Assessing the impacts of climate change on biodiversity: is below 2 °C enough?

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Abstract

Large changes in biodiversity are expected to occur if climate change continues at its current pace. Adverse effects include changes in species habitats and compositions, and consequently changes in ecosystem functioning. We assessed the magnitude of expected changes of biodiversity by performing a meta-analysis of the responses of species distributions to climate change. We focused on the proportion of local remaining species and their habitats. We summarized 97 studies and calculated two effect-size metrics from their results to quantify changes in biodiversity. These metrics are the fraction of remaining species (FRS) and the fraction of remaining area (FRA) with suitable climate for each species. Both metrics calculate deviations from the original biodiversity state and together they indicate biodiversity intactness. We found an expected gradual decrease in both FRS and FRA with significant reductions of 14% and 35% between 1 and 2 °C increase in global mean temperatures. Strong impacts are projected for both mammals and plants with FRS reductions of 19%. The climate-change response of biodiversity varies strongly among taxonomic groups and biomes. For some taxonomic groups the FRA declines strongly beyond 3 °C of temperature increase. Although these estimates are conservative, as we assume that species are unable to disperse or adapt, we conclude that already at moderate levels (i.e., 1–2 °C) of temperature increase a significant decrease of original biodiversity is projected. Our research supports the pledge to limit climate change to 1.5 °C and preferably lower to protect biodiversity.

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1 Introduction

Biodiversity is under increasing threats by many anthropogenic pressures (Alkemade et al. 2009; Leadley et al. 2014; Tittensor et al. 2014; Visconti et al. 2015; Johnson et al. 2017; Ripple et al. 2017). A major pressure of biodiversity decline in this century is climate change (Parmesan and Yohe 2003; Thomas et al. 2004; Warren et al. 2011; Bellard et al. 2012; Pacifici et al. 2015; Urban 2015). Climate change affects biodiversity as climate variables largely determine the geographical distribution ranges of species (i.e., species' climate envelopes; Box 1981; Guisan and Zimmermann 2000; Pearson and Dawson 2003). Hence, in areas where climate is no longer suitable, species shift their geographical ranges and go extinct locally, depending on their dispersal capacities (Guisan and Zimmermann 2000; Bellard et al. 2012). Species' phenology and physiology and community structures and ecosystem functions are also affected (Bellard et al. 2012). All these negative impacts exacerbate the challenge to manage and conserve biodiversity (CBD 2019).

The average global temperature has increased by almost 1 °C since 1880, and the adverse effects of such increase on biodiversity are already witnessed and documented by many studies (Thomas et al. 2004; Parmesan 2006; Butchart et al. 2010; Cardinale et al. 2012; Cook et al. 2012; IPCC 2013; Peñuelas et al. 2013; sCBD 2014; Pacifici et al. 2017; Pecl et al. 2017). They all show that the decline of biodiversity continues worldwide as many ecosystems lose suitable conditions for the survival of a proportion of their species. Some studies project the already observed negative impacts on species (e.g., Parmesan et al. 2013; Warren et al. 2013), and their results feed into the ongoing debate of constraining the increase of global temperatures (e.g., by the climate-change target to keep global temperature increase well below 2 °C above pre-industrial levels in the Paris Agreement (UNFCCC 2015; Rogelj et al. 2018)). Yet, how biodiversity will respond to a global mean temperature increase of 2 °C, or any increase close to this target, is not yet clear and represents a fundamental research challenge.

The primary objective of this study is to quantify the response of terrestrial biodiversity to climate change covering global mean temperature increase up to 6 °C in 2100 (and implicitly considering associated climate variables, such as precipitation change) above the pre-industrial level. For this purpose, we performed a meta-analysis of studies that used bioclimatic models and climate-change scenarios. These studies reported climate-change effects on contemporary ecosystems and different taxonomic groups around the world. The climate-change level in these studies was indicated by their scenario's global mean temperature increase. Most climate-change scenarios project that global mean temperature continues to increase to between 2 and over 5 °C in 2100 (Kintisch 2009; Moss et al. 2010; IPCC 2013; Rogelj et al. 2018). Similar to previous modeling studies that assessed the overall decline of biodiversity (e.g., Alkemade et al. 2009), we focused on the proportion of *remaining* biodiversity. We calculated two effect metrics: the fraction of remaining (i.e., persisting) species (FRS) at a location and the fraction of remaining area (FRA) with suitable climate for species. These metrics assess the changes of species richness over a region compared to the original situation in the selected study. Both metrics indicate a deviation from the original biodiversity state and indicate biodiversity intactness (Scholes and Biggs 2005; Alkemade et al. 2009). FRS indicates a decrease of species within the study region. FRA indicates a suitable climate-area (e.g., habitat) contraction within the study region. A potential increase of species or extending its geographical range is excluded from these metrics. As a result, FRS and FRA generally indicate a decline regardless of the global temperature interval. The changes in species composition can also indicate consequences for ecosystem's functioning, but we do not address this. The results of our meta-analysis allow

to generalize projected trends and to assess effects across a broad range of climate-change projections. The established meta-regression models can be used in models, such as the GLOBIO model (Alkemade et al. 2009; Alkemade et al. 2011), to assess biodiversity change in scenario studies in combination with other pressures of global biodiversity loss.

2 Methods and materials

2.1 Systematic literature review

In June 2016, we queried the ISI Web-of-Science database to identify bioclimatic modeling studies that assess the effects of global mean temperature increase on terrestrial biodiversity. We reviewed all studies following the guidelines provided by the Collaboration for Environmental Evidence (CEE) (CEE 2013) (see Online Resource 1 for a detailed description of the process). The guidelines indicate the stages for conducting a systematic research in environmental science, and these stages were combined into three main steps.

Firstly, we defined several search terms and classified them into four main search strings to conduct the review: (i) Climate change elements: (climat* SAME change*) OR (temperature SAME change*) OR (temperature SAME increase) OR (global SAME warming) OR (climat* SAME warming); (ii) biodiversity elements: (biodiversity) OR (diversity SAME species) OR (species SAME richness*) OR (species SAME distribution*) OR (species SAME abundance*) OR (species SAME occurrence*) OR (species SAME turnover) OR (species SAME loss*) OR (species SAME gain*) OR (species SAME composition) OR (species SAME assemblage*); (iii) bioclimatic modeling elements: (bioclimat* model*) OR (niche* model*) OR (climat* model*) OR (distribution model*) OR (habitat model*) OR (ecologic* model*) OR (occurrence model*) OR (species distribution model*) OR (model* distribution*) OR (model* range*) OR (climat* envelope*) OR (envelope* model*); and (iv) modeling projection elements: (future SAME distribution*) OR (climat* SAME scenario*) OR (climat* SAME projection) OR (climat* SAME prediction) OR (climat* SAME pathway*). Additionally, we defined seven inclusion criteria to determine the pertinence of the studies (see criteria in Online Resource 1). These criteria allowed to further restrict the selection by rejecting those studies that did not support our objective. All studies were screened by title for their relevance to the purpose of our study. Those studies selected were then screened by abstract and, when providing limited information in their abstracts, were fully screened, both in content and supporting material. Secondly, the potentially relevant studies were critically revised to select those fulfilling the inclusion criteria. Finally, the relevant data were extracted from all selected studies and synthesized in a biodiversity-impact database. These data included number of species and their area with suitable climate in the original and the projected climate situations, taxonomic group, study location, spatial resolution, and the used global mean temperature increase. Many studies that reported climate effects on single species or exotic species (particularly weeds and insect pests, and aquatic species) were excluded from the database. These studies do not provide data on the original species composition or do not consider terrestrial species.

2.2 Calculation of effect sizes

We calculated the effect sizes, which are measures commonly used in meta-analyses, for each selected study. For studies that assessed the number of species affected by increasing

temperatures, we used the fraction of species remaining at a location (fraction remaining species (FRS) as the effect size; for studies assessing the loss of area with suitable climate for a species, we used the fraction of remaining area with suitable climate (fraction remaining area (FRA)) under a projected increase of global mean temperature (Fig. 1). Both FRS and FRA are effect sizes compared to the original situation in the selected study. The original situation refers to the ecosystem's condition before its climate changed (i.e., original area with suitable climate). Results from multiple climate-change scenarios and time periods, or different bioclimatic modeling algorithms (e.g., generalized linear model, generalized additive model, maximum entropy modeling) that are reported in a study, were all included as separate effect sizes in our database.

We specifically estimated the proportion of *remaining* biodiversity (i.e., a conservative option assuming that species are unable to disperse or adapt) for three main reasons: (i) on average, the projected climate distributions of species are closer to projections without dispersal than projections with full dispersal (Midgley et al. 2006; Hellmann et al. 2016); (ii) uncertainty associated to the capacity of species to disperse (Pearson and Dawson 2003; Pearson et al. 2006) or adapt (Berry et al. 2013) under climate change is reduced; and (iii) FRS and FRA fit into the domain of the GLOBIO model, more specifically, they relate to the relative Mean Species Abundance (MSA) indicator from GLOBIO (Alkemade et al. 2009) and the Biodiversity Intactness Index (BII) (Scholes and Biggs 2005; Newbold et al. 2016) of the local remaining biodiversity.

FRS is calculated as average of ratios between the remaining number of species and the original number of species within each locality (e.g., a grid cell) of the study area's map after projected climate change:

$$\text{FRS} = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{S_{di}}{S_{oi}} \qquad (1)$$

where S_{di} is the expected number of remaining species in grid cell i after climate change as characterized by global mean temperature increase (°C) and S_{oi} is the number of species in grid cell i in the original situation. n is the total number of grid cells. FRS is a relative index between 0 (no original species present) and 1 (all original species present). FRS decreases if the climate is not suitable anymore for a species at one of the grid cells within the study area. FRS represents the *local* response of species to climate change (e.g., in a specific grid cell).

FRA is calculated per species as the ratio between the original suitable climate area and the remaining suitable climate area:

$$\text{FRA} = \frac{1}{S} \cdot \sum_{j=1}^{S} \frac{A_{dj}}{A_{oj}} \qquad (2)$$

where A_{dj} is the remaining suitable climate area for species j after climate change, A_{oj} is the suitable climate area for species j in original situation without climate change, and S is the number of species. FRA is also a relative index between 0 (no original suitable climate area) and 1 (suitable climate area unchanged).

We estimated sampling variances for both effect sizes FRS and FRA to determine the weight to be assigned during the meta-analysis. The calculation of sampling variances is provided in the Online Resource 1.
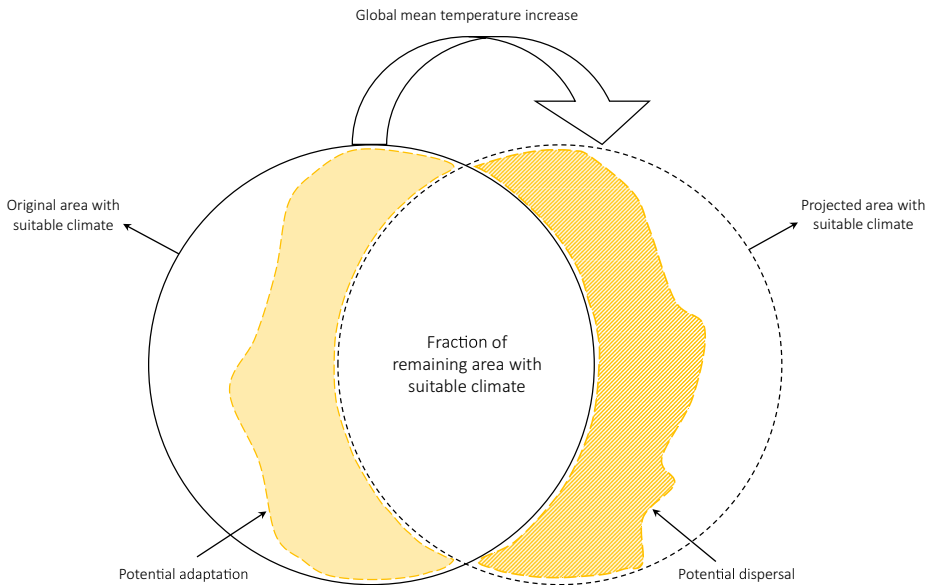
Fig. 1 Schematic illustration to indicate the FRA under projected global mean temperature increase

2.3 Harmonization of climate-change effects

All studies reported their baseline and projected climate conditions. Following Warren et al. (2011), we converted projected temperatures from the climate-change scenarios for each study to a common pre-industrial reference (approximately 1880) (Eq. 3). To this end, the assumed temperature increase between pre-industrial and the *1961–1990* climatic normal was 0.3 °C, between pre-industrial and *1981–1990* was 0.5 °C, and between pre-industrial and *1990* was 0.6 °C. These are the baseline conditions often reported by the selected studies (see Online Resource 2).

$$GMTI_n = T_{scen} + \Delta T_{pre-ref} \tag{3}$$

where $GMTI_n$ is global mean temperature increase converted to a common pre-industrial reference point for study n, T_{scen} is the projected temperature, and $\Delta T_{pre-ref}$ is the assumed temperature increase between the pre-industrial and the baseline conditions, which are both driven by (or based on) climate-change scenarios. We defined four intervals of temperature increase for the meta-analysis: 1–2 °C, 2–3 °C, 3–4 °C, and ≥ 4 °C. Temperature increases between 0 and 1 °C usually correspond to short-term climate-change scenarios depicting low carbon emissions and/or stringent mitigation policies.

2.4 Meta-analysis

We conducted a meta-analysis to derive the pooled effect for all effect sizes as a response to global mean temperature increase. We used the package "*Metafor*" in the R-3.2.2 software (Viechtbauer 2010) and the rma.mv() function assuming independence between the effect size and sampling variance. The included studies are a selection from a larger population of bioclimatic modeling studies (see Online Resource 2).

We ran mixed-effect models with random-effect structures (see Online Resource 1). We compared them using the Bayesian information criterion (BIC). We then fitted random-effect meta-models with restricted maximum likelihood (REML) to different taxa subsets. These are "all species," "plants," "vertebrates," "birds," "mammals," "herptiles," and "insects," for the effect sizes FRS and FRA, and for all four intervals of global mean temperature increase. We introduced the variable "biomes" as a moderator to determine sources of heterogeneity (see Moderator Variable and Table OR1.1 in Online Resource 1).

For the meta-analyses and the meta-regression analyses ratios are often transformed using logit or log transformations to reach normality assumption for the effect sizes (Urban 2015; Benítez-López et al. 2017). We ran the mixed-effect models separately for the untransformed effect sizes FRS and FRA, the logit-transformed and the $\log_{10}$-transformed FRS and FRA, and checked the results for robustness (see Mixed-effect models in Online Resource 1). In addition, meta-regression analyses were used to relate pooled effect sizes FRS and FRA to global mean temperature increase.

We visually inspected the funnel plots of asymmetry to explore the possibility of publication bias (Viechtbauer 2010; Kuiper et al. 2014). We assessed heterogeneity by the formal test of heterogeneity "Q" (Borenstein et al. 2009; Viechtbauer 2010). Variability among the effect sizes was expected due to differential characteristics of the studies (e.g., different taxonomic groups, biomes, and temperature-change intervals).

3 Results

The systematic literature search yielded 302 relevant studies after the title screening. These studies were screened by abstract, out of which 138 fulfilled the criteria for full text screening. We finally selected 97 studies that assessed species composition of the originally occurring species at a location spanning publication dates between 1992 and 2015. Figure 2 shows the results from the systematic literature review. The selected studies allowed the calculation of 370 effect sizes for FRS (data from 60 studies) and 146 for FRA (data from 50 studies). The
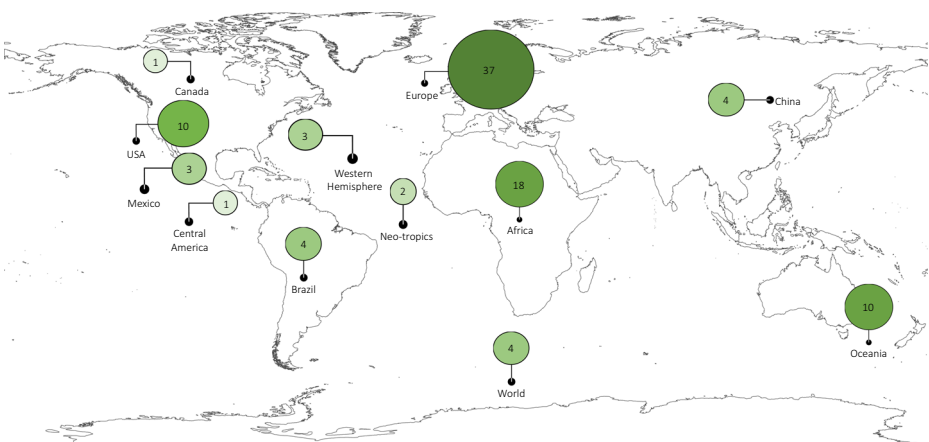
Fig. 2 Locations and number of selected bioclimatic studies

studies and the relevant information extracted are provided in the Online Resource 2. The types of bioclimatic models in the selected studies cover, in some cases, the entire distribution of each species studied. For instance, these models were derived for a continental species distribution or for endemic species. In other studies the models do not cover the entire range of all species and this likely slightly overestimates the effects of climate change.

The meta-analyses show similar results for untransformed, logit-transformed, and log-transformed effect sizes, suggesting robustness of these results. Here we present the results of $\log_{10}$-transformed FRS and FRA, which is the most commonly used transformation. Results for untransformed effect sizes and logit-transformed FRS and FRA are provided in Tables OR3.5–OR3.8 in the Online Resource 3. We retained the random-effect structures (1 | Study ID + 1 | Extent) for the meta-analysis of FRS (BIC = − 502.4888) and (1 | Extent) for the meta-analysis of FRA (BIC = 14.8613) (see Table OR3.1 in Online Resource 3 for results of all random-effect structures).

Results from the meta-regressions to estimate the response changes of FRS and FRA to global mean temperature increase are shown in Fig. 3. The effect sizes decrease with increasing climate change—the rate of decrease is generally larger for FRA than for FRS.

Table 1 provides the results of the random-effect meta-models for FRS and FRA for all species. FRS and FRA were significantly lower under each global mean temperature increase interval. Overall, the FRS and FRA were reduced by 19% (95% confidence interval: 14–23%) and 47% (95% confidence interval: 37–55%), respectively (see Fig. OR3.1 Forest plots in Online Resource 3).

The first interval 1–2 °C for the all species group results in a FRS of 86% (95% confidence interval: 79–93%) and a FRA of 65% (95% confidence interval: 56–75%). These estimates

Fig. 3 Meta-regressions on global mean temperature increase for log10 effect sizes. a Fraction of remaining species and b fraction of remaining area with suitable climate. Confidence intervals (CI 95%) are shown by the shadowed line. Each effect size is represented by a circle, and the size of the circle indicates the number of species in the original study
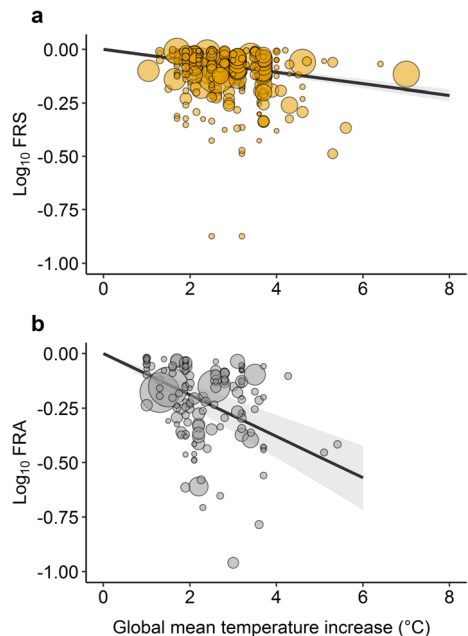
Table 1 Meta-analysis results for "all species"

GMTI interval (°C)	n	Effect size (log₁₀)	Effect size Back-transformed	SE	P value	Z value	CI (lb)	CI (ub)	Q	P(Q)	k
FRS											
Pooled effect[a]	370	−0.0898	0.8132	0.0121	<0.0001	−7.4036	−0.1136	−0.066	1506.2561	<0.0001	60
1–2	57	−0.0677	0.8556	0.0184	0.0002	−3.673	−0.1039	−0.0316	117.4953	<0.0001	25
2–3	156	−0.0815	0.8288	0.0127	<0.0001	−6.3965	−0.1065	−0.0566	506.0702	<0.0001	38
3–4	140	−0.1062	0.7831	0.0201	<0.0001	−5.2845	−0.1456	−0.0668	565.2286	<0.0001	27
≥4	17	−0.1686	0.6783	0.036	<0.0001	−4.6037	−0.2439	−0.0982	244.4234	<0.0001	12
FRA											
Pooled effect[b]	146	−0.2729	0.5335	0.0355	<0.0001	−7.6889	−0.3424	−0.2033	208.6342	0.0004	50
1–2	69	−0.1902	0.6454	0.0333	<0.0001	−5.7101	−0.2555	−0.1249	31.1578	1	26
2–3	38	−0.3045	0.4960	0.0554	<0.0001	−5.4929	−0.4132	−0.1959	83.1113	<0.0001	22
3–4	36	−0.3376	0.4596	0.0695	<0.0001	−4.8603	−0.4737	−0.2015	72.6694	0.0002	22
≥4	3	−0.337	0.4603	0.1348	0.0124	−2.4992	−0.6013	−0.0727	1.2365	0.5389	3

The changes in FRS and FRA across different intervals of global mean temperature increase are indicated by the effect size, both in the log₁₀ and back-transformed. All species group includes vertebrates, plants, and insects from the entire dataset

[a] Pooled effect is the summary of the weighted average among all effect sizes for FRS

[b] Pooled effect is the summary of the weighted average among all effect sizes for FRA

imply that under a global mean temperature increase of up to 2 °C, terrestrial ecosystems could lose on average 14% of their current local species and that species could lose on average 35% of their suitable climate area. The intervals 2–3 °C and 3–4 °C result in larger reductions of FRS and FRA compared to the first interval: FRS is projected to reduce to 83% (95% confidence interval: 78–88%) and 78% (95% confidence interval: 72–86%), and FRA to 50% (95% confidence interval: 39–64%) and 46% (95% confidence interval: 34–63%), respectively. However, the largest reductions occur under a global mean temperature increase beyond 4 °C: only 68% of the local current species are projected to remain on average across the Earth's terrestrial ecosystems (95% confidence interval: 57–80%) and their suitable climate area will likely be reduced to less than 46% (95% confidence interval: 25–85%). These responses are based on a wide range of climate projections with up to 6 °C increase in bioclimatic studies assessing distributions for birds and plants species (e.g., Shoo et al. 2005; Sekercioglu et al. 2008; Meyer et al. 2016).

FRS and FRA responses differ among taxonomic groups. The responses of the taxonomic group plants are lower than for vertebrates in all temperature-increase intervals (Fig. 4; see Table OR3.2 in
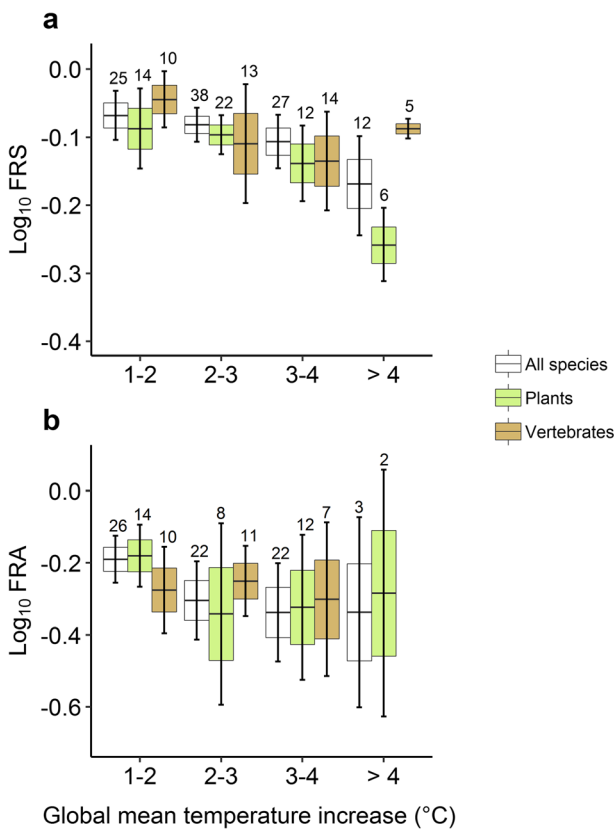

Fig. 4 Mixed-effect model results per taxonomic group plants and vertebrates for **a** fraction of remaining species and **b** fraction of remaining area with suitable climate. Whiskers indicate confidence intervals (CI 95%) and boxes demarcate standard errors. Top numbers indicate the number of studies (k) providing data for each group

Online Resource 3). In the interval of 1–2 °C, the fraction of local originally occurring plant species is reduced by 18%, whereas the vertebrate species fraction is reduced by 10%. Under a more extreme temperature-increase interval (e.g., 3–4 °C), the suitable climate area for plant species is reduced by 53% and for vertebrate species by 50%. These results differ significantly from the original situation (see values in Table 1). The visual inspection of the funnel plots of asymmetry for FRS and FRA (Fig. OR3.2 and Fig. OR.3.3 in Online Resource 3) indicates that a bias is absent.

We found that mammals show the largest reduction in FRS, which quickly declines beyond 2 °C. Contrary to this FRS case, FRA for birds reduces to a larger extent under all intervals (Fig. OR3.4 and Table OR3.3 in Online Resource 3).

Estimates of FRS and FRA can also be used to rank biomes to indicate sensitivities to climate change. The resulting effect-size estimates from our mixed-effect models were used to run meta-regressions to assess the response of biomes to global mean temperature increase (Fig. 5 and Fig. OR3.5 in Online Resource 3 for the FRA results). We found that deserts, temperate forests, and shrublands experience the largest reductions in FRS and tropical and boreal forests in FRA. These are thus likely the most sensitive biomes to increasing global temperatures.
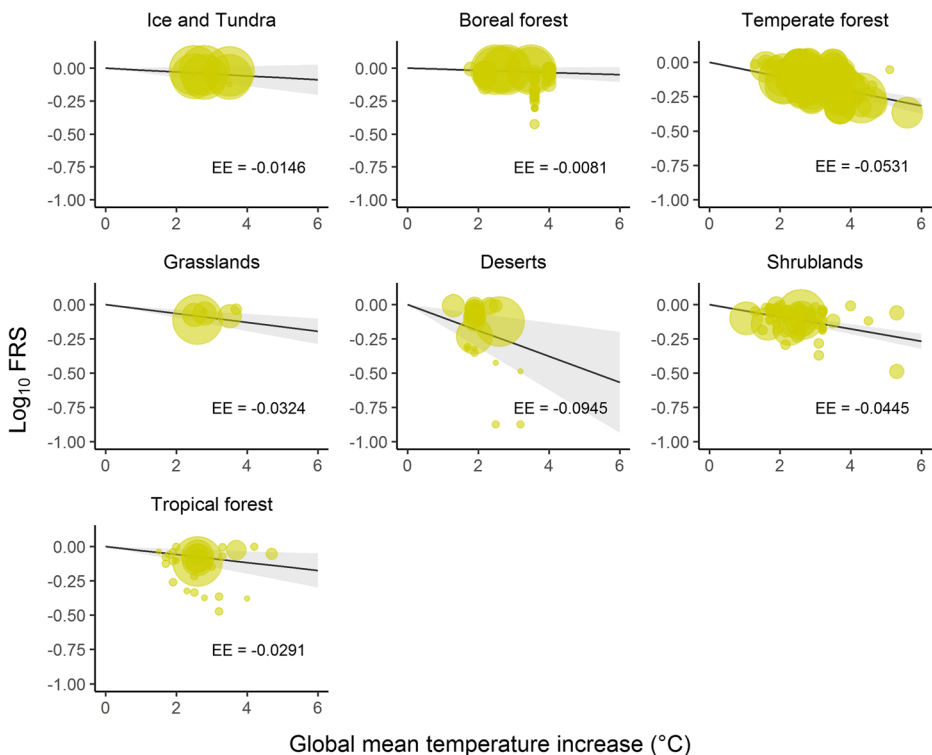
Fig. 5 Mixed-effect model—meta-regressions on global mean temperature increase for different terrestrial biomes. Circles indicate the $\log_{10}$ effect size fraction of remaining species, and the size of the circles corresponds to the number of species in the original study. Results obtained with meta-regression and 95% confidence

4 Discussion and conclusions

The projections of both the FRS and the FRA overall show continuous decreases. This indicates losses of local species richness (on average by 14% at 2 °C of global mean temperature increase) and losses of suitable climate area of many species (on average by 35% at 2 °C of global mean temperature increase). These results indicate that many species will be extirpated locally and disappear from areas where they now occur. This finding is supported by other studies (e.g., Wiens 2016) and will certainly challenge species conservation in many places (Johnson et al. 2017; Warren et al. 2018). However, this does not mean that total species richness will necessary decrease as new species can potentially expand their ranges and establish, depending on their ability to disperse (Hellmann et al. 2016), but such emerging species are logically ignored in our effect sizes.

We estimated that reductions exacerbate as global mean temperature goes beyond 2 °C. For example, at 3 °C of global mean temperature increase the local species richness decreased on average by 17% and the suitable climate area of species by 50%. In addition, these effects are expected not only to increase biodiversity losses but also to accelerate for every degree rise in global mean temperature. As a result, all the local decreases will likely lead to global extinctions.

The results of FRS and FRA vary among taxonomic groups and biomes. This means that the species responses are closely related to their individual sensitivities and exposures to changes in temperature (Urban et al. 2016). For example, the response of vertebrate species to increases in global mean temperature was a decrease in both FRS (on average 10% at 2 °C of global mean temperature increase) and FRA (on average 47% at 2 °C of global mean temperature increase). We found that within the vertebrate group, mammals are projected to undergo the largest local species reduction (i.e., overall FRS reduced by 22%). Our finding is consistent with previous studies (Pacifici et al. 2017), which conclude that many threatened mammals are also negatively affected by climate change. For plant species, the projected FRS and FRA decreased by 18% and 34%, respectively, at 2 °C of global mean temperature increase. The lower plant species' FRS response probably resulted from a higher variability among effect sizes (Q test for heterogeneity in Table OR3.2 and funnel plots of asymmetry in Fig. OR3.1 in Online Resource 3) than the variability for vertebrate species' FRS. This high variability likely relates to methodological issues (e.g., different modeling algorithms) that are inherent to bioclimatic modeling and that affect species-range shifts and abundances. Although exotic and aquatic species were excluded from our study, the different climate-change responses of these groups (e.g., Schnitzler et al. 2007; Kalwij et al. 2015) contribute to the challenge of setting a climate-protection target. Our analysis with the mixed-effect model with biomes as a moderator resulted in a lower heterogeneity in effect sizes compared to plants and vertebrate species. This indicates that biomes is an important explanatory variable when assessing the projected effect of global mean temperature increase on biodiversity.

FRS and FRA focus on assessing the remaining proportion of biodiversity under the conservative assumption of no dispersal. On average, no dispersal is close to reality for most species (Midgley et al. 2006; Hellmann et al. 2016). This implies that FRS and FRA generally indicate decreases. FRS is consistent with indices that estimate the naturalness or intactness, such as the BII (Scholes and Biggs 2005) or the MSA (Alkemade et al. 2009; Alkemade et al. 2011). As these indices are officially accepted by the Convention on Biologically Diversity to indicate the expected responses of original occurring species, our outcomes can also be used in

international assessments of biodiversity change, such as the Global Biodiversity Outlook (sCBD 2014) and other global studies (e.g., PBL 2012; Kok et al. 2018). FRS, however, differs from other biodiversity indices, such as the Species Richness Index (Newbold et al. 2014), because FRS ignores new species for which the future climate becomes suitable. FRA accounts for suitable climate-area reduction of local species. Previous studies that analyzed suitable habitat of species to estimate global species richness patterns (e.g., Visconti et al. 2015) and/or the average proportional change in species distributions to estimate species extinction risks (e.g., Thomas et al. 2004) used similar approaches as our FRA. These studies inform developing goals for local biodiversity conservation and designing protected areas (Newbold et al. 2014; Virkkala et al. 2014). However, such studies also ignore reductions in areas with suitable climate of the originally occurring local species and the local community compositions.

Contrary to the instant loss of biodiversity caused by some non-climatic anthropogenic pressures, climate change triggers more gradual and long-term effects on species (Bertrand et al. 2011) and such temporal dynamics must be considered to interpret the FRS and FRA results. In this study, we estimated the effects of global mean temperature increase assuming that any increase materializes simultaneously, but in reality higher increases in temperature are projected to occur at the end of this century, whereas increases of 2 °C are possible already in 2050 (van Vuuren et al. 2011; IPCC 2013). Although our results support the notion that higher impacts of climate change will occur with higher temperatures, our results do not provide evidence that a climate target of keeping global temperature well below 2 °C protects biodiversity. Therefore, we support the pledge to keep climate change below 1.5 °C and preferably lower, as this helps to maintain the composition of local communities and their climatically suitable areas.

Understanding the climate-change impacts on biodiversity helps to prioritize biodiversity conservation strategies (Gärdenfors 2001; Broennimann et al. 2006). Our results generically relate climate change and biodiversity loss. This relationship is useful to assess relative adverse effects of different climate-change scenarios and to stress the importance of holding climate change well below 2 °C. Furthermore, our results can be used to explore interactions between climate change and other biodiversity-loss pressures, and estimate interactive effects. This implies that reducing the rate of biodiversity loss is critical and only possible if all pressures are reduced or eliminated (sCBD 2014). This means that it would be helpful if the UN Conventions on Biological Diversity and Climate Change closely collaborate to address multiple urgent environmental challenges.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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