forest)**	6.472	6.017	1.076	0.282
	Grassland	Not in the dataset			
	Lakes	4.613	7.555	0.611	0.542
	Other ecosystems	2.307	5.854	0.394	0.694
	Rivers	- 14.737	7.928	- 1.859	0.063
Ecosystem type	**Intercept (aquatic)**	8.7717	4.1009	2.139	0.0324
	Terrestrial	- 0.2238	3.9511	- 0.057	0.9548
Study duration	**Intercept**	8.182276	3.542390	2.310	0.0209
	Duration in years	0.006282	0.036002	0.175	0.8615

Table IX: Statistical information on the models used to test for the influence of different predictors on the direction of climate change effects on biodiversity in observational studies

Model type	**Generalized linear mixed model fit by maximum likelihood (Laplace Approximation); family: binomial (logit); random effect: (1| study_ID)**				
Data	Observational studies	Observational studies	Observational studies	Observational studies	Observational studies
Predictor	Taxonomic group	Climate (global) change variable	Ecosystem	Ecosystem type	Study duration
Predictor levels	Fauna / flora / others	Indirect climate change effects / interactions with land use / snow and glacier cover decrease / temperature increase / decreased water availability	Forest / Grassland / Lakes / Rivers / others	Aquatic / terrestrial	
Response	Effect direction (positive / negative)	Effect direction (positive / negative)	Effect direction (positive / negative)	Effect direction (positive / negative)	Effect direction (positive / negative)
Akaike information criterion	365.2	366.7	370.5	364.9	353.9
BIC	380.5	389.7	393.5	376.4	365.4
Log-likelihood	- 178.6	- 177.4	- 179.3	- 179.4	- 173.9
Deviance	357.2	354.7	358.5	358.9	347.9
Residual degrees of freedom	337	335	335	338	338

Table X: Model output of the GLMMs (see Table IX) used to test for the influence of different predictors on the likelihood to see a positive (vs. negative) effect of climate change on biodiversity in observational studies

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Taxonomic group	**Intercept (Fauna)**	1.65407	0.43679	3.787	0.000153
	Flora	0.70075	0.56638	1.237	0.216002
	Other organisms	0.01883	0.69255	0.027	0.978312
Climate (global) change variable	**Intercept (indirect climate change effects)**	0.4890	2.0147	0.243	0.808
	Interactions with land use	0.8811	2.0987	0.420	0.675
	Snow and glacier cover decrease	1.5794	2.0837	0.758	0.448
	Temperature increase	1.5157	2.0199	0.750	0.453
	Decreased water availability	0.5830	2.0366	0.286	0.775
Ecosystem	**Intercept (forest)**	2.1519	0.7079	3.040	0.00237
	Grassland	- 0.5122	0.8650	- 0.592	0.55378
	Lakes	- 0.1298	1.0023	- 0.130	0.89692
	Other ecosystems	- 0.2426	0.7747	- 0.313	0.75417
	Rivers	- 0.3039	0.9759	- 0.311	0.75548
Ecosystem type	**Intercept (aquatic)**	1.94994	0.59308	3.288	0.00101
	Terrestrial	- 0.04385	0.59470	- 0.074	0.94123
Study duration	**Intercept**	1.05868	0.35502	2.982	0.00286
	Duration in years	0.02846	0.01037	2.744	0.00606

Table XI: Statistical information on the models used to test for the influence of different predictors on the probability of a study concerning climate change effects on biodiversity being a simulation (vs. observational) study

Model type	**Generalized linear mixed model fit by maximum likelihood (Laplace Approximation); family: binomial (logit); random effect: (1| study_ID)**		
Data	All studies	All studies	All studies
Predictor	Taxonomic group	Ecosystem type	Climate (global) change variable
Predictor levels	Fauna / flora / others	Aquatic / terrestrial	Indirect climate change effects / interactions with land use / snow and glacier cover decrease / temperature increase / decreased water availability
Response	study being a simulation study (vs. an empirical study)	study being a simulation study (vs. an empirical study)	study being a simulation study (vs. an empirical study)
Akaike information criterion	89.8	88	93.8
BIC	108.7	102.1	122.1
Log-likelihood	- 40.9	-41.0	- 40.9
Deviance	81.8	82.0	81.8
Residual degrees of freedom	823	824	821

Table XII: Model outputs of the GLMMs (see Table XI) used to test for the influence of different predictors on the probability of a study being a simulation (vs. observational) study

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Taxonomic group	**Intercept (Fauna)**	14.452	2.088	6.920	4.51e-12
	Flora	- 0.546	2.646	- 0.206	0.837
	Other organisms	1.450	6.820	0.213	0.832
Ecosystem type	**Intercept (aquatic)**	14.32720	2.55189	5.614	1.97e-08
	Terrestrial	0.08467	2.91003	0.029	0.977
Climate (global) change variable	**Intercept (indirect climate change effects)**	13.2214	8.0962	1.633	0.102
	Interactions with land use	1.0147	8.6264	0.118	0.906
	Snow and glacier cover decrease	2.6219	10.4033	0.252	0.801
	Temperature increase	1.1846	8.1425	0.145	0.884
	Decreased water availability	0.6734	8.3649	0.081	0.936

Table XIII: Statistical information on the models used to test for the influence of different predictors on the probability of a study treating reduced water availability in order to assess the effects of climate change on biodiversity

Model type	**Generalized linear mixed model fit by maximum likelihood (Laplace Approximation); family: binomial (logit); random effect: (1| study_ID)**			
Data	Simulation studies	Simulation studies	Simulation studies	All studies
Predictor	Taxonomic group	Ecosystem type	Study duration	Study being an observational or simulation study
Predictor levels	Fauna / flora / others	Aquatic / terrestrial		Observational / simulation
Response	Decreased water availability (0/1)	Decreased water availability (0/1)	Decreased water availability (0/1)	Decreased water availability (0/1)
Akaike information criterion	30.6	28.8	28.8	126.7
BIC	43.9	38.8	38.7	139.7
Log-likelihood	- 11.3	-11.4	-11.4	- 60.4
Deviance	22.6	22.8	22.8	120.7
Residual degrees of freedom	200	201	201	564

Table XIV: Model outputs of the GLMMs (see Table XIII) used to test for the influence of different predictors on the probability of a simulation study treating reduced water availability in order to assess the effects of climate change on biodiversity

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Taxonomic group	**Intercept (Fauna)**	1.255e+01	2.641e+01	0.475	0.635
	Flora	2.125e+00	2.620e+01	0.081	0.935
	Other organisms	1.110e+03	4.745e+07	0.000	1.000
Ecosystem type	**Intercept (aquatic)**	13.87847	6.37776	2.176	0.0295
	Terrestrial	0.08379	6.75111	0.012	0.9901
Study duration	**Intercept**	12.70721	5.26490	2.414	0.0158
	Duration in years	0.01588	0.06769	0.235	0.8145

Table XV: Model output of the GLMM (see Table XIII) used to test for the influence of different predictors on the probability of a study treating reduced water availability in order to assess the effects of climate change on biodiversity

Predictors (fixed effects)	Predictor levels	Estimate	Standard error	z-value	Pr(>|z|)
Study being an observational or simulation study	**Intercept (observational)**	13.114	2.592	5.059	4.22e-07
	Simulation	- 26.062	3.287	- 7.930	2.19e-15

Table XVI: Statistical information on the models used to test for the influence of different predictors on the probability of an observational study treating reduced water availability in order to assess the effects of climate change on biodiversity

Model type	**Generalized linear mixed model fit by maximum likelihood (Laplace Approximation); family: binomial (logit); random effect: (1| study_ID)**		
Data	Observational studies	Observational studies	Observational studies
Predictor	Taxonomic group	Ecosystem type	Study duration
Predictor levels	Fauna / flora / others	Aquatic / terrestrial	
Response	Decreased water availability	Decreased water availability	Decreased water availability
Akaike information criterion	105.7	103.7	103.5
BIC	121.3	115.4	115.2
Log-likelihood	-48.8	-48.9	- 48.8
Deviance	97.7	97.7	97.5
Residual degrees of freedom	359	360	360

Table XVII: Model outputs of the GLMMs (see Table XVI) used to test for the influence of different predictors on the probability of an observational study treating reduced water availability in order to assess the effects of climate change on biodiversity

Predictors (fixed effects)	**Predictor levels**	**Estimate**	**Standard error**	**z-value**	**Pr(>|z|)**
Taxonomic group	**Intercept (Fauna)**	- 12.50993	2.11065	- 5.927	3.08e-09
	Flora	- 0.70990	2.90459	- 0.244	0.807
	Other organisms	0.08308	3.07798	0.027	0.978
Ecosystem type	**Intercept (aquatic)**	- 13.1482	3.1461	- 4.179	2.92e-05
	Terrestrial	0.5335	3.1818	0.168	0.867
Study duration	**Intercept**	- 12.05832	2.12081	- 5.686	1.3e-08
	Duration in years	- 0.02808	0.06949	- 0.404	0.686

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