Climate change impacts on the phylogenetic diversity of the world's terrestrial birds: more than species numbers

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Keywords: species distribution models, mean pairwise distance, Faith phylogenetic diversity, species range shifts; ecological forecasting; ISIMIP

Type of paper: Primary research article

Running head: Phylogenetic diversity and climate change

38 **Abstract**

39 Ongoing climate change is a major threat to biodiversity and impacts on species distributions and

40 abundances are already evident. Heterogenous responses of species due to varying abiotic tolerances

41 and dispersal abilities have the potential to further amplify or ameliorate these impacts through

42 changes in species assemblages. Here we investigate the impacts of climate change on terrestrial bird

43 distributions and, subsequently, on species richness as well as on different aspects of phylogenetic

44 diversity of species assemblages across the globe. We go beyond previous work by disentangling the

45 potential impacts on assemblage phylogenetic diversity of species gains vs. losses under climate

46 change and compare the projected impacts to randomized assemblage changes.

47 We show that climate change might not only affect species numbers and composition of global species

48 assemblages but could also have profound impacts on assemblage phylogenetic diversity, which,

49 across extensive areas, differ significantly from random changes. Both the projected impacts on

50 phylogenetic diversity and on phylogenetic structure vary greatly across the globe. Projected increases

51 in the evolutionary history contained within species assemblages, associated with either increasing

52 phylogenetic diversification or clustering, are most frequent at high northern latitudes. By contrast,

53 projected declines in evolutionary history, associated with increasing phylogenetic over-dispersion or

54 homogenisation, are projected across all continents.

55 The projected widespread changes in the phylogenetic structure of species assemblages show that

56 changes in species richness do not fully reflect the potential threat from climate change to ecosystems.

57 Our results indicate that the most severe changes to the phylogenetic diversity and structure of species

58 assemblages are likely to be caused by species range shifts rather than range reductions and

59 extinctions. Our findings highlight the importance of considering diverse measures in climate impact

60 assessments and the value of integrating species-specific responses into assessments of entire

61 community changes.

62

63 **Introduction**

64 Global warming has been identified as one of five main anthropogenic drivers of global biodiversity

65 loss (IPBES, 2019; Secretariat of the Convention on Biological Diversity, 2020). Whilst global

66 warming might not represent a major threat to many species currently (Tilman et al., 2017), it is

67 projected to increasingly threaten biodiversity in the future (Broennimann et al., 2006; Engler et al.,

68 2011; Foden et al., 2013; Thomas et al., 2004). First responses of species to climate change have

69 already been reported (Chen et al., 2011; Higgins et al., 2014; Jonathan Lenoir et al., 2020; Radchuk et

70 al., 2019), covering the three possible ways in which species can adapt to global warming, i.e. through

71 changes in their phenology, physiology or by shifting their ranges (Bellard et al., 2012). In particular,

72 changes in species abundance and distribution have already been observed in various taxa across the

73 globe (Bowler et al., 2017; Maclean et al., 2008; Stephens et al., 2016; Thomas, 2010). Many of these

74 observed range shifts have been towards higher latitudes and altitudes (Hickling et al., 2006; Parmesan

75 et al., 1999; Walther et al., 2002), but species-specific range shifts in different directions also occur

76 (Chen et al., 2011; Moritz et al., 2008; VanDerWal et al., 2013). These idiosyncratic range shifts have

77 the potential to be especially problematic, since they will likely result in a reshuffling of species

78 assemblages. Potential consequences could include changes to the competitive balance between

79 species within these assemblages (Ockendon et al., 2014) and altered predator and prey densities

80 (Harley, 2011) as well as changes to the trait composition of local assemblages (Barbet-Massin & Jetz,

81 2015; Gallagher et al., 2013) and subsequently the provision of ecological functions (Pecl et al., 2017;

82 Schleuning et al., 2020).

83 Compositional changes in species assemblages, caused by extinctions or range shifts, also have the

84 potential to affect the underlying phylogenetic structure and diversity of the assemblage (Menéndez-

85 Guerrero et al., 2020; Saladin et al., 2020). Such compositional changes can be assessed using

86 different aspects of phylogenetic diversity. The total evolutionary diversity of a species assemblage is

87 one such metric and measures the amount of evolutionary history that is stored within the assemblage

88 (Flynn et al., 2011; Hardy & Senterre, 2007). Under the assumption that the evolutionary history of an

89 assemblage indicates its evolutionary potential for adaptive change (Faith, 1992a; Forest et al., 2007),

90 a loss of phylogenetic diversity could reduce the evolutionary potential of the assemblage, leaving it

91   increasingly vulnerable to environmental change (Faith & Richards, 2012). This aspect of

92   phylogenetic diversity is frequently calculated using Faith's phylogenetic diversity (named Faith PD

93   hereafter), which is the sum of the branch lengths of all species occurring within the assemblage back

94   to their most recent common ancestor (Faith, 1992a). An alternative metric is the phylogenetic

95   relatedness of the species assemblage, assessed using the mean phylogenetic distance (MPD). MPD is

96   a measure of the deeper phylogenetic diversity of a species assemblage (Leprieur et al., 2016;

97   Swenson & Umaña, 2014). It gives an indication of the average relatedness of the species in an

98   assemblage. Under the assumption that closely related species have a tendency to share more similar

99   traits than very distantly related species (Burns & Strauss, 2011), for example, an increase in the

100   relatedness of species within an assemblage could imply a reduction in the diversity of traits present.

101   This, in turn, could increase the vulnerability of an assemblage to environmental change (Faith, 1992a;

102   Forest et al., 2007) but see (Jarzyna et al., 2020; Mazel et al., 2017).

103   Overall, MPD and Faith PD provide information on two very different aspects of the phylogenetic

104   diversity of species assemblages; whilst the former measures the total standing evolutionary diversity

105   across all species present (Barker, 2002), the latter measures the inverse of the average relatedness

106   between all species pairs (Webb, 2000). Faith PD has often been found to be highly correlated to

107   species richness for various taxa (Barker, 2002; Schipper et al., 2008), with some local exceptions

108   where the correlation is less strong (Fritz & Rahbek, 2012; Voskamp et al., 2017). In contrast, MPD is

109   independent of species richness (Fritz & Rahbek, 2012; Schipper et al., 2008). Since they differ

110   mathematically, these measures have the potential to change independently of each other when species

111   assemblages are changing (Tucker et al., 2017). Comparing these two measures when investigating

112   temporal change in species assemblages yields additional information on the underlying phylogenetic

113   changes that are taking place.

114   There are four potential directions in which the phylogenetic structure of species assemblages could

115   shift when undergoing climate-induced compositional changes: a) MPD could increase whilst Faith

116   PD decreases leading to increasing phylogenetic over-dispersion, i.e. increasingly distantly related

117   species in an assemblage that represent lower values of evolutionary history; b) both MPD and Faith

118   PD could decrease leading to increasing homogenisation; c) both MPD and Faith PD could increase

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119   leading to increasing diversification; or d) MPD could decrease whilst Faith PD increases leading to

120   increasing phylogenetic clustering of the species assemblage, i.e. increase in clusters of closely related

121   species that represent high values of evolutionary history.

122   In addition to the spatial turnover in species, changes in species richness (i.e. the gain and loss of

123   species into and from a species assemblage) could result in non-random changes to the phylogenetic

124   structure of species assemblages. For instance, if extinction risk is clustered across the tree of life due

125   to similarity in species traits that confer vulnerability, this can result in the loss of entire clades and

126   families and subsequently a disproportionate amount of evolutionary history (Russell et al., 1998).

127   Previous studies have found this clustered pattern in Red List extinction risk assessments of taxa that

128   include mammals, angiosperms and birds (Bromham et al., 2012; Davies & Yessoufou, 2013; Fritz &

129   Purvis, 2010; Vamosi & Wilson, 2008). By contrast, when looking at extinction risk based on climate

130   change projections across Europe and South Africa for the same taxa, no phylogenetic signal was

131   found (Pio et al., 2014; Thuiller et al., 2011).

132   Rather than assessing the impacts of extinction across a whole phylogeny, evaluating the spatial

133   variation in impacts of global or local extinctions on the phylogenetic structure of species assemblages

134   could reveal how local changes in species composition impact the local phylogenetic structure. It is

135   possible that impacts of species loss under climate change on phylogenetic diversity do not differ from

136   a random extinction process when assessed on a global scale, but still have a strong phylogenetic

137   impact at the local scale, weeding out entire clades from species assemblages (Huang et al., 2012).

138   Changes in the spatial patterns of phylogenetic diversity under climate change have been shown at a

139   regional scale under different climate change projections, for mammals, angiosperms and birds

140   (González-Orozco et al., 2016; Pio et al., 2014; Thuiller et al., 2011). However, a study investigating

141   potential local changes in phylogenetic diversity as caused by the projected loss of plant, mammal or

142   insect species across the Cape of South Africa under climate change, found little difference from a

143   random extinction process in most places (Pio et al., 2014). It is not clear to what extent such findings

144   hold true for other taxa and more broadly across the world. Furthermore, local phylogenetic diversity

145   under climate change will not only be subject to change through species losses but also through

146   species that newly arrive into an area. Identifying areas where changes in species richness lead to non-

147   random changes in phylogenetic diversity is important, since in those areas the projected changes in

148   species richness will not reflect the entire range of impacts on the species community. For example,

149   decreasing species richness could lead to significant homogenisation of assemblages or to significant

150   phylogenetic over-dispersion, with very different implications for trait diversity and potential for

151   changing competitive interactions and ecosystem function.

152   Here, we first (a) investigate how projected climate-induced range shifts and (local) species

153   extinctions affect the spatial pattern of phylogenetic diversity for an entire taxon, the world's terrestrial

154   bird species. Secondly, (b) we compare how the projected changes in each species assemblage differ

155   from what would be expected at random given the projected local species richness change and, for the

156   first time, disentangle non-random changes through species entering and leaving an assemblage.

157   Our hypotheses are that (a), due to the high correlation between species richness (SR) and

158   Faith PD, spatial changes in SR will be largely reflected in the spatial changes in Faith PD, whilst

159   changes in MPD will frequently differ from this pattern. In particular, we expect Faith PD (and hence

160   SR) and MPD to behave differently in those areas of the world where highly directional range shifts

161   are projected to occur. Such consistent directional shifts are expected by many species at the higher

162   northern latitudes and due to collective shifts of species towards higher altitudes (Devictor et al., 2008;

163   J Lenoir et al., 2008; Sekercioglu et al., 2008; Virkkala & Lehikoinen, 2014). These directional shifts

164   could potentially select for species with similar traits, leading to increasing phylogenetic clustering;

165   this process would be identified through an increase in SR and Faith PD at the higher northern

166   latitudes and the higher altitudes (the receiving species assemblages), accompanied by a simultaneous

167   reduction in MPD in these areas, through related species with similar traits coming into the

168   assemblages.

169   Considering the potential for non-random changes of phylogenetic diversity across species

170   assemblages, we test a second hypothesis that (b) changes through projected species loss are

171   decoupled from changes through projected species gain within assemblages. For example, a given

172   assemblage could lose significant phylogenetic diversity through species loss under climate change,

173   but also gain significantly through species gain, so the overall change in phylogenetic diversity would

174   be marginal, though the phylogenetic structure of the assemblage could change significantly. We

175   hypothesise that the increase in Faith PD in higher northern latitudes and higher altitudes should be

176   lower than expected at random from the number of species gained, due to the increasing phylogenetic

177   clustering. This clustering would also be expected to lead to significant declines in MPD (i.e.

178   significant increase in average relatedness). Contrarily, a increase in Faith PD that is higher than

179   expected from simply the gain of species into assemblages could occur in areas with less directional

180   range shifts, i.e. in regions where species assemblages are more likely to be reshuffled rather than

181   mostly gaining species. In these cases, significant changes in MPD could identify whether

182   assemblages experience diversification (MPD increase) or phylogenetic clustering (MPD decrease). In

183   contrast, non-random changes through the loss of species are harder to predict since they will depend

184   on the unique evolutionary history a species brings to a local assemblage and which would be lost by

185   its extinction or disappearance from the area. Areas that have a high number of species from ancient

186   linages, like montane areas in tropical Africa or the northern Andes (Fjeldså & Lovette, 1997; Hughes

187   & Eastwood, 2006), are most likely to undergo a non-random decrease in Faith PD through a loss in

188   species richness. In such regions, significant parallel decreases in MPD would indicate strong

189   homogenisation, whereas significant increases in MPD would indicate increasing phylogenetic over-

190   dispersion.

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Materials and Methods

Species distribution and climatic data preparation, as well as the format for species distribution models (SDMs) and the design of the chosen dispersal buffer follow methods described in Hof et al (2018). Here, we provide an abridged summary of these methods (Hof et al., 2018), with full details in the supplementary material. The extent of our study is global, and focussed on all terrestrial areas excluding Antarctica.

Species data

We obtained expert range maps for 9882 terrestrial bird species from BirdLife International (Birdlife International and NatureServe, 2015), considering only areas where a species was resident or occurring regularly during the breeding season. Non- breeding distributions where excluded from the analysis, because the climatic requirements of a species during the breeding season are most crucial for its survival and the non-breeding distributions of migratory species are less well known (Eyres et al., 2017; Howard et al., 2020).

Climate data

We calculated the 19 bioclimatic variables, as described by Hijmans *et al*. (Hijmans et al., 2005), using the merged and bias-corrected meteorological forcing datasets EartH2Observe, WFDEI and ERA-Interim as provided by ISIMIP (Lange, 2016). As baseline period we used 1980 – 2009 (centred around 1995). For future projections we used the climate data provided by ISIMIP2b (Frieler et al., 2017), which comprises data from each of four different general circulation models (GCMs), i.e. MIROC5, GFDL-ESM2M, HadGEM2-ES and IPSL-CM5A-LR, for a medium warming scenario (RCP 6.0) (but see Fig. S2 to S5 and Table S2 and S3, for equivalent results based on a low warming scenario (RCP 2.6)). As a future timeframe we used end-of-century projections (2065 – 2095, centred around 2080). All climate data were provided on a 0.5° x 0.5° latitude–longitude grid.

Species distribution models (SDMs)

We used two types of SDMs, generalized additive models (GAM, (Hastie & Tibshirani, 1990; Wood, 2006)) and boosted regression trees (GBM, (Ridgeway, 2007)), to derive the relationship between a species' current range extent and the bioclimatic variables, following the methods in Hof et al (2018). To prepare the projected species distributions for the phylogenetic analysis, we followed the common

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220   practice of applying thresholds to transfer the projected suitability values into binary presence-absence

221   data (Freeman & Moisen, 2008). We applied species-specific thresholds that maximized the fit to the

222   current data, using the true skill statistic (MaxTSS) (Allouche et al., 2006). Incorporating species'

223   dispersal ability into future projections is vital, since the assumption of unlimited dispersal is likely to

224   lead to unrealistic projections (Araújo et al., 2006; Berg et al., 2010; Travis et al., 2013). However,

225   empirical natal dispersal data are available for only a very small proportion of the global terrestrial

226   bird species (Paradis et al., 1998). Therefore, we restricted the projected future distribution of each

227   species using estimated dispersal buffers. This approach follows previous studies that evaluated the

228   impact of various dispersal buffers (Barbet-Massin & Jetz, 2015; Zurell et al., 2018) on projected

229   changes in species richness, but instead of applying a constant buffer distance across all species, we

230   applied species-specific dispersal buffers. The size of the buffer was calculated as $\frac{d}{2}$, where d equals

231   the diameter of the largest range polygon of a species (see Hof et al., 2018 for a comparison of the

232   impact of varying sizes of dispersal buffers on species richness; and Fig. S5 to S7 and Table S4 and S5

233   for impacts on the projected phylogenetic measures using a more restricted dispersal assumption).

234   **Phylogenetic data**

235   For the phylogenetic analysis we used the first full species-level phylogeny of extant birds (Jetz et al.,

236   2012). We compiled a consensus tree using 150 randomly sampled trees out of the 10.000 possible

237   tree topologies provided. For the analysis we chose the tree topologies based on the Hackett taxonomic

238   backbone, which is the more recent of the two high-level avian topologies (Hackett et al., 2008),

239   employed by Jetz et al. (2012). The maximum clade credibility tree topology was calculated using

240   BEAST v1.8.4 (Drummond & Rambaut, 2007), applying the 50% majority rule and using median

241   node heights. We matched the taxonomy used by Jetz et al. (2012) with the BirdLife version 5.0

242   taxonomy (Birdlife International and NatureServe, 2015), resolving all conflicting species, which

243   resulted in a final combined dataset on the breeding range and phylogeny for 8768 species.

244   **Projected spatial patterns in phylogenetic diversity metrics**

245   To extract potential changes in species richness (SR), Faith PD as well as the mean pairwise distance

246   (MPD), we derived current and future species assemblages for each grid cell globally based on the

247   projected species distributions.

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248   *Change in SR* was simply calculated as the proportional change between the number of species

249   projected to occur in a grid cell currently and in the future.

250   *Change in Faith PD* was calculated Faith PD for the species projected to occur in a grid cell, for both

251   time periods, following the methods of Faith (Faith, 1992a). Faith PD is one of the most commonly

252   used measures to calculate phylogenetic diversity (Cadotte et al., 2010). It summarizes how much of a

253   phylogenetic tree is represented in a community by adding all branch lengths that connect the species

254   within the community (Faith, 1992a). Change in Faith PD was then calculated as the proportional

255   change between the current and future Faith PD value of a grid cell.

256   *Change in MPD* was calculated as the mean of all branch lengths that connect each pair of species

257   within a community (Clarke & Warwick, 1998; Kembel et al., 2010; Webb et al., 2002). It gives an

258   indication of how closely related individuals are, on average, within a community (Tucker et al.,

259   2017). Subsequently, change in MPD was again calculated as the proportional change between the

260   current and future MPD value of a grid cell.

261   **Projected non-random changes in phylogenetic assemblage structure**

262   We evaluated whether the projected changes in Faith PD and mean pairwise distance (MPD) were

263   different from what could be expected if the species that moved in or out of an area were randomly

264   distributed across the phylogeny. These randomizations are necessary because the structure of the

265   phylogeny determines the possible extent of projected changes in Faith PD and MPD given a

266   particular species assemblage and number of species moving in or out (May, 1990; Purvis et al.,

267   2000). We decomposed the net change in SR in a given assemblage (grid cell) into the species

268   persisting under climate change, the species projected to be lost (through extinction or emigration),

269   and the species projected to be gained (through colonisation) under climate change (Fig. 1).

270   Random changes in both phylogenetic measures of a species assemblage (grid cell), through species

271   loss, were calculated using the list of species projected to be currently present in the assemblage. The

272   same number of species as projected to be lost (by the SDMs) from the assemblage was then

273   repeatedly (1000 times) dropped from the current species assemblage at random, and both

274   phylogenetic measures were recalculated each time (Fig. 1a). The change in Faith PD or MPD was

275   then calculated as Faith $PD_{remaining}$ *minus* Faith $PD_{current}$ or $MPD_{remaining}$ *minus* $MPD_{current}$, respectively

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276   (Fig. 1a). Finally, based on the 1000 repeats we calculated a two-sided p-value as the proportion of

277   random values that were smaller or larger than the observed value. This p-value indicates if there was

278   a significant difference between the projected change in the phylogenetic measures and the changes

279   based on random species removals.

280   When projecting potential changes to species assemblages under climate change, there will not only be

281   species that are lost from the assemblage, but also species that are gained by the assemblage (Fig. 1b).

282   To calculate if the change in both phylogenetic measures, based on species projected to be gained by

283   the assemblage (colonising the assemblage), was different from what one would expect if species

284   would have been gained at random, we again compared the lists of species IDs projected to occur in

285   the assemblage currently and in future. We extracted the number of species that are projected to be

286   gained by the assemblage (grid cell) and then, using this number, we randomly added new species to

287   those that were projected to remain in the assemblage under climate change, using a species pool

288   defined based on estimated species' dispersal abilities as explained in more detail below (Fig. 1b). The

289   change in Faith PD or MPD was then calculated as Faith $PD_{(remaining + gain)}$ *minus* Faith $PD_{remaining}$ or

290    $MPD_{(remaining + gain)}$ *minus* $MPD_{remaining}$, respectively. Again, we calculated a two sided p-value indicating

291   if there was a significant difference between the projected change and the random change in both

292   phylogenetic measures based on random species being gained by the assemblage.

293   Drawing random species to be gained by an assemblage (grid cell) from a species pool containing the

294   whole list of terrestrial birds included in the analysis (8269 globally distributed species) would yield

295   highly unlikely results, because many species would be unable to move into the area due to climate or

296   habitat requirements, dispersal ability or dispersal barriers. To produce more realistic projections, we

297   created assemblage-specific (grid cell-specific) species pools to draw the species from (Fig. 1b). To

298   create these species pools we used the estimated species-specific dispersal buffers we applied for the

299   projections (see SDM methods). For each species assemblage we extracted the mean estimated

300   dispersal distance across all species occurring within the assemblage, to have an estimate on how far

301   birds are projected to disperse within this area. We then used this mean distance to create a buffer

302   around the species assemblage (grid cell). The species pool for an individual assemblage subsequently

303   contained all the species that occurred within this buffer. We used these assemblage-specific dispersal

304   buffers because the average natal dispersal distance varies globally, with on average much shorter

305   dispersal distances in the tropics (Janzen, 1967; Salisbury et al., 2012).

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307   The final dataset containing the species assemblage values needed to run the analysis and create the

308   plots can be found on Zenodo (10.5281/zenodo.4262462). The R code for the analysis is provided on

309   GitHub (https://github.com/AlkeVoskamp/Climate_change_PD_MPD.git). *BOTH WILL BE MADE*

310   *PUBLIC UPON ACCEPTANCE*

311

312   **Results**

313   **Projected spatial patterns in phylogenetic diversity metrics**

314   The projected changes in species richness (SR) within assemblages (grid cells) do not differ greatly

315   across continents but do differ within them (Fig. 2a). These SR changes are spatially highly correlated

316   with projected changes in Faith PD across the globe (Fig. 2b). Although proportional losses in both SR

317   and Faith PD are likely to be most extreme in species-poor regions (e.g. deserts of Middle East,

318   Sahara, Australia and southern Africa), we also project high proportional losses in some of the very

319   species-rich regions of the world (Fig. 2d and 2e). Across the species-rich regions the proportional

320   changes in Faith PD and SR are especially severe in parts of South America, such as the Amazon

321   region, Uruguay and northern Argentina, as well as on New Guinea, but assemblages with losses up to

322   30 % can be found across all continents (Fig 2d and 2e). Assemblages with a projected proportional

323   gain in both measures are especially widespread at high northern latitudes across the Nearctic and

324   Palearctic realm (Fig 2d and 2e).

325   The projected changes in mean phylogenetic distance (MPD) differ substantially from the projected

326   changes in SR (Fig. 2c) and Faith PD. Looking at the same areas described above for changes in SR

327   and PD, we find, that assemblages for which we project a decrease in MPD are widespread across the

328   northern Nearctic and Palearctic (Fig. 2f), whereas assemblages projected to experience an increase in

329   MPD are located in the southern parts of the Amazon, Uruguay and northern Argentina as well as New

330   Guinea. Overall, the spatial patterns of projected change in MPD are often opposite to those in Faith

331   PD and SR (Fig. 2d-f). An example for this opposite trend in the three indicators are the changes

332   projected across Europe. Increases in Faith PD (and gains in SR) are mainly projected in the northern

333   parts, across the UK and Scandinavia, whereas decreases are projected to be widespread across

334   mainland Europe including Spain (Fig. 2g-h). On the contrary, Scandinavia and the UK are projected

335   to experience decreases in MPD, whereas increases are scattered across mainland Europe including

336   Spain (Fig. 2i).

337   Overall, when looking at projected changes in the two phylogenetic structure metrics (Fig. 2), we find

338   that Faith PD and MPD are changing into opposite directions in approximately 60% of the global

339   terrestrial area (Table 1). Exploring the correlation and divergence between Faith PD and MPD further

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340   (Fig. 3, Table 1), we find that 30% of the global species assemblages (grid cells) are projected to

341   experience an increase in MPD and a decrease in Faith PD, i.e. a loss in average relatedness and a loss

342   in standing evolutionary history, leading to increasing phylogenetic over-dispersion of these species

343   assemblages. In 15% of the species assemblages globally, both MPD and Faith PD decrease, leading

344   to increasing relatedness and decreasing evolutionary history, i.e. an increasing homogenisation of

345   these species assemblages. Further, 29% of the species assemblages experience a decrease in MPD

346   and an increase in Faith PD, indicating increasing relatedness and evolutionary history which leads to

347   phylogenetic clustering of the species assemblages. Finally, 26% of the species assemblages are

348   experiencing increases of both MPD and Faith PD, indicating losses of relatedness and gains in

349   evolutionary history that translate to overall increasing diversification of these species assemblages

350   under global warming.

351   **Projected non-random changes in phylogenetic assemblage structure**

352   We identify areas where the projected changes in each phylogenetic diversity metric, i.e. Faith PD and

353   MPD, are higher or lower than we would expect from the projected changes in SR, by randomising the

354   identity of species that were gained by or lost from a species assemblage. Focussing only on the areas

355   where the projected changes differ significantly from what would be expected at random, based on the

356   two-sided p-value, we find that areas where the decrease in Faith PD (through the loss in SR) was

357   significantly less than expected from randomized species moving out of the assemblage occur on all

358   continents but are most frequent in the northern Palearctic and Nearctic (Fig. 4a). In these areas,

359   assemblages are projected to lose species through climate change that represent unusually low

360   amounts of evolutionary history. In contrast, areas with a significantly stronger decrease in Faith PD

361   than we would expect at random (through the loss of species) also occur on all continents but are most

362   common in central South America and southern African regions (Fig. 4a). These areas are therefore

363   projected to lose species that represent disproportionately high amounts of evolutionary history in their

364   respective assemblages.

365   Focussing on the increases, we find that areas with significantly lower increases in Faith PD than

366   would be expected through equivalent random species gains are most frequent at high northern

367   latitudes, stretching across the entire Nearctic and Palearctic realm, but also across parts of South

368   America and Australia (Fig. 4b). This category of significantly lower increase in Faith PD is the most

369   widespread in extent, indicating that not only are more areas projected to gain more species than lose

370   them (cf. Fig. 2d), but also that the species gains in these areas do not lead to the expected increases in

371   evolutionary history in a large part of the world. Areas with a significantly higher increase in Faith PD

372   than expected by chance (through the gain in SR) are much less common and are mainly located in

373   northern Africa, northern central America and the eastern half of South America (Fig. 4b). These areas

374   are projected to gain species that represent unusually high amounts of evolutionary history, potentially

375   making those assemblages more diverse and increasing their evolutionary potential.

376   For the changes in MPD, we find areas where the projected loss in SR leads to significantly lower

377   declines in MPD than equivalent random losses occur globally, but are generally most extensive in the

378   Nearctic and Palearctic realm (Fig. 4c). In these areas, mean relatedness either decreases or does not

379   increase as much as expected from the projected species loss, indicating that assemblages are projected

380   to lose species that were significantly less closely related to remaining species than expected under

381   random loss. In contrast, the projected loss in SR leads to a significantly stronger decrease in MPD

382   than expected at random in Northern Africa, Arabia and the Middle East, but also to significant but

383   less strong decreases across the Americas as well as in southern Africa and west Siberia (Fig. 4c). In

384   these areas average relatedness of species within assemblages either increases significantly more, or

385   declines significantly less, than expected under random species loss; this suggests that the species

386   projected to be lost are disproportionately more closely related to the remaining species.

387   Similar to the projected changes in Faith PD, the non-random changes in MPD are much stronger from

388   species gain under climate change (Fig. 4d) than from species loss (Fig. 4c). Areas where the increase

389   in SR leads to significantly less increase in MPD than expected from equivalent random species

390   additions are nearly completely restricted to the Nearctic realm as well as the northern Himalayas and

391   Qinghai-Tibet Plateau (Fig. 4d). In these areas, assemblages tend to gain species that are significantly

392   more closely related to existing species than expected at random. Areas where the increase in MPD is

393   significantly higher than would be expected by an equivalent gain in random species are widespread

394   across most continents (Fig. 4d), indicating that average relatedness across most of the world

395 decreases through species projected to be gained under climate change, i.e. that assemblages gain

396 species that are more distantly related to existing species than expected at random.

397 When comparing the significant non-random increases vs. decreases in phylogenetic diversity within

398 each assemblage, we find that there are numerous assemblages where projected significant changes in

399 phylogenetic structure overlap, e.g. stronger decreases than expected from random species loss and, at

400 the same time, weaker increases than expected from random species gain (Table 2). Projected future

401 changes in Faith PD that differ significantly from equivalent random species losses or gains overlap

402 most in assemblages that show a stronger decrease and coinciding stronger increase of evolutionary

403 history than expected, i.e. these assemblages will lose more phylogenetic diversity than if species were

404 lost randomly and simultaneously gain more phylogenetic diversity than if species were gained

405 randomly (>14% of global assemblages; Table 2, second row). This indicates that particularly high

406 proportions of assemblages in most continents (in South America, Africa, North America and Europe)

407 are projected to experience species reshuffling through both species losses and gains. Our results are

408 similar for MPD, where >14% of global assemblages are projected to decrease significantly more than

409 under random species loss and simultaneously increase significantly less than under random species

410 loss, indicating that the species losses and gains will both cause an unusually strong increase in net

411 relatedness of species in these assemblages (Table 2, second row; particularly in South America,

412 Africa, North America, and Asia). For Faith PD, the only other category of coinciding significantly

413 non-random changes is that of simultaneous stronger decrease and weaker increase (Table 2, first

414 row), indicating that >10% of assemblages in Europe and North America are projected to experience

415 unusually strong decreases in Faith PD and therefore lose significant amounts of evolutionary history

416 through both species losses and gains. For MPD, a vast majority of assemblages does not experience

417 any of the overlap categories, with the exceptions of the above-mentioned ones, although nearly 10%

418 of European assemblages are projected to experience simultaneous stronger increases and stronger

419 decreases in relatedness than expected under random species loss and gain (Table 2, third row). This

420 further corroborates the results for Faith PD, indicating that a high proportion of assemblages in

421 Europe stand to experience major species reshuffling.

422

423 **Discussion**

424 We found that the projected impacts of climate change not only affected the amount of evolutionary

425 history stored within species assemblages but also had significant impact on the phylogenetic structure

426 of species communities. The independent changes in the two phylogenetic diversity measures, Faith

427 PD and MPD, resulted in four main directions in which the phylogenetic structures of species

428 communities can change. The frequency with which these structural changes occurred showed a

429 latitudinal gradient, with increases in the amount of evolutionary history contained within species

430 assemblages, associated with either increasing phylogenetic diversification or clustering, being most

431 frequent at high northern latitudes. By contrast, declining evolutionary history, associated with

432 increasing phylogenetic over-dispersion or homogenisation, occurred across all continents. Overall,

433 the projected changes in Faith PD and MPD differed significantly from what we would expect if

434 random species were being gained or lost across large areas of the globe, indicating that the

435 phylogenetic assemblage structure might be changed completely in the future through local species

436 loss and gain that is strongly selective in terms of phylogeny.

437 **Projected spatial patterns in phylogenetic diversity metrics**

438 As expected, our results showed that the spatial patterns of proportional changes in species richness

439 (SR) and Faith PD are highly correlated on a global scale (Fig. 2b), thus the projected losses as well as

440 gains in assemblage SR is largely reflected in their decreases and increases in Faith PD (Figure 1). By

441 contrast, the changes in mean phylogenetic distance (MPD) are independent from the changes in SR

442 and Faith PD and frequently show an opposite pattern. These striking differences are corroborated by

443 the strong spatial patterns in those changes that are significantly non-random (Fig 4, Table 2,

444 supplementary discussion).

445 Focussing on the example of Europe (Figure 2), the increase in Faith PD in combination with the

446 simultaneous decrease in MPD across the UK and Scandinavia indicates that, although these areas

447 tend to gain species, the projected future assemblages might comprise more closely related species in

448 the future than currently. The projected gains in species in these areas are in line with already observed

449 northwards shifts of terrestrial bird species (Thomas & Lennon, 1999; Virkkala et al., 2014). The

450 projected simultaneous decrease in MPD in these areas supports the idea that species responses to

17

451   climate change might in some cases be linked to species traits, with species that have similar traits

452   showing similar responses (Leach et al., 2015; Mason et al., 2019). If these traits are clustered across

453   the phylogeny, which is the case for some traits (Barnagaud et al., 2014; Böhning-Gaese & Oberrath,

454   1999); but see (Khaliq et al., 2015; Losos, 2008)), this could explain the projected gain in species

455   richness and increase in Faith PD as well as the simultaneous increase in relatedness within northern

456   species assemblages.

457   A decrease in Faith PD (and loss of species) in combination with a simultaneous increase in MPD is

458   projected to occur widely across mainland Europe and is especially widespread across Spain (Figure

459   2), indicating that future species assemblages in these areas are projected to be less related despite the

460   overall decrease in species numbers. Focussing on Spain, one possible explanation for these changes

461   could be that species which currently have their breeding grounds limited to northern Africa are

462   projected to move into Spain under climate change (Barbet-Massin et al., 2010; Guiterrez, 2001),

463   potentially adding species to the assemblages in Spain that are very different from currently occurring

464   species. These interpretations made for the example of Europe can be made for other regions in a

465   similar fashion. In general, our results show that it is important to consider additional biodiversity

466   indices to the usual SR metrics to evaluate potential impacts of the redistribution of species under

467   climate change; in this case, even though the changes in SR are mostly matched by the change in Faith

468   PD, the mismatch with MPD shows that different aspects of biodiversity of a species assemblage can

469   be affected in different ways.

470   The extinction of species from, and introduction of species into species assemblages can lead to

471   phylogenetic restructuring (Winter et al., 2009). For example, it is well supported that anthropogenic

472   impacts such as habitat alteration or species invasions into assemblages can lead not only to taxonomic

473   but also phylogenetic homogenisation of species communities, through mechanisms of extinction and

474   replacement (McKinney & Lockwood, 1999; Nowakowski et al., 2018; Olden et al., 2018).

475   Interpreting what changes to the phylogenetic structure of species assemblages could mean in

476   conservation terms is difficult. Generally, more phylogenetically diverse communities have been

477   associated with higher ecosystem stability (Cadotte et al., 2012) and the continuity of ecological

478   functions and services (Cadotte et al., 2011). Furthermore, species assemblages with a higher

479   phylogenetic diversity are thought to be more resilient to ecological disturbance (Faith, 1992a).

480   Therefore, those assemblages that maintain a high Faith PD or experience an increase in Faith PD

481   could be less vulnerable and continue to contribute to the delivery of ecosystem services relative to

482   assemblages where PD declines (Faith et al., 2010). A decrease in MPD that leads to increased

483   clustering within species assemblages might also be problematic. As closely related species frequently

484   share similar traits, clustering could increase competition between species within an assemblage

485   (Procheş et al., 2008). Overall, our analysis shows that species range shifts under climate change are

486   not only affecting species numbers but are likely to impact the phylogenetic structure of species

487   assemblages in ways that could affect the stability of communities and also the future provision of

488   ecosystem services and ultimately human wellbeing (Faith et al., 2010; Srivastava et al., 2012).

489   Looking at the potential impacts of climate change on the phylogenetic structure of species

490   assemblages in more detail we showed that the species assemblages are projected to change into each

491   of four possible directions (Figure 3). We classified these four different directions into four types of

492   potential changes to the phylogenetic structure of species assemblages, which are predominant in

493   different parts of the world (Figure 3). Firstly, we interpreted those assemblages that are undergoing a

494   projected loss in Faith PD with a simultaneous gain in MPD as experiencing increasing phylogenetic

495   over-dispersion, meaning there will be fewer species that are very distantly related (Cavender⸗Bares

496   et al., 2004; Webb et al., 2002). Phylogenetic over-dispersion can often be observed in ecological

497   communities that are thought to have evolved under competitive exclusion (Cooper et al., 2008;

498   Dehling et al., 2014; Emerson & Gillespie, 2008; Slingsby et al., 2006). For the projections under

499   climate change, this pattern might be largely driven by the loss of species from assemblages, since the

500   increase in phylogenetic over-dispersion occurs widely in species rich, tropical areas that are also

501   projected to undergo high species losses (Fig. 1d and 2b).

502   Second, we interpreted those assemblages with a projected loss of MPD and gain in Faith PD as

503   experiencing increasing phylogenetic clustering, meaning that they are gaining species but these are

504   mostly related to each other or to the species already occurring in the assemblage. Phylogenetic

505   clustering has been observed in species assemblages that evolved under environmental filtering, which

506   selected for species that are able to cope with the same conditions (Asefa et al., 2017; Emerson &

507   Gillespie, 2008); but see (Cadotte & Tucker, 2017; Kraft et al., 2015). Under our climate change

508   projections this type of compositional change is mainly found at high northern latitudes as well as

509   along the southern Andes and the Tibetan plateau (Fig. 3b). This is in line with our hypothesis that

510   uniform responses across species, like highly directional range shifts (such as widespread shifts

511   towards higher latitudes and altitudes; (Devictor et al., 2008; J Lenoir et al., 2008; Sekercioglu et al.,

512   2008; Virkkala & Lehikoinen, 2014)) might select for species with similar traits and subsequently

513   increase phylogenetic clustering.

514   Third, we interpreted species assemblages with a projected loss in both MPD and Faith PD as

515   undergoing an overall increase in phylogenetic homogenisation, meaning that they are also

516   experiencing a loss in Faith PD (and hence evolutionary history) whilst the overall relatedness

517   between species slightly decreases, leaving the assemblage with fewer and more closely related

518   species than before. Phylogenetic homogenisation is often observed in species communities that have

519   undergone anthropogenic disturbance, like habitat conversion through urbanisation or agricultural

520   expansion or intensification (Liang et al., 2019; Sol et al., 2017). Under the climate change projections

521   utilized here, phylogenetic homogenisation occurs least frequently (Table 1), mainly across Eastern

522   Europe (Fig. 3b), and is characterized by relatively small changes in all three measures SR, Faith PD

523   and MPD (Fig. 3a). That we do not see drastic losses here could be due to the high mobility of many

524   bird species. Looking at the impacts for other, less mobile, taxa or assuming a no-dispersal scenario

525   would likely increase the number of assemblages in this group due to potentially higher extinction

526   (Foden et al., 2013).

527   Finally and fourth, we interpreted those assemblages with a projected increase in both MPD and Faith

528   PD as undergoing increasing diversification, meaning that the assemblages are becoming overall more

529   phylogenetically rich with an increase in evolutionary history and a decrease in the overall relatedness

530   of the species. These increases are mostly projected into currently species poor regions such as parts of

531   the North American, European and Asian Taiga and some of the world's deserts, such as the Saharan,

532   Arabian, Australian and Kalahari deserts (Fig. 3b). This distribution is probably due to the fact that in

533   species-poor regions, the addition of even just one species is highly likely to increase phylogenetic

534   diversity for simple mathematical reasons.

535   **Projected non-random changes in phylogenetic assemblage structure**

536   The magnitude in which phylogenetic diversity is changing depends on the structure of the

537   phylogenetic tree (Cadotte & Davies, 2016; Heard & Mooers, 2000; Vellend et al., 2011) and, for

538   Faith PD, can mirror or deviate from the taxonomic diversity (Frishkoff et al., 2014). In contrast to

539   earlier studies that projected global extinction risk from climate change to be evenly distributed across

540   the phylogeny for some taxa (Pio et al., 2014; Thuiller et al., 2011), we show that projected changes in

541   the phylogenetic diversity of species assemblages under climate change can differ significantly from

542   equivalent random changes to the species pool (Fig. 4). Looking at the decreases in Faith PD and

543   MPD through the loss of species, we project that for terrestrial bird species there are substantial areas

544   across the globe where phylogenetic diversity decreases or increases more than expected at random.

545   Especially for Faith PD, the non-random decreases might be connected to the local loss of ancient

546   lineages, since assemblages where Faith PD decreases more than expected at random are mostly

547   located in tropical Africa and South America which host higher numbers of ancient lineages (Procheş

548   et al., 2015; Voskamp et al., 2017). By contrast, assemblages where Faith PD decreases less than

549   expected at random are mostly located at high northern latitudes which are known to host fewer

550   ancient lineages (Procheş et al., 2015). Our findings conflict somewhat with a study that investigated

551   non-random declines in Faith PD under climate change in various mammal, plant and insect families

552   in the Floristic Cape Region of South Africa and found that the observed decline differed little from

553   random simulations (Pio et al., 2014). This difference in the results might reflect variation between

554   taxa, or the fact that the latter analysis was conducted in a biodiversity hotspot that is rich in endemics

555   and old lineages (Cape floristic region has over 1500 plant genera, 30% of which occur nowhere else

556   globally), but is more likely due to the scale of the analysis.

557   Importantly, aside from investigating potential non-random declines in phylogenetic diversity, we

558   used novel methods to disentangle the impacts of projected assemblage gains and losses under climate

559   change. We found that, in particular, the impacts of assemblage gains differ significantly from random

560   across large areas globally. Our results show that identifying areas where the changes in phylogenetic

561   diversity differ from random is important, since they could be more widespread than previously

562   assumed, and our analyses highlight where projected richness changes might not fully reflect the risk

563   that climate change poses to communities.

564   When disentangling the impacts of species loss and gain, we identified areas in the world where the

565   impacts of species losses and gains on the phylogenetic diversity of the assemblages are causing

566   changes in the same direction. The outcome could be positive, where the PD or MPD increases,

567   through species entering an assemblage, are significantly higher than expected whilst the PD or MPD

568   decreases, through species being lost from the same assemblage, are significantly lower than expected.

569   Or the outcome could be negative, with lower PD or MPD gains than expected based on species gains

570   and greater PD or MPD declines than expected based on species losses. For such assemblages, the

571   overall changes in phylogenetic diversity will be clearly positive or negative. By contrast, there are

572   also situations where the loss and gain of species have different implications for the assemblage

573   phylogenetic diversity, highlighting the utility of a multi-metric approach to studying impacts. For

574   example, in such areas the species gains can lead to a greater PD or MPD than expected but, at the

575   same time, species losses lead to lower PD or MPD than expected (or vice versa). In such

576   assemblages, the net change in PD or MPD might be close to zero, but the underlying changes in the

577   species composition, are nonetheless high, indicating greater shifts in assemblage composition than

578   would be apparent if gains and losses of species were not separately assessed. Our results show that

579   disentangling the impacts of species gains and losses can aid understanding of how assemblage

580   phylogenetic diversity might be impacted by climate change, and that important aspects of this impact

581   might be masked if only considering overall phylogenetic diversity change or if only focussing on

582   losses.

583   **Data limitations and model uncertainties**

584   There are several data-related and methodological caveats that need to be considered when interpreting

585   the results of this study. Firstly, we were gridding species distribution range maps at a 0.5° x 0.5° grid

586   (circa 55x55 km) resolution. Aside from the debate around the utility of range maps for SDMs (Herkt

587   et al., 2017), the coarse resolution of the resultant distribution data and the associated climate data

588   used in the modelling may lead to potential misinterpretation of the finer-scale relationships between

589   species occurrences and climate. However, our global assessment for all bird species could only be

590   conducted at this scale due to a paucity of more highly resolved occurrence data, as is common with

591   almost all similar global analyses. Consequently, our study is useful in outlining broad trends in

592   potential assemblage changes but should not be extended to infer locality- or species-specific

593   responses.

594   Additionally, our projections of species' current and future ranges are solely based on the climatic

595   niche of a species. Both changes in land cover and land-use as well as biotic interactions will have an

596   impact on the future ranges of the modelled species (Engelhardt et al., 2020; Godsoe & Harmon, 2012;

597   Sirami et al., 2017). Furthermore, biotic interactions will also have an impact on the likelihood of the

598   future establishment of species (Mitchell et al., 2006). Whilst some promising modelling approaches

599   incorporate biotic interactions into SDMs (Kissling et al., 2012), this is still a major challenge (Zurell

600   et al., 2020), especially when working on a global scale and considering entire higher taxa. Similarly,

601   our ability to integrate land-use and climate change remains limited (Sirami et al., 2017). Although

602   there have been advances in the understanding of species-specific habitat suitability (Methorst et al.,

603   2017; Rondinini et al., 2011) and efforts to derive links between land-use change and biodiversity loss

604   (Newbold et al., 2014, 2015), obtaining biologically relevant data at the scale of this study remains a

605   challenge. Nevertheless, despite these sources of uncertainties, we believe our method is robust and

606   highlights broad geographic trends in potential phylogenetic change as well as identifying ways in

607   which both heterogeneous and homogenous responses of species to climate change could impact the

608   phylogenetic structure of species assemblages.

609   **Implications for conservation**

610   The value and practicability of using phylogenetic diversity indices for conservation purposes has

611   been widely discussed (Winter et al., 2012). Phylogenetic measures can add valuable information for

612   conservation planning (Pollock et al., 2015, 2017), and the preservation of phylogenetic diversity

613   could be key to the resilience of communities to environmental change (Faith, 1992a, 1992b). Among

614   the different actions planned to reduce biodiversity loss and reach the 2050 Vision on Biodiversity,

615   climate change action plays a significant role (Secretariat of the Convention on Biological Diversity,

616   2020). Although no phylogenetic signal in climate change vulnerability had been identified prior to

617   this study, our results showing strong heterogeneity in assemblage-level changes reinforce the utility

618   of phylogenetic indices for climate impact studies. Whilst our results should not be interpreted at a

619   local scale, they do highlight the implications that climate change induced range shifts could have on

620   the phylogenetic diversity of species assemblages. The widespread projected changes to phylogenetic

621   diversity we demonstrate, indicate a potential for strong changes to the diversity of species' traits and

622   attributes important for maintaining functioning ecosystems. They thus emphasise the need to

623   minimise future climate change although, for the conservation of biodiversity, climate change

624   mitigation strategies must run alongside reductions in other drivers of biodiversity loss (Leclère et al.,

625   2020).

626

627   **Acknowledgements**

628   We thank Dan Rosauer for valuable discussions on the study design and methodology.

629

630   **Author contributions**

631   AV and SGW conceived the initial idea. AV, SAF and CH designed the study. AV analyzed the data

632   with input from SAF, CH, MFB and SGW. AV wrote the manuscript with comments from all

633   contributing authors.

634

635   **Conflict of interest**

636   The authors declare no conflict of interest.

637

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1093

1094

1095   **Fig. 1:** Methods used to compare the projected changes in Faith PD (called PD in the flow diagram)

1096   and mean phylogenetic distance (MPD) of a species assemblage (grid cell), based on species that are

1097   projected to be lost from (a) and gained into (b) the assemblage, with the expected changes in Faith

1098   PD/MPD based on the same number of species being lost and gained at random. In this example, we

1099   assume that a) there were 10 species in the assemblage initially and we project 7 species to remain in

1100   the assemblage (with 3 species projected to emigrate or go extinct). To calculate the expectation for

1101   random species loss, we then drop 3 random species from the list of ten species 1000 times, i.e. the

1102   species pool is just the focal assemblage in this case. We then recalculate the two metrics of

1103   phylogenetic assemblage structure for each random assemblage, and compare this expected change

1104   under random species loss to the projected change in the two metrics. Then, we assume that b) seven

1105   species remain in the assemblage and two species are projected to be gained to the assemblage. To

1106   calculate the expectation for random species gain, we draw 2 random species from the species pool

1107   1000 times, where the colonist species are drawn randomly from a pool of candidate species that occur

1108   within a colonisable distance of the focal assemblage; the mean dispersal ability for each species is

1109   estimated as half the value of the longest range diameter (D). We then recalculate the two metrics of

1110   phylogenetic assemblage structure for each random assemblage, and compare this expected change

1111   under random species gain to the projected change in the two metrics.

1112

1113   **Fig. 2:** Projected changes in species richness (SR), Faith's phylogenetic diversity (Faith PD) and

1114   mean phylogenetic distance (MPD) under a medium emission scenario (RCP6.0) and a medium

1115   dispersal scenario by 2080. (a) shows the percentage change in SR against absolute change in SR; (b)

1116   the percentage change in Faith PD against percentage change in SR; (c) the percentage change in MPD

1117   against percentage change in SR (d) the spatial distribution of percentage change in SR; (e) the spatial

1118   distribution of percentage change in Faith PD and (f) the spatial distribution of percentage change in

1119   MPD. The percentage change for all three measures is shown in detail for Europe (g – i). Red indicates

1120   a negative change (e.g. loss in species richness, Faith PD or MPD), blue indicates a positive change

1121   (e.g. gain in species richness, Faith PD or MPD).

1122

1123 **Fig. 3:** Comparison of the direction of projected changes in phylogenetic assemblage structure as

1124 indicated by mean phylogenetic distance (MPD) versus by Faith's phylogenetic diversity (Faith PD)

1125 under a medium emission scenario (RCP 6.0) assuming a medium dispersal scenario by 2080. The

1126 scatterplot (a) shows percentage change in MPD against percentage change in Faith PD, divided into

1127 four categories of change using the median along each axis. The map (b) shows the spatial distribution

1128 of the species assemblages falling into one of these four categories, and the bar chart (c) shows the

1129 number of assemblages per category across different continents. The four defined categories are: grid

1130 cells with a projected gain in MPD and loss in Faith PD leading to increasing phylogenetic

1131 overdispersion of these species assemblages (blue); grid cells with a projected loss in both MPD and

1132 Faith PD, leading to increasing homogenisation of these species assemblages (purple); grid cells with

1133 a projected loss of MPD and gain in Faith PD, indicating increasing phylogenetic clustering of these

1134 species assemblages (red); and grid cells with a projected gain in both MPD and Faith PD, indicating

1135 increasing diversification within these species assemblages (yellow).

1136

1137 **Fig.4:** The significance and direction of projected changes in Faith's phylogenetic diversity (Faith PD)

1138 and mean phylogenetic distance (MPD) of species assemblages (grid cells), through species that are

1139 projected to be lost from (a and c) and gained into (b and d) assemblages, in comparison to expected

1140 changes if species were lost and gained at random. Difference values for species being lost from an

1141 assemblage are calculated as shown in Fig 1**.** For the maps of change in Faith PD/MPD through

1142 species being lost from an assemblage (a and c), red indicates that the loss of Faith PD/MPD caused

1143 by the species that are projected to be lost from the assemblage is significantly higher than what would

1144 be expected if the same number of random species would be lost; blue indicates that the loss is

1145 significantly lower than what would be expected if random species would be lost (significance is

1146 derived using a two-sided p-value < 0.05 or > 0.95). For the maps of change in Faith PD/ MPD

1147 through species being gained into an assemblage (b and d), red indicates that the gain in Faith

1148 PD/MPD through the species projected to be gained into the assemblage is significantly lower than

1149 what would be expected if the same number of random species would be gained into the assemblage,

1150 blue indicates that the gain is significantly higher than what would be expected if random species

1151　would be gained. A gain or loss in Faith PD signifies a significant increase or decrease in total

1152　evolutionary history represented, respectively; a gain or loss in MPD signifies a significant decrease or

1153　increase in average relatedness, respectively. White areas in each map have no significant changes

1154　compared to random species gain or loss. Results are shown for a medium emission scenario (RCP6.0)

1155　and a medium dispersal scenario by 2080.

1156

1157　**Table 1:** The overall terrestrial area, globally and per continent, that falls into the four different

1158　categories of combined change in two phylogenetic structure metrics, Faith's phylogenetic diversity

1159　(Faith PD) and mean phylogenetic distance (MPD) (as shown in Fig. 3): increasing homogenisation

1160　(loss of PD and MPD); Increasing clustering (gain in PD and loss of MPD); Increasing over-dispersion

1161　(loss of PD and gain in MPD) and Increasing diversification (gain in PD and MPD). The area extent is

1162　given in km^2 as well as in the percentage of the total terrestrial area, per continent and globally. The

1163　extent of the area projected to fall into the four different categories is derived assuming a medium

1164　emission scenario (RCP6.0) and a medium dispersal scenario by 2080.

1165

1166　**Table 2:** Combined projected changes in Faith's phylogenetic diversity (Faith PD) and mean

1167　phylogenetic distance (MPD), indicating the proportions of those assemblages across the globe where

1168　each measure changes significantly compared to both, a randomized gain and a randomized loss of

1169　species (as shown in Fig. 4). The area extent is given in km^2 as well as in terms of percentage of the

1170　total global land mass; percentage values above 10% are printed in bold. The extent of the area

1171　projected to fall into the four different combinations is derived assuming a medium emission scenario

1172　(RCP6.0)　and　a　medium　dispersal　scenario　by　2080.

1173 **Table 1**

	Increasing homogenisation		Increasing clustering		Increasing over-dispersion		Increasing diversification	
	Area in km²	*%*	*Area in km²*	*%*	*Area in km²*	*%*	*Area in km²*	*%*
Africa	4,321,971	15	5,572,879	19	13,159,337	44	6,813,364	23
Asia	4,928,362	17	6,055,430	29	12,751,917	42	7,307,249	23
Australia	2,345,390	28	1,830,899	22	2,834,075	33	1,467,003	18
Europe	3,223,093	12	7,390,459	37	2,937,947	10	9,160,714	41
North America	2,969,140	12	7,371,192	41	7,060,167	23	5,383,293	25
South America	1,603,745	9	3,829,585	22	9,151,380	52	3,015,050	17
Global km²	19,391,701		32,050,444		47,894,823		33,146,674	
Global %	14		29		31		27	

1174 **Table 2**

1175

Combinations of significantly non-random changes	Continent	Faith PD		MPD	
		Area in km^2	%	Area in km^2	%
More decrease than under random species loss **AND** **Less increase than under random species gain**	*Africa*	617,294	2.01	95,040	0.30
	Asia	1,018,127	3.54	95,338	0.28
	Australia	49,022	0.55	9,979	0.13
	Europe	2,542,569	**10.97**	6,202	0.03
	North America	2,444,568	**10.24**	623,843	0.05
	South America	562,389	3.07	8,958	0.05
	Global	7,233,968	6.41	839,360	0.80
More decrease than under random species loss **AND** **More increase than under random species gain**	*Africa*	5,242,431	**17.32**	5,594,644	**18.25**
	Asia	3,115,838	9.96	4,477,026	**14.17**
	Australia	445,208	5.17	776,455	8.85
	Europe	2,908,113	**12.34**	1,816,491	7.48
	North America	3,955,785	**16.53**	3,647,676	**16.23**
	South America	4,963,732	**27.18**	3,876,950	**21.82**
	Global	20,631,107	**14.76**	20,189,242	**14.17**
Less decrease than under random species loss **AND** **More increase than random species gain**	*Africa*	964,809	3.33	644,903	2.22
	Asia	879,000	2.79	1,766,252	5.81
	Australia	240,567	2.83	176,295	2.15
	Europe	1,332,718	7.06	2,314,457	**9.82**
	North America	373,769	1.79	986,123	4.50
	South America	344,488	2.04	389,379	2.14
	Global	4,135,350	3.65	6,277,408	5.34
Less decrease than under random species loss **AND** **Less increase than under random species gain**	*Africa*	91,834	0.32	9,050	0.03
	Asia	356,260	1.19	508,642	1.6
	Australia	13,936	0.16	0	0
	Europe	1,228,379	6.61	63,660	0.30
	North America	231,209	1.12	185,502	0.78
	South America	97,367	0.55	18,408	0.10
	Global	2,018,983	2.25	785,262	0.59

1176   **Supplementary material**

1177   **Figure S1:** Map of the distribution of the species that had to be excluded from the analysis due to

1178   limited range extent or low model performance

1179   **Figure S2:** *Adapted figure 2:* Projected changes in SR Faith PD and MPD for RCP 2.6 under a

1180   medium dispersal scenario

1181   **Figure S3:** *Adapted figure 3:* Comparison of phylogenetic assemblage structure for RCP 2.6 under a

1182   medium dispersal scenario

1183   **Figure S4:** *Adapted figure 4:* Projected changes in Faith's phylogenetic diversity (Faith PD) and mean

1184   phylogenetic distance (MPD) of species assemblages for RCP 2.6 under a medium dispersal scenario

1185   **Figure S5:** *Adapted figure 2:* Projected changes in SR Faith PD and MPD for RCP 6.0 under a low

1186   dispersal scenario

1187   **Figure S6:** *Adapted figure 3:* Comparison of phylogenetic assemblage structure for RCP 6.0 under a

1188   low dispersal scenario

1189   **Figure S7:** *Adapted figure 4:* Projected changes in Faith's phylogenetic diversity (Faith PD) and mean

1190   phylogenetic distance (MPD) of species assemblages for RCP 6.0 under a low dispersal scenario

1191   **Table S1:** Species numbers included in the different steps of the analysis

1192   **Table S2:** *Adapted table 1:* The overall terrestrial area, globally and per continent, that falls into the

1193   four different change categories for RCP 2.6 under a medium dispersal scenario

1194   **Table S3:** *Adapted table 2:* Combined projected changes in Faith's phylogenetic diversity and mean

1195   phylogenetic distance for RCP 2.6 under a medium dispersal scenario

1196   **Table S4:** *Adapted table 1:* The overall terrestrial area, globally and per continent, that falls into the

1197   four different change categories for RCP 6.0 under a low dispersal scenario

1198   **Table S5:** *Adapted table 2:* Combined projected changes in Faith's phylogenetic diversity and mean

1199   phylogenetic distance for RCP 6.0 under a low dispersal scenario
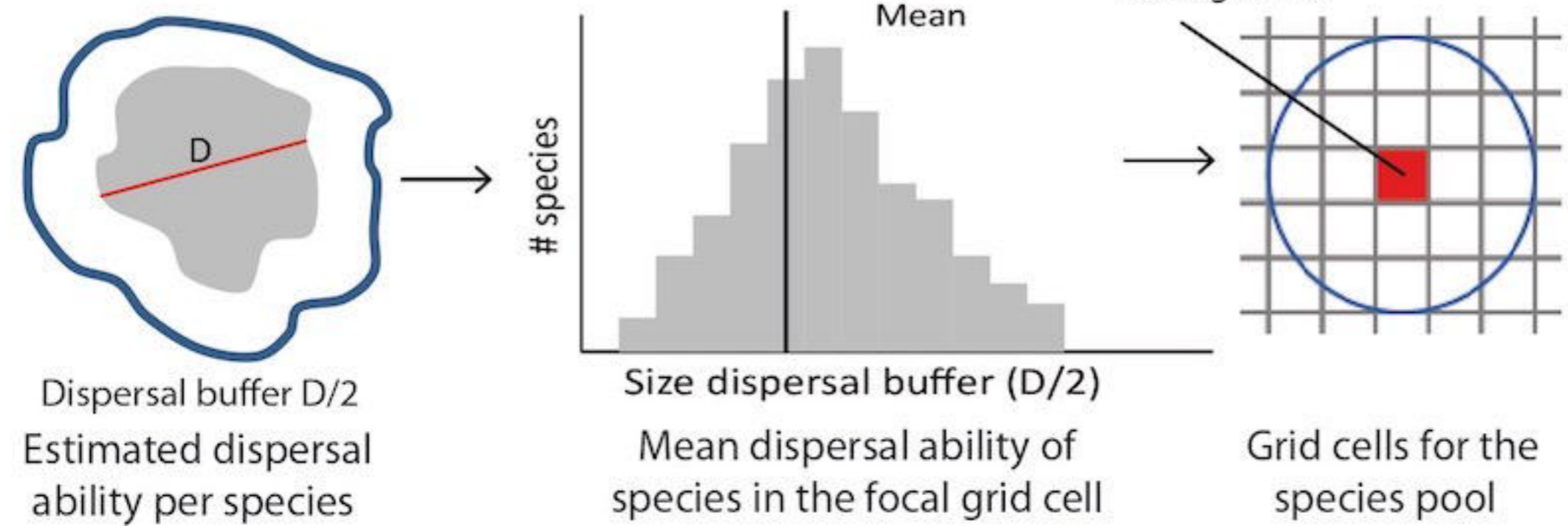
a) Is projected (M)PD change (through species moving out of a species assemblage or going extinct) higer/lower than random?

Focal grid cell (a single species assemblage)

Current
10 species

2080
7 species

-> 3 species are moving out

Current SR (10 species)
Current PD (7000 myr)
Current MPD (xx myr)

Future SR (7 species)

Remaining PD (6500 myr)
Remaining MPD (xx myr)

Calculate (M)PD 1000x based on 3 random species moving out

Projected future (M)PD
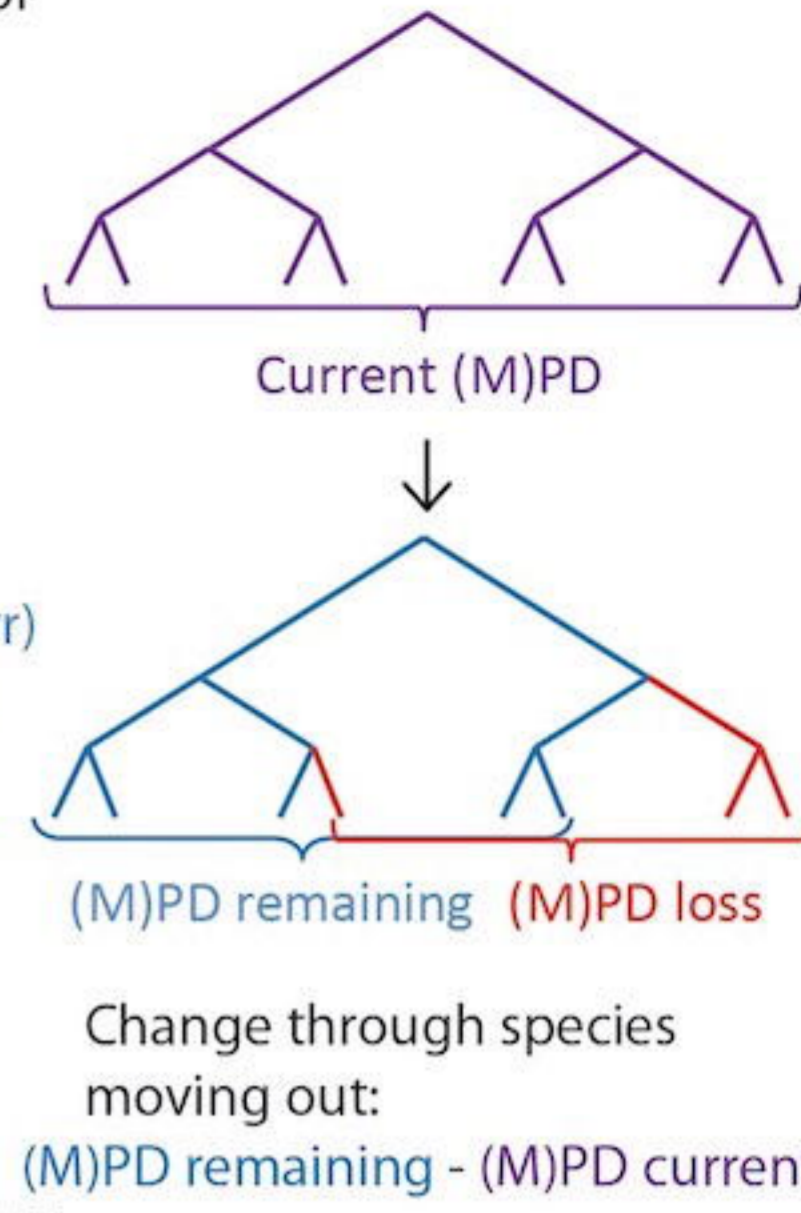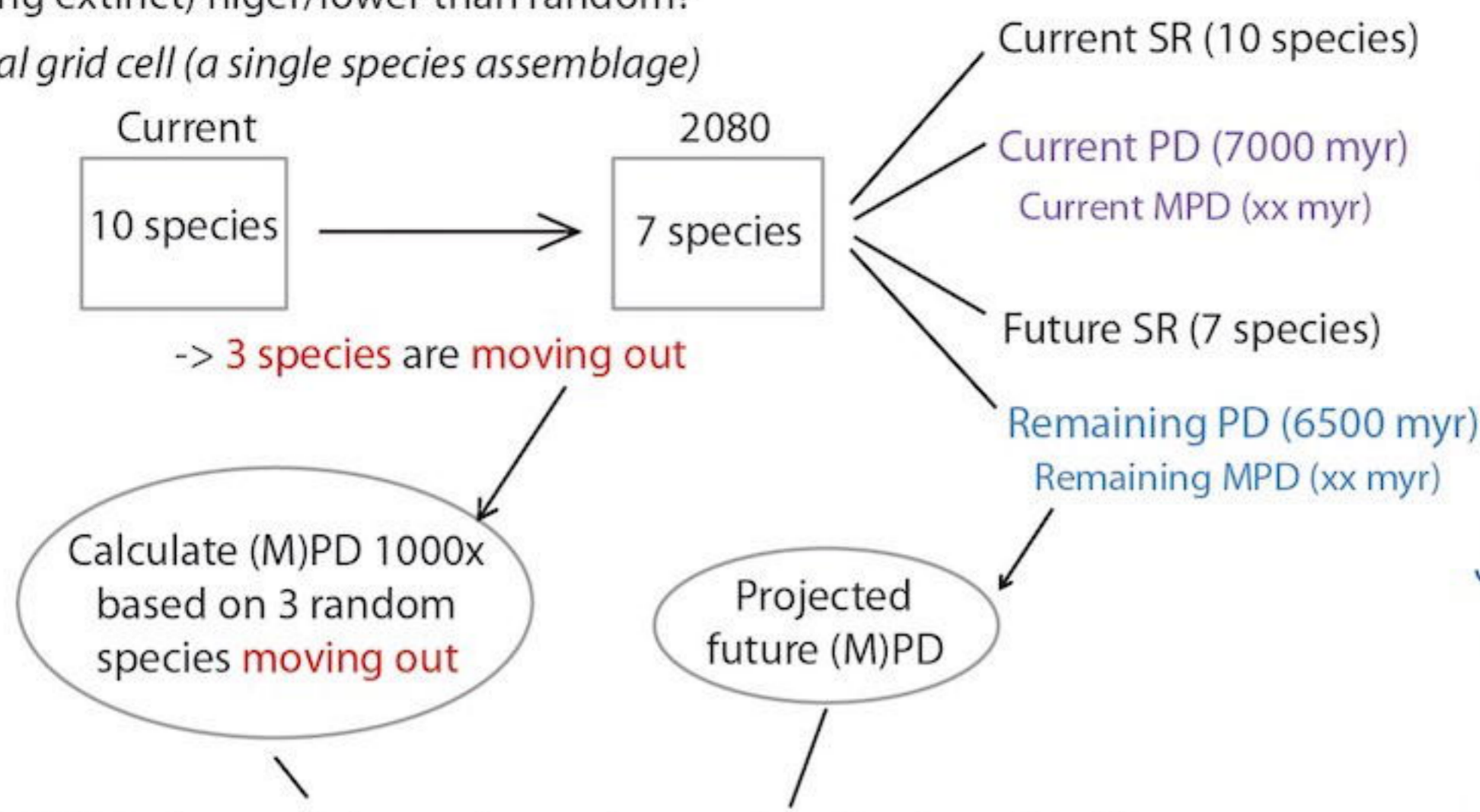
Is (M)PD change higher or lower than random for the grid cell?

Species pool for randomisation procedure (species moving out)

Focal grid cell

Grid cell for the species pool

Current (M)PD

(M)PD remaining   (M)PD loss

Change through species moving out:
(M)PD remaining - (M)PD current
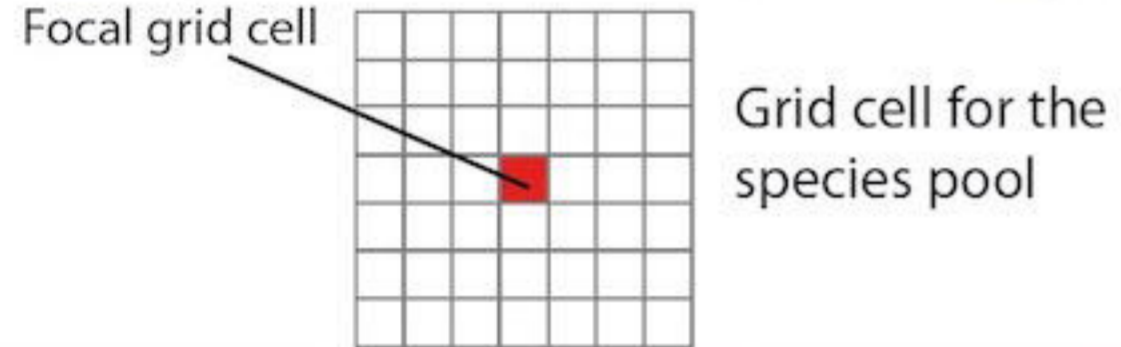
b) Is projected (M)PD change (through species moving in to a species assemblage) higer/lower than random?

Same focal grid cell (a single species assemblage)

2080
7 species remaining

9 species

-> 2 species are moving in

Remaining SR (7 dpecies)

Remaining PD (6500 myr)
Remaining MPD (xx myr)

Future SR (9 species)

Future PD (6800 myr)
Future MPD (xx myr)

Calculate (M)PD 1000x based on 2 random species moving in

Projected future (M)PD

Is (M)PD change higher or lower than random for the grid cell?

(M)PD gain   (M)PD remaining

(M)PD (remaining + gain)

Change through species moving in:
(M)PD (remaining + gain) - (M)PD remaining

Species pool for randomisation procedure (species moving in)

Focal grid cell
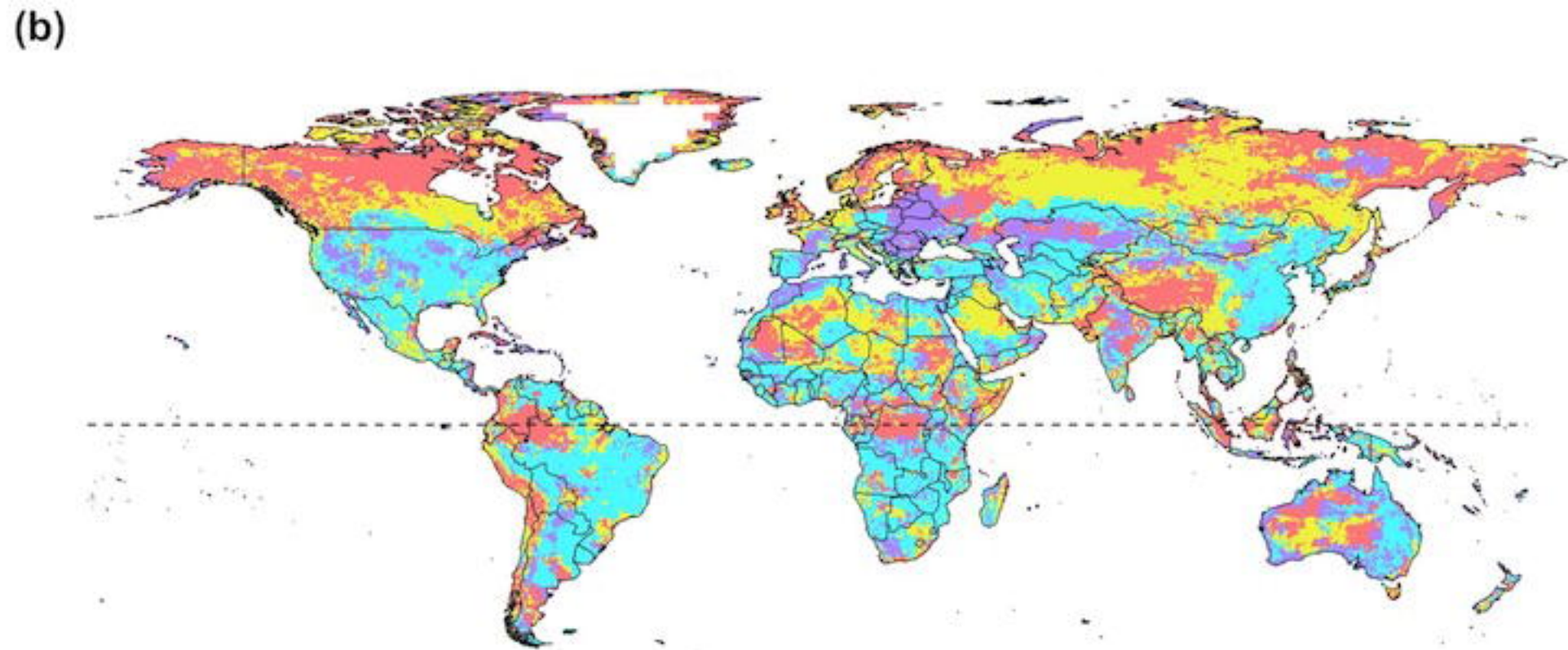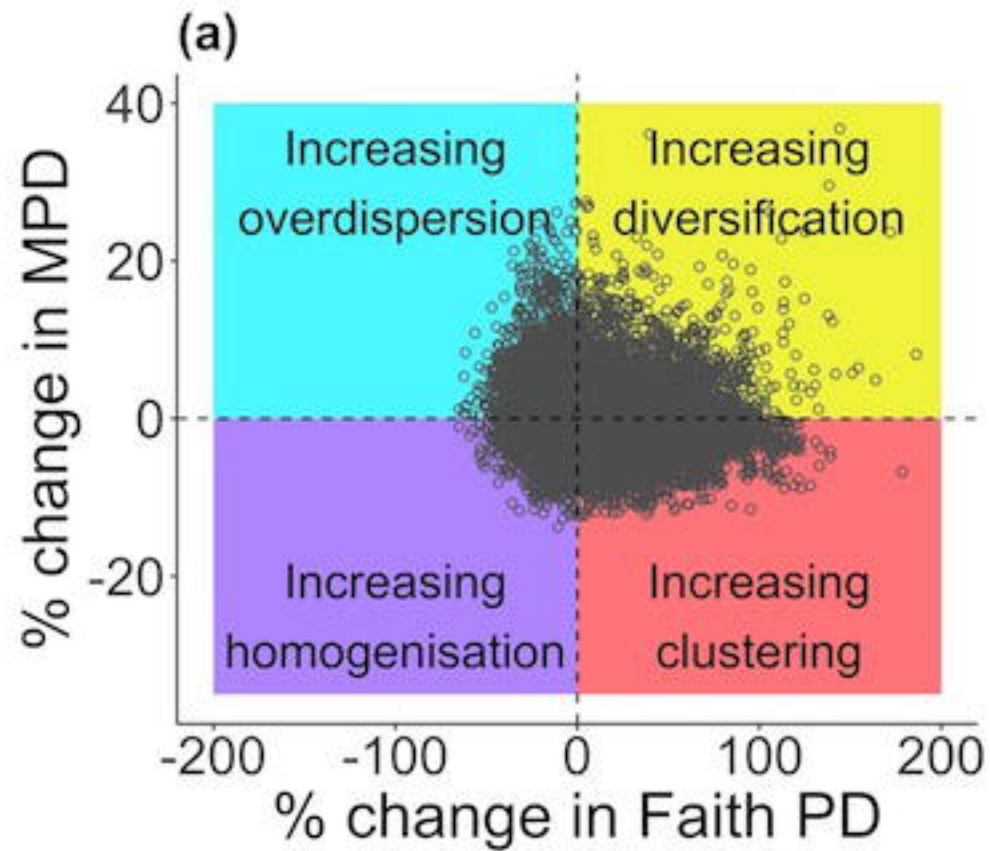
D

Dispersal buffer D/2

Estimated dispersal ability per species

Mean

species

Size dispersal buffer (D/2)

Mean dispersal ability of species in the focal grid cell

Grid cells for the species pool

(a)

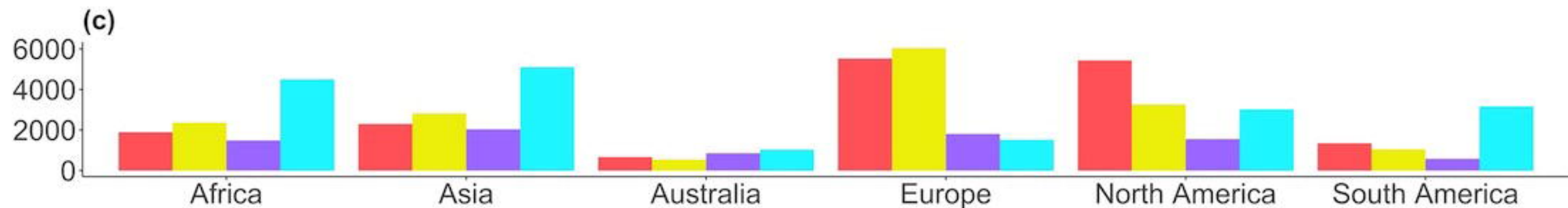% change in MPD

Increasing overdispersion

Increasing diversification

Increasing homogenisation

Increasing clustering

% change in Faith PD

(b)

(c)

\# of species assemblages

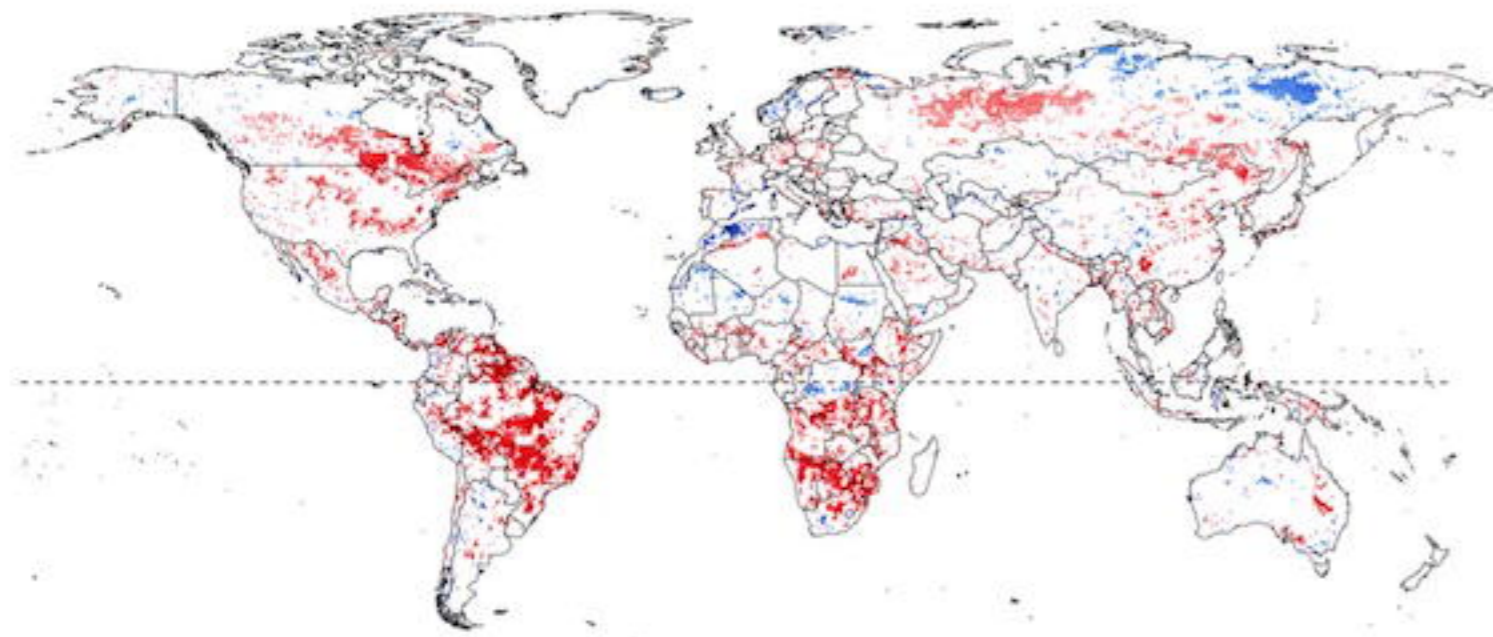Africa   Asia   Australia   Europe   North America   South America
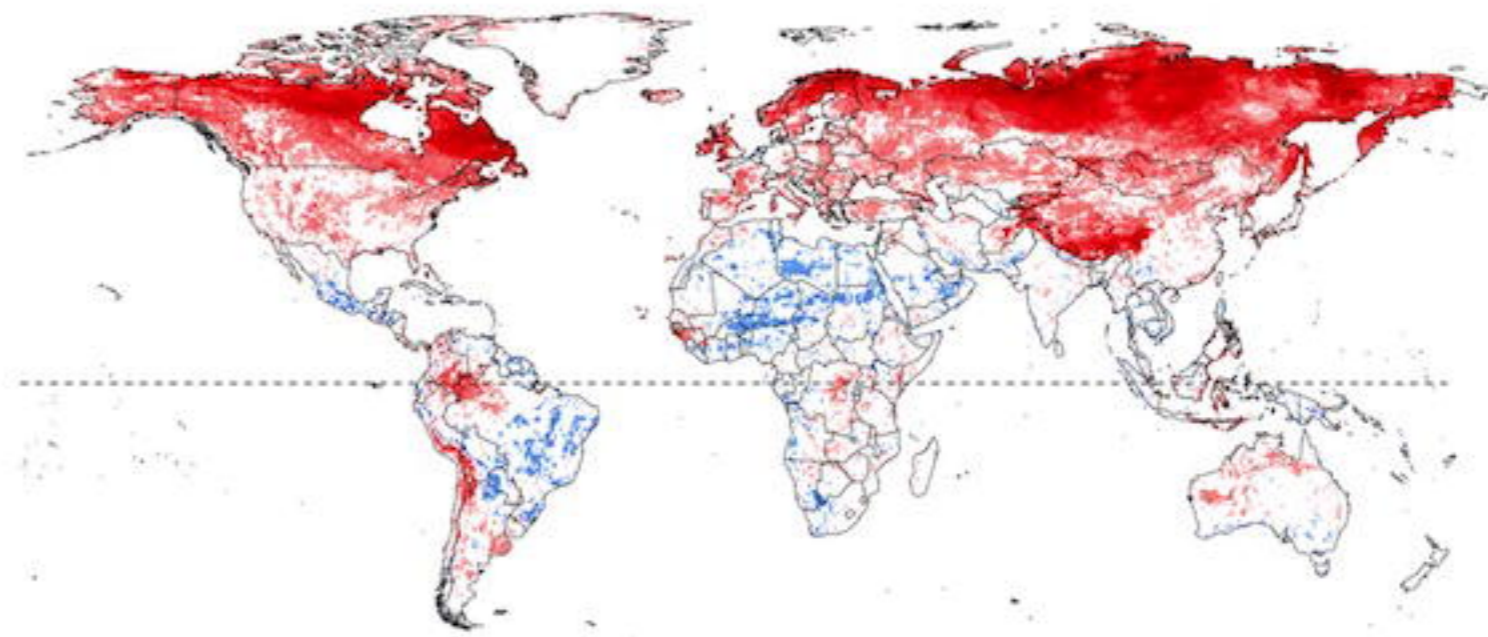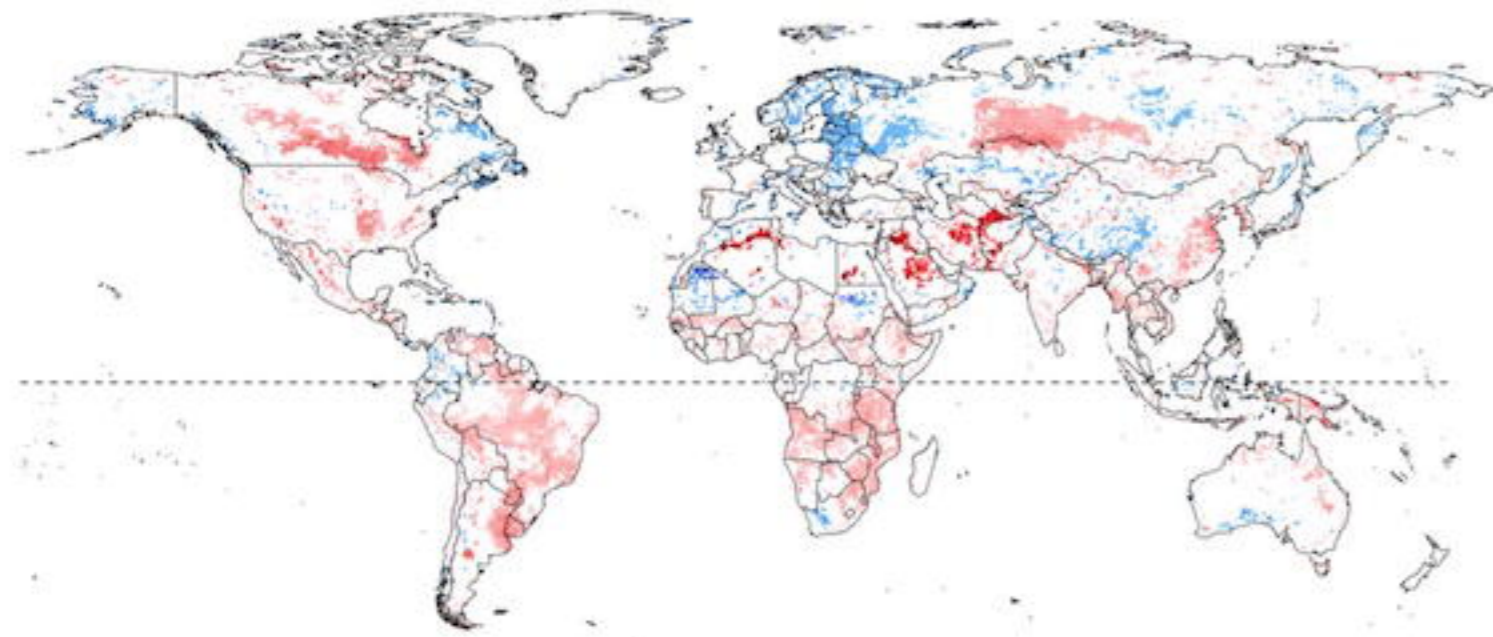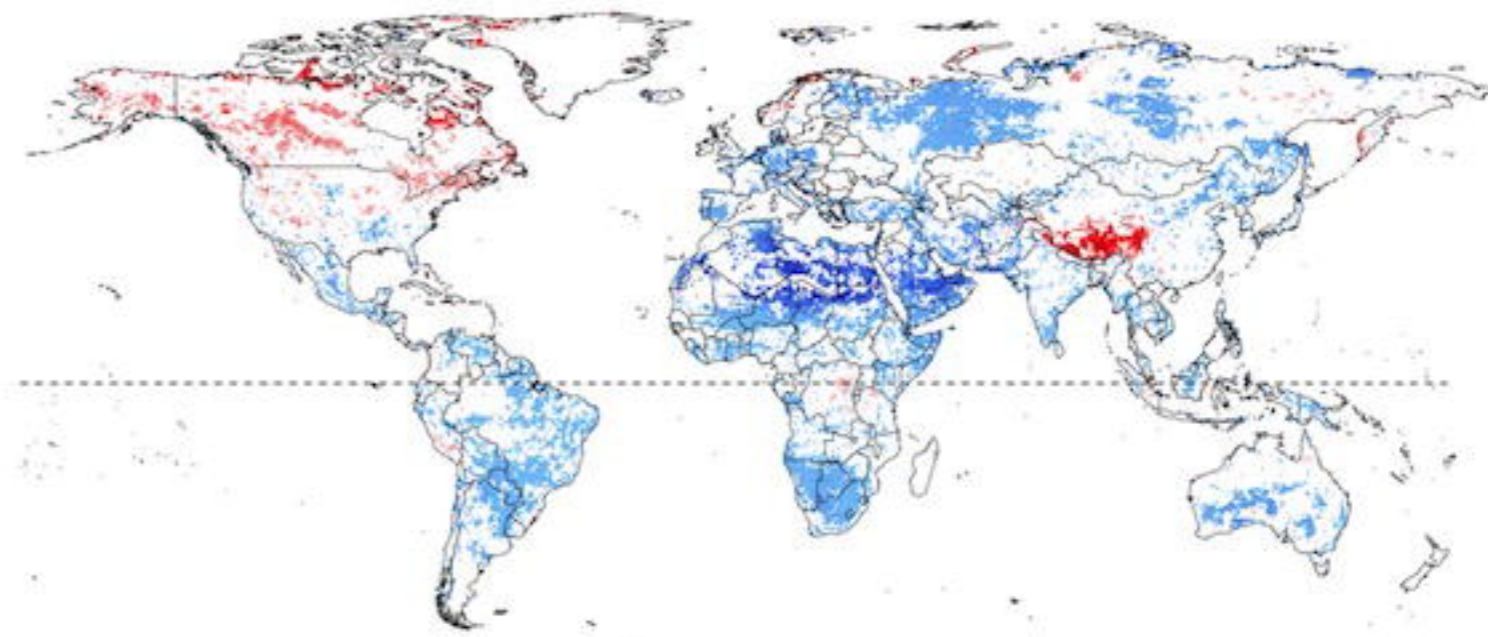
(a) Change through species loss

(b) Change through species gain

Projected PD change - random PD change

Stronger decrease than random

Weaker decrease than random

Projected PD change - random PD change

Stronger increase than random

Weaker increase than random

(c)

(d)

Projected MPD change - random MPD change

Stronger decrease than random

Weaker decrease than random

Projected MPD change - random MPD change

Stronger increase than random

Weaker increase than random