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Beyond counts and averages: relating geodiversity to dimensions of biodiversity

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Beyond counts and averages: relating geodiversity to dimensions of biodiversity

Running title: Geodiversity across dimensions of biodiversity

Abstract

Aim

We may be able to buffer biodiversity against the effects of ongoing climate change by prioritizing the protection of habitat with diverse physical features (high geodiversity) associated with ecological and evolutionary mechanisms that maintain high biodiversity. Yet, the relationships between biodiversity and habitat vary with spatial and biological context. In this study we compare how well habitat geodiversity — spatial variation in abiotic processes and features — and climate explain biodiversity patterns of birds and trees. We also evaluate the consistency of biodiversity-geodiversity relationships across ecoregions.

Location

Contiguous United States

Time period

2007-2016

Taxa studied

Birds, trees

Methods

We quantified geodiversity with remotely-sensed data and generated biodiversity maps from the Forest Inventory and Analysis and Breeding Bird Survey datasets. We fit multivariate regressions to alpha-, beta-, and gamma-diversity, accounting for spatial autocorrelation among

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2
3 23 Nature Conservancy ecoregions and relationships among taxonomic, phylogenetic, and
4
5 24 functional biodiversity. We fit models including climate alone (temperature, precipitation),
6
7 25 geodiversity alone (topography, soil, geology), and climate + geodiversity.
8

9 26 **Results**

10
11 27 A combination of geodiversity and climate predictor variables fit most forms of bird and tree
12
13 28 biodiversity with less than 10% relative error. Models using geodiversity and climate performed
14
15 29 better for local (alpha) and regional (gamma) diversity than turnover-based (beta) diversity.
16
17 30 Among geodiversity predictors, variability of elevation fit biodiversity best; interestingly,
18
19 31 topographically diverse places tended to have higher tree diversity but lower bird diversity.
20
21

22 32 **Main conclusions**

23
24 33 Although climatic predictors tended to have larger individual effects than geodiversity, adding
25
26 34 geodiversity improved climate-only models of biodiversity. Geodiversity was correlated with
27
28 35 biodiversity more consistently than climate across ecoregions, but models tended to have poor
29
30 36 fit in ecoregions held out of the training dataset. Patterns of geodiversity could help prioritize
31
32 37 conservation efforts within ecoregions. However, we need to understand the underlying
33
34 38 mechanisms more fully before we can build models transferable across ecoregions.
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37

38 39 **Keywords**

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40 40 biodiversity, geodiversity, Breeding Bird Survey (BBS), Forest Inventory and Analysis (FIA),
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42 41 alpha-diversity, beta-diversity, gamma-diversity, conservation
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42 Introduction

43 In the face of an ongoing sixth mass extinction, society is challenged to minimize biodiversity
44 loss through conservation efforts (Ceballos *et al.* 2015). While many conservation policies and
45 strategies focus on conserving particular species (e.g., the United States Endangered Species
46 Act, the International Union for Conservation of Nature Red List), there is growing interest in
47 broadening conservation to include preserving parcels of Earth's surface that promote diversity
48 even as species shift their ranges in response to climate change (Beier & de Albuquerque
49 2015). For example, The Nature Conservancy (TNC) prioritizes preserving areas with high
50 geodiversity — variation in Earth's abiotic processes and features — through their 'Conserving
51 Nature's Stage' (CNS) campaign (Beier & de Albuquerque 2015). Conserving nature's stage
52 requires a firm understanding of biodiversity-geodiversity relationships, yet we know little about
53 how these relationships vary across space, among taxa, and across different dimensions of
54 biodiversity (Zarnetske *et al.* 2019). Addressing this knowledge gap is key to advancing
55 conservation prioritization.

56 Geodiversity represents natural variation in geologic, geomorphic, and soil features (Gray 2004,
57 2008) and can be measured in a variety of ways. Most studies focus on elements of topography
58 (roughness, elevation, slope and aspect), geology (geologic diversity, landscape complexity),
59 soils (pH, organic matter, nutrient availability), or hydrology (variation of hydrological features
60 such as rivers, ponds and lakes; Hjort *et al.* 2012; Wang *et al.* 2013; Kaskela *et al.* 2017). Some
61 geodiversity definitions include climate, using variables such as temperature, precipitation,
62 evapotranspiration, water balance, and solar radiation, while others explicitly exclude climate
63 from their definition (Gray 2004; Parks & Mulligan 2010; Tukiainen *et al.* 2017). A
64 comprehensive definition of geodiversity includes all abiotic features and processes found within
65 Earth's atmosphere, lithosphere, hydrosphere, and cryosphere (Record *et al.* in press;
66 Zarnetske *et al.* 2019).

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3 67 Abiotic variation may promote increased variety of available niches for organisms (Tews *et al.*
4
5 68 2004), and high geodiversity is likely to indicate biodiversity hotspots (Lawler *et al.* 2015, but
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7 69 see Noss *et al.* 2014). However, little is known about how geodiversity of Earth's surface
8
9 70 compares to climate in explaining variation in biodiversity, whether relationships generalize
10
11 71 across geographic locations, and what types of biodiversity have the closest relationship with
12
13 72 geodiversity. Despite the potential importance of geodiversity for explaining patterns of
14
15 73 biodiversity, models explaining patterns of biodiversity rarely include geodiversity (Bailey *et al.*
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17 74 2018). Furthermore, conservation frameworks, including CNS, typically advance the idea that
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19 75 conserving geodiversity will result in positive outcomes for biodiversity writ large (Beier & de
20
21 76 Albuquerque 2015). This assumption must be tested empirically, especially given potential
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23 77 tradeoffs among orthogonal dimensions of biodiversity within and among taxa: conserving one
24
25 78 aspect of biodiversity might have a neutral or even negative effect on other aspects. In this
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27 79 study, we use bird and tree occurrence data and remotely-sensed environmental data from
28
29 80 across the United States to increase our understanding of biodiversity-geodiversity
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31 81 relationships. Geodiversity, in conjunction with climate, predicts patterns of species diversity of
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33 82 plants (Tukiainen *et al.* 2017; Bailey *et al.* 2018) and animals (Parks & Mulligan 2010; Alahuhta
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35 83 *et al.* 2018) across disparate biomes. Informed by these previously documented patterns, our
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37 84 **Prediction 1** is that combining geodiversity and climate predictors will significantly improve the
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39 85 goodness-of-fit of models explaining biodiversity of birds and trees.
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44 86 Recent work shows that the biodiversity-geodiversity relationship depends on spatial grain and
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46 87 extent (Bailey *et al.* 2017; Zarnetske *et al.* 2019). Nevertheless, most studies have focused on
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48 88 alpha-diversity (local diversity) measured within a plot. In contrast, most large-scale mapping
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50 89 studies characterizing diversity have equated diversity with gamma-diversity, or the size of the
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52 90 regional species pool (Currie & Paquin 1987; Jenkins *et al.* 2015). Only a few have accounted
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54 91 for the three *levels* of biodiversity: alpha-diversity, beta-diversity (turnover among plots) and
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3 92 gamma-diversity (Meynard *et al.* 2011; Gossner *et al.* 2013). Beta-diversity represents
4
5 93 compositional turnover among local communities, linking local diversity (alpha-diversity) to
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7 94 regional species pools (gamma-diversity). We expect that the relationship between geodiversity
8
9 95 and beta- and gamma-diversity will be stronger than alpha-diversity, because high geodiversity
10
11 96 often reflects high diversity of habitats within regions and therefore more unique local species
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13 97 assemblages (Stein *et al.* 2014). This leads to **Prediction 2**: Geodiversity will explain more
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15 98 variability in the beta and gamma levels of biodiversity than alpha-diversity.
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19 99 The relationship between geodiversity and biodiversity may also vary with the *dimensions* of
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21 100 biodiversity (taxonomic, functional and phylogenetic diversity). Targeting functional and
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23 101 phylogenetic diversity is especially important for conserving unique ecological function (Steudel
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25 102 *et al.* 2016) and evolutionary history (Davis *et al.* 2018) in the face of the current biodiversity
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27 103 crisis. Because phylogenetic (Winter *et al.* 2012) and functional (Lamanna *et al.* 2014)
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29 104 biodiversity are explicitly linked to different ecological and evolutionary mechanisms, they may
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31 105 provide deeper insight into ecological and evolutionary processes that underlie regional
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33 106 variation in diversity. However, few studies of geodiversity have investigated these multiple
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35 107 dimensions of biodiversity (Meynard *et al.* 2011); most studies have considered only taxonomic
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37 108 diversity (e.g., Safi *et al.* 2011; Stevens & Gavilanez 2015). Because each dimension of
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39 109 biodiversity represents a unique mechanistic connection with the environment, we predict
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41 110 **(Prediction 3)** that the different dimensions of biodiversity will have different relationships with
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43 111 geodiversity.
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47 112 Relationships between dimensions of biodiversity and geodiversity vary across geographic and
48
49 113 environmental space. In some areas and environmental contexts, one form of geodiversity
50
51 114 might be a more reliable predictor of biodiversity than elsewhere. For example, topographic
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53 115 complexity generates a diversity of climatic conditions at small to intermediate spatial scales
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55 116 ranging from meters (Bennie *et al.* 2008) to tens of kilometres (Badgley *et al.* 2017), which may
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3 117 buffer species against local extinctions as climate warms (Dobrowski 2011; Lenoir *et al.* 2013).
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5 118 Such buffering is, however, conditional on climatic context: if an entire landscape is far outside
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7 119 of the physiological range of tolerance for some taxonomic or functional groups, geodiversity is
8
9 120 likely to be unimportant for maintaining local biodiversity. For example, along the central
10
11 121 California coast, land and ocean surface temperatures contrast strongly and there is high
12
13 122 heterogeneity in topography and associated cloud and fog patterns. Such conditions support
14
15 123 relatively high local richness of tree species (Barbour *et al.* 2007). Inland, in contrast, the
16
17 124 average climate of the Coast Range is more arid and fog is absent (Ackerly *et al.* 2010), so only
18
19 125 the coolest facets of the landscape support any level of tree cover. In this context, topographic
20
21 126 heterogeneity is still associated with higher tree diversity, but the relationship is likely to be
22
23 127 weaker. For these reasons, we predict (**Prediction 4**) that the influence of different geodiversity
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25 128 predictors on biodiversity will vary across ecoregions. In particular, mountainous ecoregions
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27 129 with more mesic climates will have more positive relationships between topographic diversity
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29 130 and biodiversity than more arid mountain ranges.
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33 131 In this study, we use bird and tree occurrence data and remotely-sensed environmental data
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35 132 from across the United States to increase our understanding of biodiversity-geodiversity
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37 133 relationships. We make the following predictions:
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40 134 (1) Geodiversity will significantly increase the explanatory power of models explaining
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42 135 biodiversity of birds and trees.
43
44 136 (2) Geodiversity will explain more variability in beta- and gamma-diversity than alpha-
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46 137 diversity.
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48 138 (3) The different dimensions of biodiversity will have different relationships with geodiversity.
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50 139 (4) The influence of different geodiversity predictors on biodiversity will vary across
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52 140 ecoregions.
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141 Methods

142 We used multivariate linear mixed models with spatial random effects to determine which
143 geodiversity predictors explain the most variation across the levels and dimensions of bird and
144 tree biodiversity in the contiguous U.S. We used biodiversity and geodiversity data collected
145 from 2007-2016.

146 Breeding Bird Survey (BBS)

147 The North American Breeding Bird Survey (BBS, <https://www.pwrc.usgs.gov/bbs/>) is an annual
148 survey of breeding birds across the U.S. and Canada begun in 1966. Volunteer observers report
149 species and counts of birds seen or heard during 3-minute observations at 50 stops spaced
150 every ~800 m along routes ~39.4 km in length (Sauer *et al.* 2013). There are ~3480 active
151 routes in the contiguous U.S. with continuous yearly stop-level data. We excluded any routes
152 with an ambiguous midpoint coordinate (discontinuous transects), leaving 3089 routes. We
153 included only the surveys conducted under the standard protocol, discarding repeat surveys and
154 any observations recorded by trainees.

155 Forest Inventory and Analysis (FIA)

156 The U.S. Department of Agriculture Forest Service's Forest Inventory and Analysis program
157 (FIA) surveys the composition and status of forests throughout the United States, with data
158 collected annually (Bechtold *et al.* 2005). Each FIA plot consists of four 7.2-m fixed radius
159 subplots. Plots are spaced roughly on a 5-km grid across forested land. Each plot is surveyed
160 approximately every 5 years (Bechtold *et al.* 2005). Each tree is identified to species. We
161 obtained the most recent survey from all forested, non-plantation FIA plots in the contiguous
162 United States (119,177 plots). Some plots in the Pacific Northwest Region included a larger

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3 163 “macroplot” around the central subplots; we excluded any trees outside the subplot boundary.
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5 164 The year of the most recent survey varied between 2012 and 2016.
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8 165 Phylogenetic and Trait Data 9

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11 166 We obtained phylogenetic trees and compiled trait information for all bird and tree species in the
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13 167 BBS and FIA databases, respectively, and used them to calculate the distance-based
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15 168 phylogenetic and functional diversity indices described below. See Appendix 1 for additional
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17 169 details.
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20 21 170 Calculation of Biodiversity Metrics 22

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24 171 For both tree and bird communities, we calculated biodiversity metrics based on species
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26 172 presence at the site level (here defined as a single FIA plot or BBS route). For trees in FIA, we
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28 173 used the most recent survey as a single time point for each site, as there is little turnover in
29
30 174 species composition between surveys and the probability of imperfect detection is low. To
31
32 175 minimize the effects of imperfect bird detection in the BBS survey, we pooled observations from
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34 176 all stops in each route and pooled all surveys from 2007-2016. See Appendix 2 for additional
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36 177 details.
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40 178 We calculated alpha-, beta-, and gamma-diversity (referred to as *levels* of biodiversity) within a
41
42 179 circle of 50 km radius around each site, originating at the centre of the FIA plot or midpoint of
43
44 180 the BBS route. We defined any BBS route whose midpoint fell within the 50-km circle around
45
46 181 the focal route midpoint to be a neighbour route (see Appendix 2). We took (1) the median
47
48 182 diversity of all sites in the radius, including the focal site (alpha), (2) the median pairwise
49
50 183 diversity of all pairs of sites in the radius, including the focal sites (beta), and (3) the aggregated
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52 184 diversity of all sites in the radius (gamma). Each diversity *level* has three *dimensions*:
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54 185 taxonomic, phylogenetic, and functional (Table S1). For taxonomic diversity, alpha-diversity and
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3 186 gamma-diversity were represented by species richness and beta-diversity by pairwise Sørensen
4
5 187 dissimilarity. The Sørensen dissimilarity index represents the degree to which pairs of
6
7 188 communities differ from one another in their species composition, independent of their species
8
9 189 richness, and encompasses both species turnover and nestedness components of beta-
10
11 190 diversity. This contrasts with beta-diversity indices based on multiplicative or additive partitions
12
13 191 of alpha- and gamma-diversity (Anderson et al. 2011). To quantify phylogenetic diversity, we
14
15 192 calculated mean pairwise phylogenetic distance (MPD) of each community with the R package
16
17 193 *picante* (Kembel et al. 2018). We randomized the phylogenetic distance matrix 999 times and
18
19 194 calculated the z-score of the observed phylogenetic distances relative to the distribution of
20
21 195 phylogenetic distances of the randomized matrices to remove dependence on richness.
22
23 196 Similarly, we calculated a distance-based metric of functional diversity by finding the Gower
24
25 197 distance between the trait values for all possible species pairs, and then calculating the mean
26
27 198 pairwise distance among all pairs of species in each community and its z-score. Because the
28
29 199 BBS surveys poorly estimate abundances of some species, we calculated incidence-based
30
31 200 biodiversity metrics for both birds and trees so that metrics are comparable between the two
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33 201 taxa.
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38 202 Geodiversity Data Sources and Processing

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41 203 We obtained and processed remotely-sensed data for the contiguous United States to generate
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43 204 geodiversity and climate data layers. Remotely-sensed geodiversity variables are particularly
44
45 205 valuable in disentangling the independent effects of climate and geodiversity. Many biodiversity
46
47 206 analyses use climatic data products that interpolate weather station data using elevation, e.g.
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49 207 Worldclim v.1 (Hijmans et al. 2005). Using elevation to derive temperature values makes it
50
51 208 difficult to evaluate independent contributions from climate and topography (Körner 2007).
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53 209 Remotely-sensed temperature represents the temperature of the land surface, in contrast with
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55 210 weather stations that measure air temperature several meters above ground level (Bechtel
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3 211 2015). In areas with very sparse coverage of meteorological stations and/or complex
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5 212 topography, the error introduced by interpolating between ground stations may be large. In
6
7 213 many regions, especially grasslands, shrublands, and croplands, surface temperature shows
8
9 214 large systematic deviations from air temperature (Mildrexler *et al.* 2011). What is more, studies
10
11 215 have shown that surface temperature may be more ecologically relevant than air temperature
12
13 216 (Pau *et al.* 2013; Still *et al.* 2014). The thermodynamic temperature of an organism, which drives
14
15 217 its respiration rate and vapor pressure deficit, is more closely related to the surface temperature
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17 218 than the surrounding air temperature. Remotely-sensed data products provide spatially
18
19 219 continuous, independent, and direct measures of climate and geodiversity for use in biodiversity
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21 220 models.

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25 221 We generated predictors from the following remotely-sensed data products: elevation from
26
27 222 SRTM (Farr *et al.* 2007), land surface temperature from MODIS MOD11A2 (Wan *et al.* 2015),
28
29 223 precipitation from CHIRPS (Funk *et al.* 2015), and gross primary productivity (GPP) dynamic
30
31 224 habitat index from MODIS (Hobi *et al.* 2017). We generated additional predictors from non-
32
33 225 remotely-sensed products including soil type category from SoilGrids (Hengl *et al.* 2017), which
34
35 226 uses remotely-sensed data to interpolate ground-based measurements, and geologic age
36
37 227 category from USGS International Surface Geology. We included GPP because spatial
38
39 228 variability in GPP integrates many geodiversity variables known to influence biodiversity via
40
41 229 resource availability (Austin & Smith 1989; Alahuhta *et al.* 2018). GPP spatial variability is
42
43 230 moderately correlated with mean annual precipitation but largely orthogonal to the other
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45 231 geodiversity variables we chose (Figure 1), indicating that it may capture additional spatial
46
47 232 variation not accounted for by the other three geodiversity variables. See Appendix 3 for
48
49 233 additional details.

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53 234 We coarsened all environmental data layers by calculating the means within 25 km² pixels to
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55 235 equal the coarsest resolution of any layer, then we aggregated all geodiversity and biodiversity

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3 236 variables within a 50-km radius around the centre of each FIA plot and the midpoint of each
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5 237 BBS route. The 50-km scale of aggregation averages over a wide range of microhabitats and
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7 238 microclimates, capturing the geodiversity-biodiversity relationship at a coarse spatial grain; it is
8
9 239 possible that a smaller grain of analysis would reveal different patterns (Zarnetske *et al.* 2019).
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11 240 For continuous predictors, we calculated the mean of all pixels partially or wholly in the 50-km
12
13 241 radius, and we used the mean terrain ruggedness index (TRI; Wilson *et al.* 2007) of the 3×3
14
15 242 pixel neighbourhood around all pixels to represent spatial variability. For discrete predictors, we
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17 243 used Shannon entropy of all pixels in the radius to represent spatial variability. Shannon entropy
18
19 244 has been shown to monotonically increase with increasing number of landscape patch types, to
20
21 245 behave consistently in both real and simulated landscapes, and to correlate positively with many
22
23 246 other measures of landscape heterogeneity (Peng *et al.* 2010). Importantly, while many past
24
25 247 studies have used variables extracted from spatially continuous layers at points to characterize
26
27 248 environmental variation, we explicitly consider spatial variation in the regions around the points
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29 249 where biodiversity was measured. Defining geodiversity in terms of this variation is critical for
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31 250 fully explaining biodiversity because a single point value cannot capture the diversity of niche
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33 251 space that may determine biodiversity (Lawler *et al.* 2015).
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38 252 Finally, we spatially grouped geodiversity and biodiversity observations using TNC's terrestrial
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40 253 ecoregions (Olson & Dinerstein 2002) to account for spatial autocorrelation in response
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42 254 variables. We selected this classification scheme over alternatives because the regions are
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44 255 defined based on biodiversity analyses conducted across many taxa, and because the number
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46 256 of ecoregions in the contiguous USA (63 after excluding 6 border regions with insufficient data)
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48 257 is high enough to adequately account for spatial autocorrelation in biodiversity responses within
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50 258 the study area without overfitting.
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259 Selection of Predictor Variables

260 We selected six predictor variables for our models: two climate variables to describe the climate
261 norms inside the radius (mean annual temperature and mean annual precipitation), and four
262 predictors to describe geodiversity or environmental heterogeneity (mean TRI of elevation and
263 GPP, Shannon diversities of geological age category and soil type). Together, the six variables
264 encompass most of the variation in geodiversity and climate among locations in the contiguous
265 United States and are only modestly correlated with one another (Figure 1), meeting model
266 assumptions. Based on our *a priori* hypothesis that geodiversity is related to biodiversity, we
267 included one predictor to represent each of the unique geodiversity data sources available to us
268 (elevation, soil type, and geological age category). In addition, we selected GPP diversity to
269 represent other aspects of geodiversity not captured by the first three variables. Our choice of
270 mean annual temperature and mean annual precipitation to represent long-run climate norms is
271 reasonable because the two variables have no relationship to one another at our scale of
272 observation (Figure 1).

273 Final Data Processing

274 First, we excluded any site within 50 km of the Canada or Mexico borders because the 50-km
275 radius around those sites contained areas without biodiversity measurements. We logit-
276 transformed the taxonomic beta-diversity variable, which is a raw dissimilarity metric varying
277 between 0 and 1 in the model. No bird sites had a taxonomic beta-diversity of exactly 0 or 1, but
278 ~16% of tree sites had taxonomic beta-diversity of exactly 0 or 1, which is outside the domain of
279 the logit function. Thus, we replaced zeroes with 0.001 and ones with 0.999. We took a spatially
280 stratified random sample of tree sites where each sampled site was a minimum of 20 km from
281 any other site, to minimize spatial autocorrelation not captured by our model. This process left

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3 282 ~3000 sites, so that sample sizes were comparable between the datasets used to fit each
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5 283 model.
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8 284 Model Fitting 9

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11 285 We fit spatial multivariate mixed models with the following fixed predictors: (1) all six predictor
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13 286 variables as fixed effects, (2) only the four geodiversity predictors as fixed effects, (3) only the
14
15 287 two climate predictors as fixed effects, and (4) no fixed effects (null model with only spatial
16
17 288 random effects). We fit multivariate models for each diversity level (alpha, beta, and gamma)
18
19 289 and each taxon (birds, trees), totalling 24 models (4 predictor sets \times 3 diversity levels \times 2 taxa =
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21 290 24). Each model had three response variables corresponding to the three dimensions of
22
23 291 biodiversity (taxonomic, phylogenetic, and functional). We used the null model z-scores to
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25 292 represent phylogenetic and functional biodiversity in all the models.
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29 293 We fit a random intercept and slope for each predictor in each TNC ecoregion. We excluded
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31 294 ecoregions with <5 sites, because random effects estimated with <5 data points are not robust.
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33 295 The excluded ecoregions were primarily in Canada or Mexico and only have a small area inside
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35 296 the contiguous United States that is at least 50 km from a land border. After excluding these
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37 297 ecoregions, 63 ecoregions remained. We estimated random slopes and intercepts for each
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39 298 ecoregion with a multilevel conditional autoregressive (CAR) structure to model the spatial
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41 299 variability in the biodiversity-geodiversity relationship among ecoregions (Besag & Kooperberg
42
43 300 1995). We specified the neighbourhood structure with an adjacency matrix identifying all pairs of
44
45 301 regions that share a border. The ecoregion random effects in the model were therefore spatially
46
47 302 structured, accounting for spatial autocorrelation in the biodiversity values of neighbouring
48
49 303 regions. We chose to model spatial dependence using discrete regions because of better out-of-
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51 304 sample prediction performance than simultaneous autoregressive models (Kress, unpublished).
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3 305 We fit the models in a hierarchical Bayesian framework using the R package *brms* (Bürkner
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5 306 2017). We modelled error in response variables as normally distributed. Finally, we
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7 307 standardized both predictor and response variables before fitting the models so that we could
8
9 308 compare effect sizes across predictors and responses. The standard deviation of each
10
11 309 coefficient represents the among-region variability of each predictor-response relationship.
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14 15 310 Model Validation

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17 311 To assess model predictive performance, we performed spatially blocked leave-one-location-out
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19 312 cross-validation (Roberts *et al.* 2017). We refit each of the models 63 times, each time holding
20
21 313 out all data points from one of the 63 ecoregions. We found the root mean squared error
22
23 314 (RMSE) of the predicted values of the withheld data from each fold to get a cross-validation
24
25 315 RMSE for each model. We also calculated the RMSE of the models fit to all the data. We
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27 316 divided all RMSE values by the range of the observed data to yield relative values that can be
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29 317 compared among models. We also calculated RMSEs using resubstitution evaluation, in which
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31 318 no data points were held out in model fitting. This procedure assesses the goodness-of-fit of
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33 319 models across the entire contiguous U.S. but does not fully correct for spatial autocorrelation.
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37 320 We calculated the Bayesian R-squared (Gelman *et al.* 2018) for each model to quantify the
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39 321 proportion of variation in the response explained by fixed and spatial random effects combined.
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41 322 Finally, we calculated the widely applicable information criterion (WAIC; Watanabe 2010) for
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43 323 each model.
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324 Results

325 Description of geodiversity and biodiversity variables

326 Correlations among geodiversity predictor variables were relatively low (Figure 1a). The
327 pairwise correlation between elevation diversity and geologic age diversity was relatively high (r
328 = 0.52), indicating that geodiversity measured as topographic variability is correlated with
329 geodiversity measured as the variety of geologic substrate ages. Notably, the correlation
330 between elevation diversity and mean annual temperature was low ($r = -0.20$). In both birds
331 (Figure 1b) and trees (Figure 1c), taxonomic and phylogenetic diversity were positively
332 correlated with one another at all levels; this relationship was strongest for birds. However, local
333 (alpha) and regional (gamma) functional diversity tended to correlate negatively with other forms
334 of biodiversity in both birds and trees.

335 Geodiversity variables (Figure 2) had unique patterns and spatial grains of variability. Climate
336 variables varied at broad scales, while geologic and topographic variables varied at scales
337 corresponding to major land features such as mountain ranges (Figure 2). Biogeographic
338 patterns were disparate across dimensions of biodiversity for birds (Figure 3) and trees (Figure
339 4). Bird diversity patterns were spatially idiosyncratic (Figure 3), while tree diversity showed a
340 strong longitudinal pattern, with taxonomic diversity highest in the east and functional and
341 phylogenetic diversity highest in the west (Figure 4).

342 Effects of climate and geodiversity across taxa and components of biodiversity

343 Among geodiversity variables, elevation variability tended to be the strongest predictor of
344 biodiversity (Figure 5). Elevation variability was associated with increased bird taxonomic beta-
345 diversity but with decreased bird phylogenetic and functional diversity at all levels. Interestingly,
346 it had a positive effect across all levels and dimensions of tree biodiversity; it was the only

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3 347 predictor with such a consistently positive relationship. Higher mean annual temperature was
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5 348 associated with lower taxonomic diversity but higher phylogenetic and functional diversity in
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7 349 birds. In contrast, for trees, precipitation was a much more important climate driver than
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9 350 temperature (Figure 5). The effect size for temperature was not distinguishable from zero for
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11 351 most levels and dimensions of tree diversity. For birds, taxonomic alpha-diversity (local
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13 352 richness) was highest in colder and wetter areas, but most other levels and dimensions of
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15 353 biodiversity showed the opposite pattern. For trees, taxonomic and functional diversity were
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17 354 higher in wetter areas, but phylogenetic diversity was higher in drier areas.

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21 355 The effects of geologic age variability and soil type variability tended to be relatively weak,
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23 356 although for birds, soil type variability positively affected taxonomic diversity, and for trees,
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25 357 geologic age variability positively affected taxonomic diversity. Spatial variability in GPP had a
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27 358 positive relationship with bird taxonomic and functional diversity and a positive relationship with
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29 359 tree turnover and regional diversity across the three dimensions of biodiversity.

30 31 32 360 Overall model performance

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36 361 The spatially blocked cross-validation showed that the models with climate or geodiversity
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38 362 predictors performed no better than the null model when predicting all biodiversity values from
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40 363 an entire ecoregion held out during model fitting (Figure 6). However, cross-validation prediction
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42 364 error for models including climate tended to be higher than for models including geodiversity.
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44 365 Model evaluation using the full dataset without holding out any locations showed that models
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46 366 including the six fixed predictors were the best fit for biodiversity of trees and birds, as shown by
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48 367 the RMSEs, WAIC values, and Bayesian R-squared values (Figure S1; Table S2). Geodiversity
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50 368 explained a consistent proportion of variation in most forms of bird biodiversity. For trees, the
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52 369 explanatory power of geodiversity depended on the level of biodiversity considered: geodiversity
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54 370 explained local (alpha) and regional (gamma) biodiversity better than turnover (beta).

371 Spatially varying biodiversity-geodiversity relationships

372 The strength of biodiversity-climate relationships varied more across ecoregions than the
373 strength of biodiversity-geodiversity relationships (Figure S2). Interestingly, the relationship
374 between mean annual precipitation and tree taxonomic and functional biodiversity tended to be
375 more strongly positive in drier western ecoregions where precipitation is limiting (Figure S10).
376 Phylogenetic diversity showed an opposite spatial pattern: drier areas in the west had higher
377 tree phylogenetic diversity. In those ecoregions, we observed high phylogenetic diversity at sites
378 dominated by gymnosperms (*Pinus* and *Juniperus* spp.) with a few associated angiosperm
379 species, notably *Cercocarpus ledifolius* and *Populus tremuloides*. These dry sites, which tended
380 to have low to intermediate taxonomic and functional diversity, may be driving the negative
381 relationship between precipitation and phylogenetic diversity in the western USA. Notably, the
382 relationship between elevation variability and biodiversity was relatively consistent across
383 ecoregions, being generally positive for trees, positive for bird taxonomic diversity, and negative
384 for bird functional and phylogenetic diversity. Other geodiversity-biodiversity relationships varied
385 idiosyncratically across space (Figures S2-S14).

386 Discussion

387 The magnitude and direction of the relationships between environmental variability and
388 biodiversity were intriguingly context-dependent, varying between birds and trees, by diversity
389 level (alpha, beta, and gamma), by diversity dimension (taxonomic, phylogenetic, and
390 functional), and by ecoregion. Below we explore potential reasons for this context-dependence
391 as they relate to the predictions we made initially.

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3 392 Effects of climate and geodiversity across components of biodiversity
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6 393 A combination of geodiversity and climate predictors predicted biodiversity within 10% relative
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8 394 error for most forms of biodiversity for both birds and trees (Figure S1). However, these more
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10 395 complex models performed worse than the null models in spatially blocked cross-validation,
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12 396 when predicting biodiversity values in ecoregions not used to fit the model (Figure 6). The poor
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14 397 performance of models outside the training dataset may indicate that similarity among
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16 398 neighboring communities of birds and trees explains the majority of variation in biodiversity, with
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18 399 deterministic effects of geodiversity and climate playing a smaller role. Alternatively this
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20 400 suggests that a large proportion of the relationship between geodiversity and bird and tree
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22 401 biodiversity is spatially context-dependent, providing only weak support for our prediction that
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24 402 geodiversity and climate together explain variation in biodiversity among ecoregions (Prediction
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26 403 1). The high level of spatial autocorrelation and high variability in relationships among
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28 404 ecoregions prevented the statistical models from identifying spatially transferable relationships
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30 405 between geodiversity and biodiversity. Nevertheless, geodiversity variables performed relatively
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32 406 better than climate variables at out-of-sample prediction (Figure 6), suggesting a potential use of
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34 407 geodiversity to identify biodiversity hotspots at local to regional scales. The poor performance of
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36 408 the models relative to null models reveals the difficulty of disentangling environmental drivers of
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38 409 biodiversity from biogeographical and historical contingency and caution against relying heavily
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40 410 on geodiversity or climate to predict biodiversity in regions far from where models are fit.
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45 411 Temperature and precipitation means had the strongest effects on diversity, across taxa and
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47 412 across the levels and dimensions of biodiversity. However, adding geodiversity predictors
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49 413 significantly increased explanatory power when evaluating models trained on the full dataset
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51 414 (Figure S1), although neither climate nor geodiversity predictors increased prediction accuracy
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53 415 in spatially blocked cross-validation (Figure 6). Among geodiversity predictors, topographic
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55 416 variability had the largest effect on biodiversity. Interestingly, topographic variability had a
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3 417 positive relationship with tree diversity across levels, but was associated with lower bird
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5 418 diversity. This may be because breeding bird diversity is driven by highly mobile migratory bird
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7 419 species seeking out high-productivity regions for breeding sites (Anderson & Shugart 1974;
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9 420 Cody 1981). The diversity of niche opportunities available to trees may depend on the
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11 421 microhabitats created by topographic variation. Niche diversity for birds may be driven more by
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13 422 the diversity of food sources, which could be reduced in more topographically rugged regions. In
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15 423 contrast with topographic variability, geologic age and soil type diversity tended to have little or
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17 424 no effect on biodiversity in the regions and taxa we studied.

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21 425 We found that geodiversity has significant effects on all diversity levels. Gamma-diversity, which
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23 426 integrates the alpha and beta levels, is best predicted by a combination of geodiversity and
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25 427 climate. This finding contrasts with Prediction 2, that geodiversity's effect would be strongest on
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27 428 turnover (beta) and regional diversity (gamma). For trees in particular, geodiversity combined
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29 429 with climate predicted beta-diversity less well than alpha- and gamma-diversity. This result may
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31 430 be due to incomplete sampling of the local community by single FIA plots. If trees have patchy
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33 431 distributions at local scales, the small-sized FIA plots may overestimate beta-diversity because
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35 432 some species that are present throughout the region will be absent from a random subset of
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37 433 plots within the focal region (Figure 4). Therefore, local sampling might obscure the true pattern
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39 434 of turnover among plots, but not the regional diversity, which integrates over many plots. We
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41 435 show that familiar maps of biodiversity, which are commonly created using species range maps
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43 436 (Currie & Paquin 1987; Brown & Lomolino 1998; Jenkins *et al.* 2015), represent gamma-
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45 437 diversity patterns, but not necessarily other forms of biodiversity. Our results show that these
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47 438 different levels of biodiversity (Figures 3 and 4) exhibit different relationships with environmental
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49 439 gradients. Our maps promote a more nuanced view of biodiversity and emphasize that each
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51 440 level and dimension has a different relationship with spatial variability in the environment.
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3 441 Although we found generally similar responses across biodiversity dimensions, differences may
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5 442 indicate ecologically or evolutionarily meaningful relationships. In general, we found similar
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7 443 responses across biodiversity dimensions because they tend to correlate positively with one
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9 444 another (Figure 1). This finding partially contradicts Prediction 3 that patterns would differ across
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11 445 dimensions. However, in support of Prediction 3, some environmental drivers had opposite
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13 446 effects on different dimensions of biodiversity (Jarzyna & Jetz 2016). This result parallels
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15 447 contrasting patterns across biodiversity dimensions previously documented in mammals (Davies
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17 448 & Buckley 2011). For example, areas with greater topographic variability tended to have higher
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19 449 bird taxonomic diversity but lower phylogenetic and functional diversity. Birds' taxonomic
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21 450 diversity might not have the same signal as phylogenetic or functional diversity because both
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23 451 the functional guilds and the phylogenetic lineages of birds differ greatly from one another in
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25 452 species richness (De Graaf *et al.* 1985). For example, there are many functionally similar and
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27 453 closely related species within the guild of small insectivorous songbirds. An increase of species
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29 454 richness in the insectivore guild would result in increased taxonomic diversity without influencing
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31 455 the other dimensions of diversity. The high numbers of bird species harboured by geodiverse
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33 456 regions likely reflects increased taxonomic diversity within speciose guilds.

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38 457 The discrepancy in relationships we observed among the dimensions of biodiversity we
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40 458 examined mirror that of a previous study examining biodiversity change over time. Increases in
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42 459 taxonomic diversity without corresponding changes in phylogenetic or functional diversity may
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44 460 indicate biotic homogenization of assemblages; 40 years of BBS surveys show a homogenizing
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46 461 trend over time (Jarzyna & Jetz 2017). While our study does not address change over time, the
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48 462 discrepancy between taxonomic and functional/phylogenetic diversity patterns with topographic
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50 463 variability and with temperature is notable. Jarzyna and Jetz also observed that the greatest
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52 464 temporal changes in diversity occurred at higher elevations and latitudes, ascribing this pattern
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54 465 to climate change. We documented a positive association between temperature and beta-

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3 466 diversity for all dimensions, but we found lower phylogenetic and functional diversity in
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5 467 topographically diverse regions (Figure 5). This result echoes the temporal pattern documented
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7 468 by Jarzyna and Jetz, suggesting that bird communities at high elevations and in cold regions
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9 469 may be relatively homogeneous and thus relatively more vulnerable to changing climate. In the
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11 470 case of breeding birds in the United States, topographically diverse regions may in fact be the
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13 471 most sensitive to environmental change.
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16 472 Phylogenetic and functional diversity have similar patterns with respect to most predictor
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18 473 variables. This finding makes sense given that many, though not all, traits are phylogenetically
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20 474 conserved (Devictor *et al.* 2010), such that phylogenetic diversity roughly approximates
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22 475 functional diversity (Winter *et al.* 2012). However, tree phylogenetic diversity increases with
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24 476 decreasing precipitation, while functional diversity and taxonomic diversity decrease. This
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26 477 suggests that the angiosperm and gymnosperm species that contribute to high phylogenetic
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28 478 diversity in low-precipitation regions may have convergently evolved suites of adaptations to dry
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30 479 environments (Méndez-Alonzo *et al.* 2012), resulting in low functional diversity at those sites.
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34 480 Spatially varying biodiversity-geodiversity relationships

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37 481 The relationship between geodiversity variables and biodiversity variables varied in direction
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39 482 and magnitude across the ecoregions of the United States. For example, elevational variability
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41 483 had a greater effect on tree biodiversity in the central and eastern United States, providing
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43 484 support for Prediction 4. In the west, climatic factors and a smaller regional species pool set
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45 485 upper bounds on richness, so the opportunity for increased richness with increased geodiversity
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47 486 is reduced relative to the east (Figure S11). In contrast, the effect of elevational variability on
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49 487 bird taxonomic diversity was more likely to be non-zero in regions of high topographic relief,
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51 488 such as the Appalachian ecoregion and the northern Rocky Mountains (Figure S5). For trees,
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53 489 the effect of precipitation on biodiversity was more likely to be significant in the drier central and
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3 490 western United States (Figure S10), where water tends to be limiting. This suggests that in
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5 491 regions where climatic factors strongly control species diversity, the influence of geodiversity on
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7 492 biodiversity is weaker. However, this result may depend on spatial extent of the study region; a
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9 493 similar model fit only for trees in the Pacific Northwest region shows a strong positive correlation
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11 494 between elevational variability and tree alpha- and gamma-diversity (Record *et al.* in press).

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14 495 The form of the geodiversity-biodiversity relationship and the particular variables that are the
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16 496 best predictors of biodiversity may not be transferable across ecoregions. This may present a
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18 497 conundrum for organisms that are migrating to track climate conditions and may encounter
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20 498 novel geological features. The Nature Conservancy documented a similar pattern: when they
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22 499 initially developed the Conserving Nature's Stage framework, they identified geological variables
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24 500 as the best predictors of biodiversity in the Northeast U.S. (Anderson & Ferree 2010). Those
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26 501 variables did not predict biodiversity well when they extended the approach to the Southeast
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28 502 (Anderson *et al.* 2014), where geologically homogeneous regions of the Coastal Plain host high
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30 503 biodiversity.

31 32 33 34 504 Conclusions and future directions

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37 505 Our study found that topographic variability was related to biodiversity independently from, and
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39 506 in different ways than, climatic means. This result suggests that using remotely-sensed
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41 507 temperature data, rather than values interpolated between weather stations using local
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43 508 elevation, may improve our ability to distinguish between the effects of climate and of
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45 509 topographic variability (Pau *et al.* 2013; Still *et al.* 2014). Remotely-sensed temperature has
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47 510 broader spatial coverage than interpolated temperature and is not inherently dependent on
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49 511 elevation. Therefore, it would be valuable to confirm whether remotely-sensed temperature is
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51 512 biologically relevant across a range of taxa (Heft-Neal *et al.* 2017).

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3 513 With the increasing intensity of global change threatening biodiversity and ecological integrity, it
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5 514 is vital to conserve nature's stage and create refugia for organisms moving to track their optimal
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7 515 climatic conditions. While past ecological research and the results of this study show that
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9 516 climate explains much of the spatial variation in biodiversity of trees and birds, geodiversity is
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11 517 related to biodiversity independently of climate. To disentangle the effects of climatic and
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13 518 topographic drivers, spatially continuous remotely-sensed data are necessary. Biodiversity-
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15 519 geodiversity relationships depend on taxonomic group, spatial location, the level and dimension
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17 520 of biodiversity considered, and the grain of analysis (Zarnetske *et al.* 2019): there is no single
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19 521 relationship valid for all conditions. To date, biodiversity-geodiversity relationships have primarily
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21 522 been characterized in a few well-studied taxa (Meynard *et al.* 2011; Hjort *et al.* 2012; Wang *et*
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23 523 *al.* 2013; but see Kaskela *et al.* 2017; Tukiainen *et al.* 2017); our study of birds and trees only
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25 524 hints at potential mechanisms underlying differences in relationships among taxonomic groups.
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27 525 Future work across a wider range of taxa would allow us to identify the mechanisms behind the
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29 526 differences. Although we need to understand the underlying mechanisms more fully before we
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31 527 can build models that are transferable across ecoregions, globally available geodiversity
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33 528 predictors can inform conservation practitioners working at a local scale to conserve different
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35 529 dimensions of biodiversity in the face of climate change.
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3 717 **Data Accessibility Statement**
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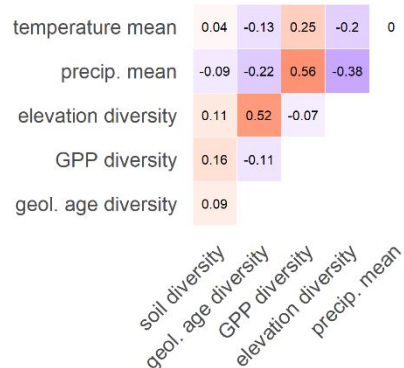
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7 718 Data and code for reviewers to reproduce all the model fitting and analysis presented in this
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9 719 manuscript is archived on FigShare at doi.org/10.6084/m9.figshare.7680083.v1 (draft version).
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11 720 Code to replicate the data preparation and cleaning stages described in the methods is also
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13 721 archived on the FigShare repository.
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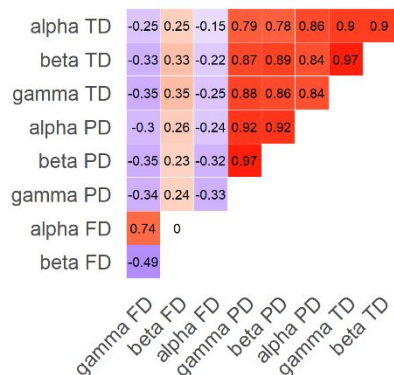
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723 Figures

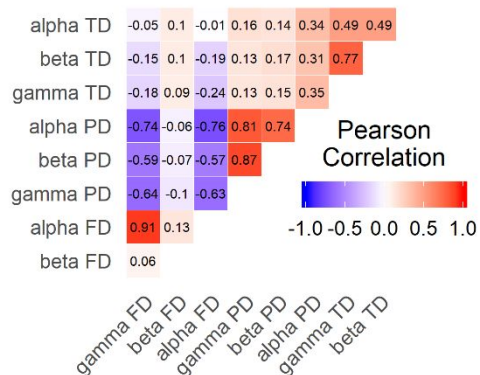
(a) environmental correlations



(b) bird biodiversity correlations



(c) tree biodiversity correlations

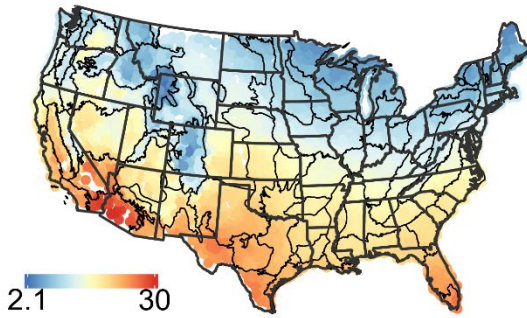


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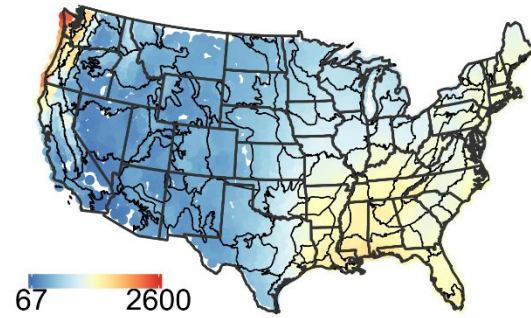
725 Figure 1. Heat maps showing correlations between pairs of environmental predictor variables
 726 including geodiversity and climate (a), bird biodiversity variables (b), and tree biodiversity
 727 variables (c). Pearson correlation coefficients are shown, along with colours showing the

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3 728 magnitude of the correlation coefficients. TD = taxonomic diversity; PD = phylogenetic diversity;
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5 729 FD = functional diversity.
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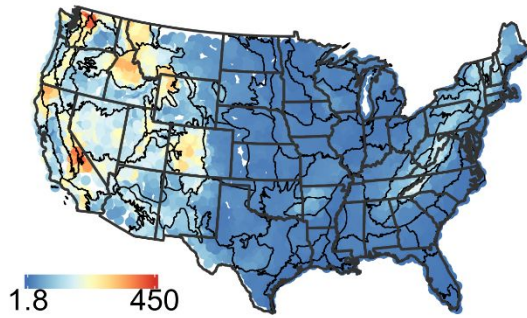
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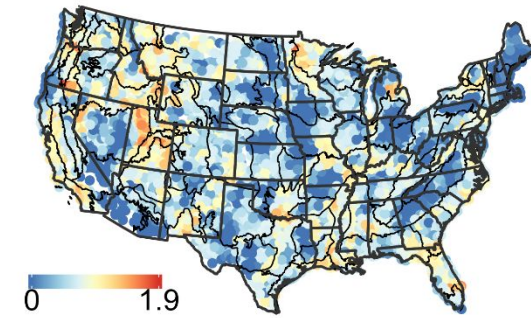
10 precipitation mean



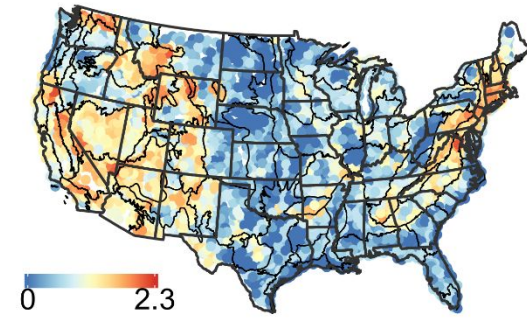
11 elevation diversity



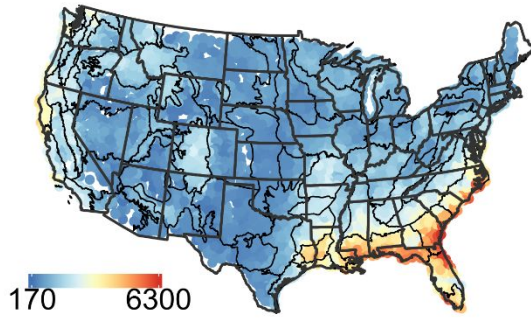
12 soil diversity



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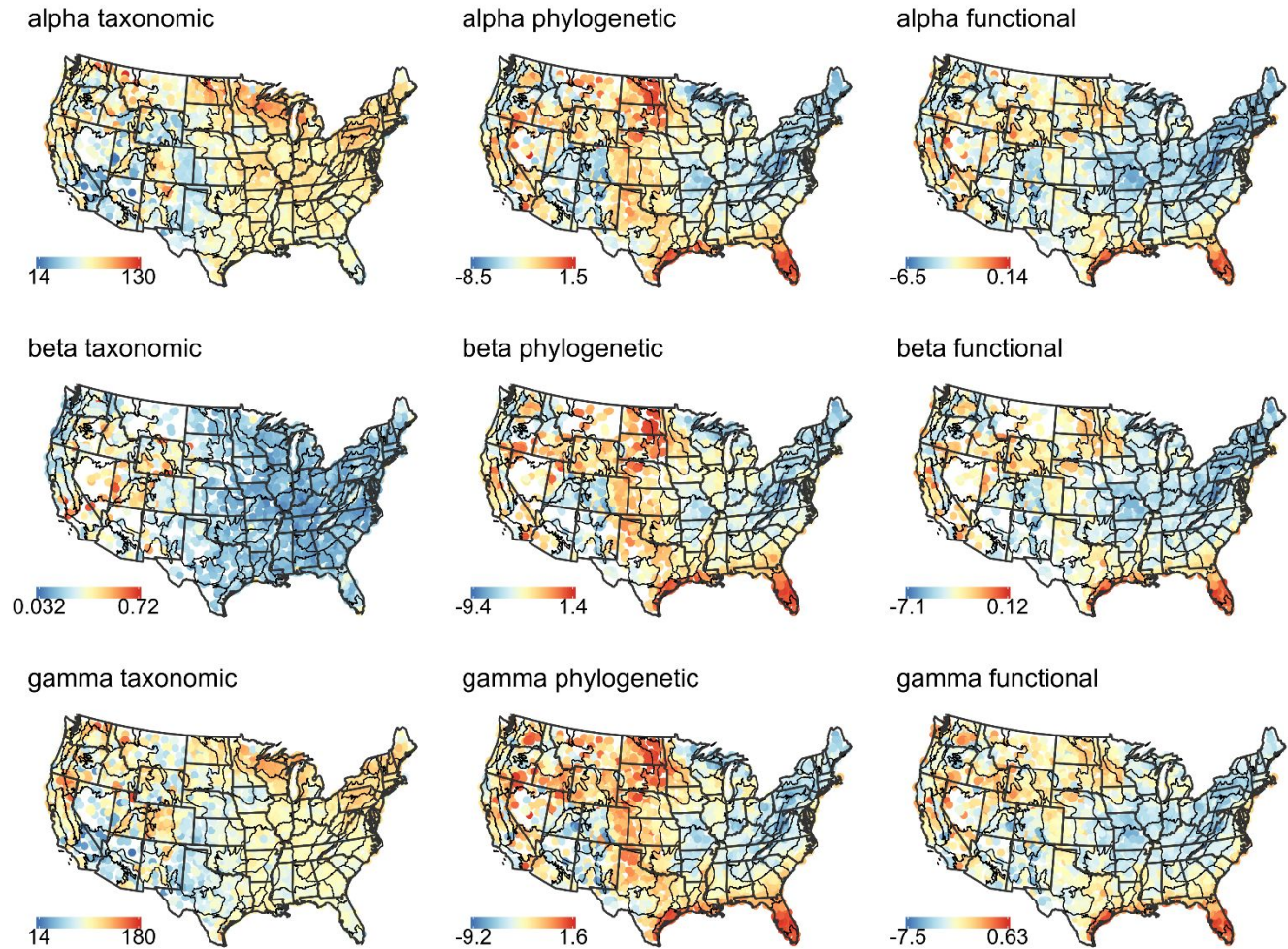


14 GPP diversity



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48 731
49 732 Figure 2: Maps of climate and geodiversity predictor variables across the contiguous United
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51 733 States, centred on BBS route midpoints and FIA plots (fuzzed locations shown).
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735 Figure 3: Maps of bird biodiversity at BBS routes, across 3 levels and 3 dimensions of

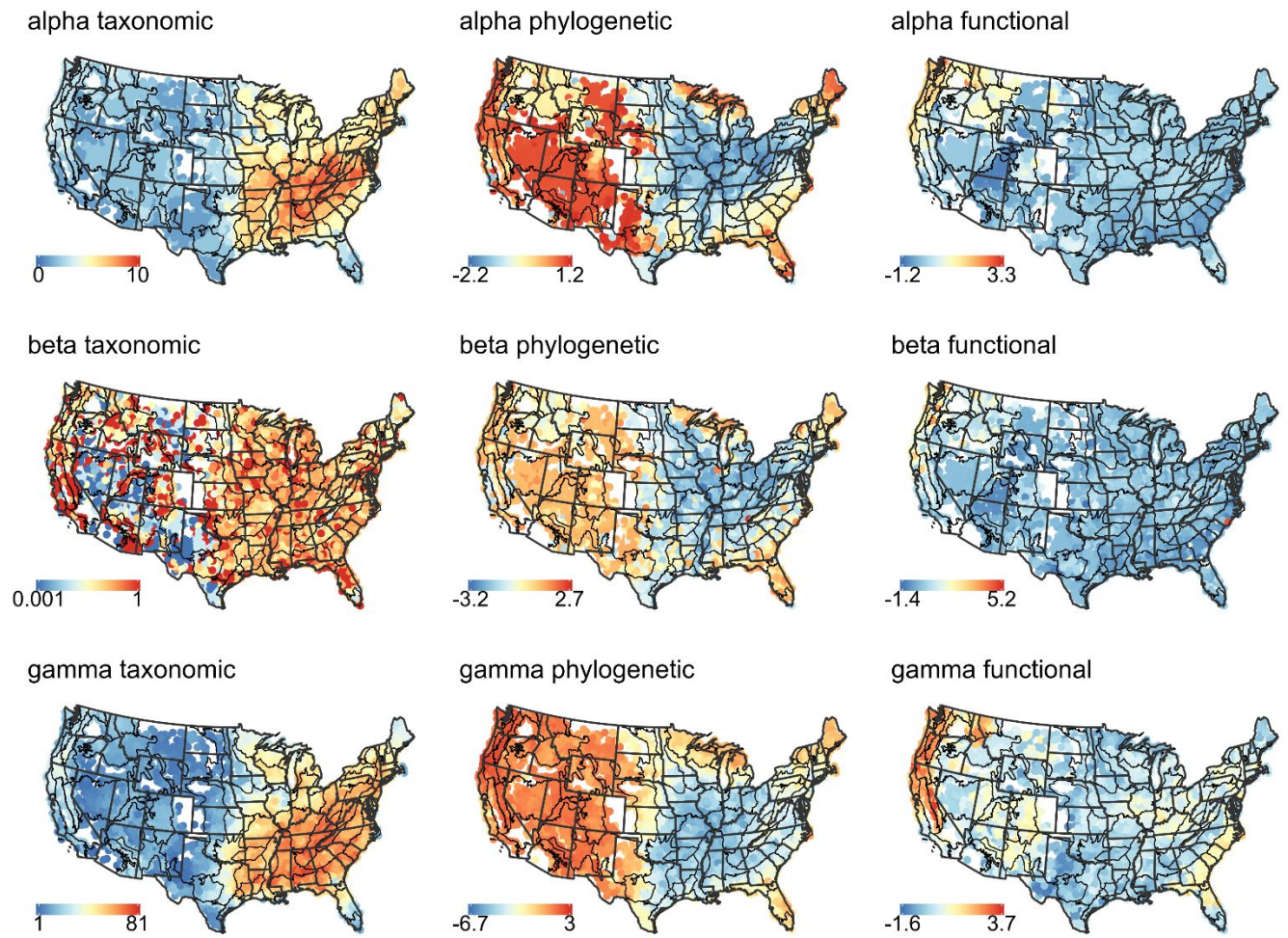
736 biodiversity. For taxonomic diversity, richness is plotted for alpha- and gamma-diversity, and

737 pairwise dissimilarity score is plotted for beta-diversity. For phylogenetic and functional diversity,

738 z-scores are plotted for all levels. Midpoints of each route are shown on the map.

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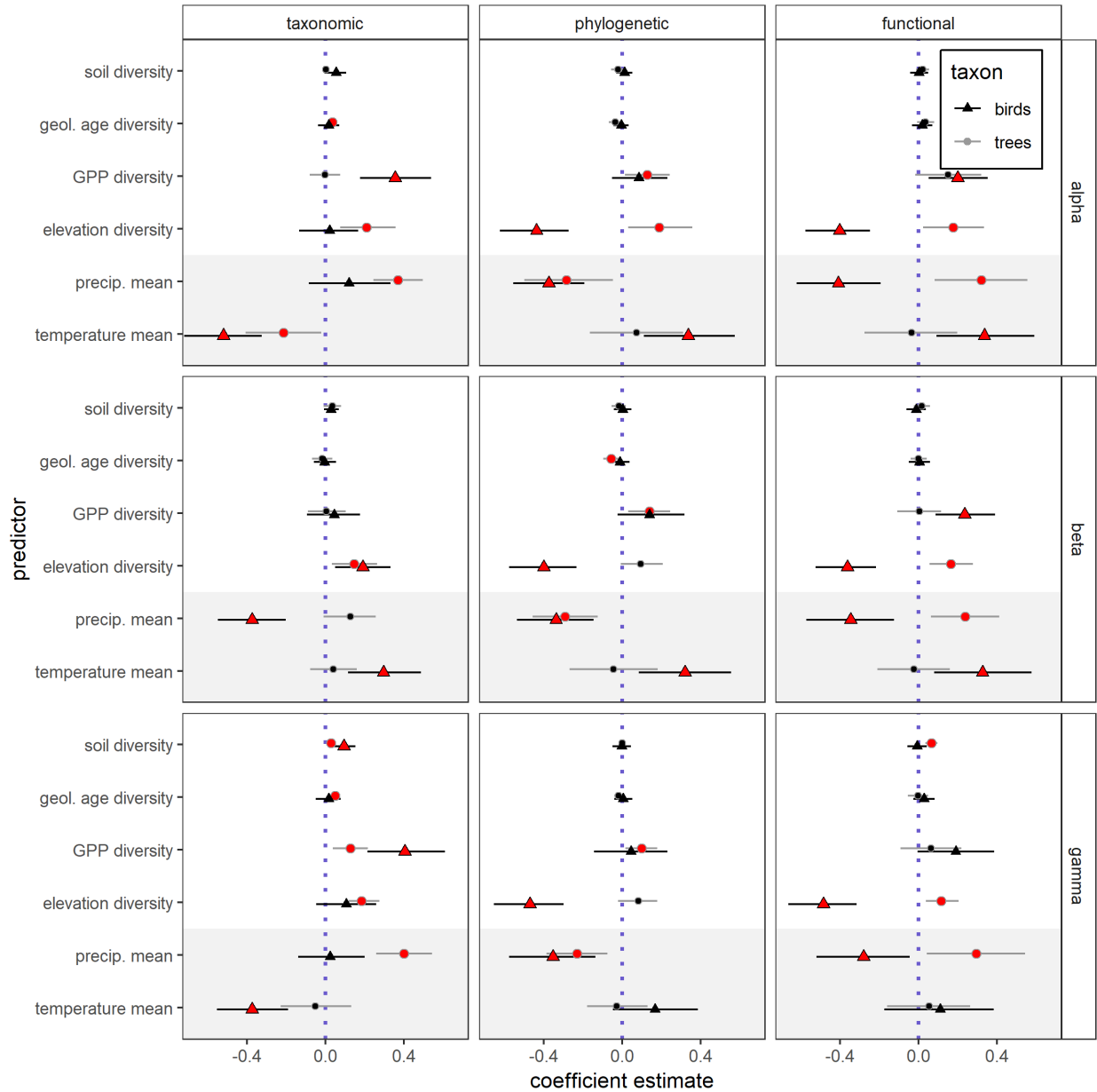
742 Figure 4: Maps of tree biodiversity at FIA plots, across 3 levels and 3 dimensions of biodiversity.

743 The same biodiversity metrics are shown as in Figure 3. Fuzzed locations of each FIA plot are

744 shown on the map.

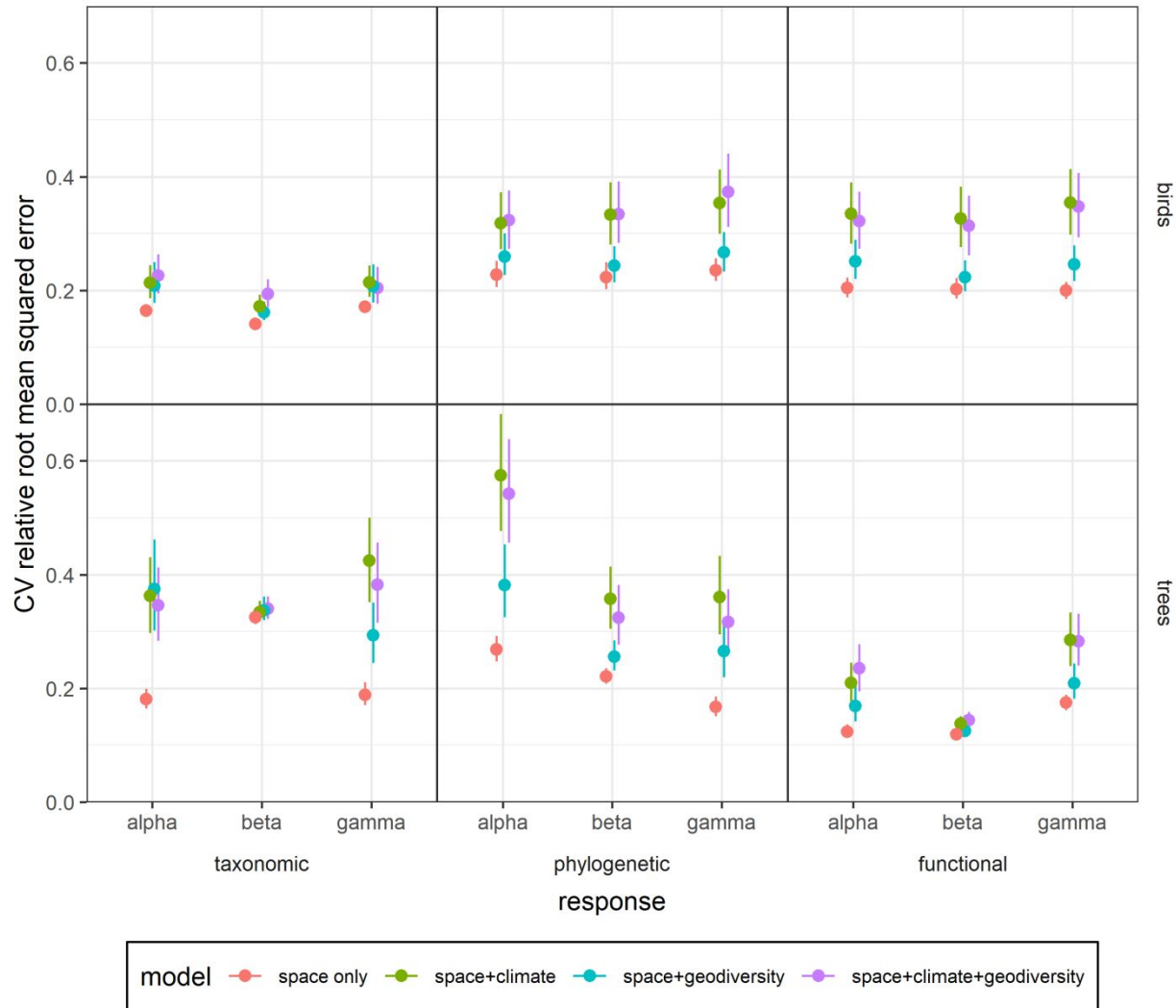
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748 Figure 5: Scaled coefficients of fixed effects for birds and trees. Error bars show 95% credible
 749 interval around parameter estimate. Parameters with credible intervals that do not overlap zero
 750 are shown in red. Within each model, predictors are scaled so that coefficients can be
 751 compared across variables within the model. Predictors representing mean climate are shaded
 752 in grey; the other predictors represent geodiversity.



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754 Figure 6: Model performance for bird biodiversity and tree biodiversity, assessed with spatially
 755 blocked leave-one-location-out cross-validation. This figure shows the root mean squared errors
 756 from the space-only or null models (red), models with climate predictors (green), models with
 757 geodiversity predictors (blue), and full models (purple) for each taxon and each response
 758 variable. Individual models were fit holding out all data points from one ecoregion, then the
 759 holdout data points were predicted and root mean squared error calculated across all
 760 ecoregions. The raw errors are divided by the range of the observed data to produce a relative
 761 value comparable among models. A lower value represents better performance of the model.
 762 Error bars are 95% credible intervals. Because each cross-validation fold excludes an entire

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3 763 region, the null model including only the spatial random effect tends to predict the held out
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5 764 values as well or better than the models including climate and geodiversity predictors. However,
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7 765 models including geodiversity predictors tend to perform as well or better than the models
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9 766 including climate predictors, especially for phylogenetic and functional diversity.
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Appendix 1: Assembly of functional traits and phylogenies for birds and trees

Birds: functional traits We obtained species mean trait values from the following two sources: the Amniote Life History Database (Myhrvold *et al.* 2016) and EltonTraits (Wilman *et al.* 2014). These databases provide measured or taxonomically imputed values for morphological and life-history traits, and foraging traits that define a species' resource niche, respectively. We used the following traits: proportion of the diet consisting of invertebrates, birds/mammals, reptiles/amphibians, fish, scavenged meat, fruit, nectar, and seeds; proportion of foraging time spent in the water below and above the surf line, on the ground, in the understory, at mid-height, in the canopy, and in the air; pelagic status; time to maturity of females and males; clutch size; number of clutches per year; average adult body mass; average and maximum longevity; mass at birth; egg mass; time of incubation; age at fledging. We also used the nocturnal status trait from EltonTraits to exclude nocturnal species, which are poorly detected by BBS protocol, from our analysis. Four traits (egg mass, mass at birth, male time to maturity, and average longevity) were correlated with other traits with Pearson's $r > 0.7$. Using a Mantel test implemented in the R package *vegan* (Oksanen *et al.* 2016), we compared the Gower pairwise distance matrix calculated from the full trait dataset with the matrix calculated from the reduced dataset without the four traits. The two matrices were highly correlated with one another (Mantel correlation statistic $r = 0.979$), indicating that the Gower distances among species are relatively insensitive to the inclusion of the correlated traits.

Birds: phylogeny We obtained a recent phylogeny of all bird species (Jetz *et al.* 2012). The phylogeny consists of a posterior distribution of 10000 trees. We randomly chose 1000 trees from this posterior distribution and generated a consensus tree with branch lengths using the R

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3 package *phytools* (Revell 2012). We used the branch lengths from this consensus tree to
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5 calculate the distance-based phylogenetic diversity indices described below.
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7 We resolved any discrepancy in scientific names among BBS, the functional trait datasets, and
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9 the bird phylogeny by using the most recent taxonomy for each species found on Avibase
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11 (<http://avibase.bsc-eoc.org/>). We excluded all individuals not identifiable to the species level
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13 (excluding 0.17% of individuals) and all individuals listed as hybrids of two species (excluding
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15 0.0003% of individuals). We assigned all taxa below the species level (subspecies or races) to
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17 the parent species (affecting 1.4% of individuals) and all species that were so recently split from
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19 another species in the dataset that they did not appear in the phylogeny or trait dataset
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21 (affecting 0.17% of individuals). After excluding the nocturnal species and unknown individuals
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23 and coarsening the subspecies to the species level, there were 605 unique species in the
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25 dataset.
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28 **Trees: functional traits** We obtained all available trait data for all species in our survey dataset
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30 from the TRY database (<http://try-db.org>) (Kattge *et al.* 2011), and supplemented these traits
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32 with data compiled by Jens Stevens (unpublished). We restricted our analysis to continuous
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34 traits that have a documented link to species performance and niche and that have at least one
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36 available observation for the majority of species in our dataset. These criteria applied to the
37
38 following traits: specific leaf area, leaf C content per area, leaf N content per area, leaf N
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40 content per dry mass, leaf P content per dry mass, leaf C:N ratio, leaf N:P ratio, leaf lifespan,
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42 photosynthetic rate per leaf area, photosynthetic rate per leaf dry mass, leaf thickness, litter
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44 decomposition rate, plant lifespan, plant shade tolerance category, rooting depth, seed dry
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46 mass, proportion vessel area per unit stem cross-sectional area, specific stem density, and
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48 stomatal conductance per leaf area. We used phylogenetic imputation implemented in the R
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50 package *Rphylopars* (Goolsby *et al.* 2017) to impute missing values. For the final analysis, we
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52 used the following six traits that had a value for almost all species to minimize the number of
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3 imputed traits: bark thickness, specific leaf area, specific stem density, seed dry mass, rooting
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5 depth, and plant lifespan.

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7 **Trees: phylogeny** We obtained a phylogeny of all trees in the FIA survey area (Potter &
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9 Woodall 2012; Potter & Koch 2014). For this phylogeny, only a single tree was available rather
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11 than a distribution of trees, so all phylogenetic diversity metrics that we calculated for FIA trees
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13 are based on this single tree assuming that it represents a consensus tree. Any discrepancies in
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15 species names between the FIA, functional trait, and phylogenetic data sources were resolved
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17 using the most recent taxonomy listed by IUCN (iucnredlist.org).
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Appendix 2: Additional details on Breeding Bird Survey data processing

Dealing with imperfect detection in the Breeding Bird Survey

Imperfect bird detection is a known issue in estimating bird diversity from point count surveys (Link & Sauer 1998; Jarzyna & Jetz 2016). Because of this, when calculating biodiversity of Breeding Bird Survey (BBS) routes, we pooled observations from all stops in each route and pooled all surveys from 2007-2016. This yielded a single incidence value for each species at each route, with a species considered present if detected at any stop during the 10-year period. This method prioritizes minimizing false negatives due to imperfect detection, but may result in increased false positives because transient species are considered present. It is impossible to simultaneously minimize Type I and Type II errors when determining whether species are present or absent. An alternative approach would be to model detection probability for each species at each site explicitly (e.g. Dorazio & Royle 2005). Because our primary concern is relative differences in richness and diversity among sites rather than absolute diversity (Kéry & Royle 2008), generating species-specific estimates of occupancy and detection probability would be unlikely to qualitatively change our inference.

Determination of Breeding Bird Survey route neighbourhoods

Criterion used to determine neighbour status. Breeding Bird Survey routes are not points, but linear features. We obtained maps of the BBS routes and identified all routes for which we could unambiguously locate the midpoint of the route. This excludes any routes that are in multiple segments, routes that include loops, or routes that trace back on themselves, resulting in 3089 routes.

We identified all pairs of neighbouring routes as those whose midpoints were 50 km or less from one another. This method ensures that for almost all routes, at least 50% of the length of the neighbouring route was within the circle for which the environmental covariates were defined. If 50% of the neighbouring route is within the circle, the average environmental conditions of the circle should adequately represent the environmental conditions of the route. The following confusion matrix illustrates the point. 8520 of 8677 pairwise comparisons in our analysis both have midpoints that are within 50 km of one another and at least half of the neighbouring route within the 50-km circle around the focal route.

	Half of route not within 50 km	Half of route within 50 km	Total
Midpoint not within 50 km	—	181	181
Midpoint within 50 km	157	8520	8677
Total	157	8701	8858

As a result, the neighbourhood criterion is relatively insensitive to whether the midpoint or 50% criterion is chosen; 98.1% of pairwise comparisons are not affected by which criterion is chosen.

Number of neighbours for each route. Using the midpoint criterion to determine

neighbourhoods, the number of neighbours for each BBS route varied between 0 and 15 (see table below). The 237 routes without neighbours did not have a beta-diversity value. These routes were not included in the beta-diversity regression models. The relatively low number of neighbours for some routes is a result of the relatively wide spacing of BBS routes, not the specific method we used to determine neighbour status.

Number of neighbours	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Number of routes	237	581	675	526	398	287	144	101	61	36	23	8	3	6	2	1

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Appendix 3: Compilation and processing of geodiversity data

All data were obtained for the contiguous U.S. or globally and processed using GDAL (GDAL/OGR Contributors 2018) and R (R Core Team, 2017) including the *rgdal* (Bivand *et al.* 2018), *gdalutils* (Mattiuzzi 2018), *rts* (Naimi 2018), *RCurl* (Lang & CRAN Team 2018), and *raster* (Hijmans *et al.* 2017) packages.

Elevation data were obtained from the NASA Shuttle Radar Topography Mission (SRTM; Farr *et al.* 2007) at 1 arcsecond (~30 m) resolution via USGS (<https://e4ftl01.cr.usgs.gov/>). From these data slope, aspect, and topographic position index (TPI) were calculated for a 3 × 3 pixel kernel around each central pixel. For each radius (see the section headed “Biodiversity Data Sources and Processing” in the main text), pixels were extracted and we calculated the mean, standard deviation, maximum, and minimum values.

Temperature variables were derived from land surface temperature (LST) data from the MODerate Imaging Spectrometer (MODIS; Wan *et al.* 2015) on board the Terra satellite (10:30 am descending node). We used the MOD11A2 product, which is LST averaged over an 8-day period at 1 km pixel resolution. These data were aggregated to monthly climatologies for 2001-2016.

Average monthly precipitation totals (mm) were calculated from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) monthly data from 2001-2015 (Funk *et al.* 2015). CHIRPS is a 0.05° resolution gridded rainfall product that combines satellite imagery and *in situ* station data, and has been shown to improve species distribution models in areas with sparse meteorological stations (Deblauwe *et al.* 2016). Monthly data were aggregated to monthly climatologies by averaging each month across the time period of 2001-2015.

The two main climate datasets - LST and precipitation - were aggregated into 19 bioclimatic variables (“bioclim variables”) as described in (Hijmans *et al.* 2005). Because LST and precipitation were available at different resolutions, and many of the bioclim variables require

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3 both, all 19 bioclim variables were calculated at both resolutions. LST was averaged to match
4 the CHIRPS precipitation resolution and CHIRPS precipitation was simply re-gridded to the LST
5 resolution. The bioclimatic variable calculation transformed the monthly climatologies into
6 annual climatologies for each location. For each bioclimatic variable, we calculated the mean,
7 standard deviation, minimum, and maximum values within each radius, as for the topographic
8 indices.

9
10 Geologic and soil information included two polygon-based maps which we rasterized: geologic
11 age (92 possible values) provided by USGS International Surface Geology (originally hosted by
12 worldgrids.org; although the original page is no longer active, for an archived version of the
13 page, see [http://85.214.253.67/dkwwk-](http://85.214.253.67/dkwwk-stable/doku.php?id=wiki:geological_and_parent_materials_maps)
14 [stable/doku.php?id=wiki:geological_and_parent_materials_maps](http://85.214.253.67/dkwwk-stable/doku.php?id=wiki:geological_and_parent_materials_maps)) and soil type (36 possible
15 values) provided by the Harmonized World Soil Database (Fischer *et al.* 2008) and interpolated
16 to a 250 m gridded product (Hengl *et al.* 2017). In contrast to the other geodiversity data layers,
17 these products were not remotely sensed. We were concerned with the diversity of geological
18 types within each radius, not the substrate and soil types themselves, so we calculated richness
19 (number of types) and diversity (Shannon entropy) of substrate and soil types for each radius.
20
21 Gross primary productivity (GPP) was calculated as an indicator of cumulative vegetation
22 productivity over the course of a year using the Moderate Resolution Imaging
23 Spectroradiometer (MODIS) data (for details see Hobi *et al.* 2017). For this analysis the GPP
24 MODIS Collection 5 product having a repeat period of 8 days and a spatial resolution of 1000 m
25 was averaged for the time period of 2003-2014 (data freely available from the Dynamic Habitat
26 Index project of the SILVIS lab: <http://silvis.forest.wisc.edu/data/DHIs>). Though GPP is not often
27 considered a component of geodiversity, we chose to classify GPP as a geodiversity variable
28 because it integrates across a number of biotic and abiotic variables.
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Peer Review

Supplementary Information: Tables and Figures

Beyond counts and averages: relating geodiversity to dimensions of biodiversity. Quentin D. Read, Phoebe L. Zarnetske, Sydne Record, Kyla M. Dahlin, Andrew O. Finley, John M. Grady, Martina L. Hobi, Sparkle L. Malone, Jennifer K. Costanza, Adam M. Wilson, Andrew M. Latimer, Keith D. Gaddis, Stephanie Pau, Scott V. Ollinger

Supplementary Tables

Table S1: Overview of biodiversity metrics by level and by dimension.

		<i>Diversity dimension</i>		
		Taxonomic	Phylogenetic	Functional
<i>Diversity level</i>	Alpha (local)	Mean richness of local communities within a 50-km radius around the focal plot	Mean pairwise phylogenetic distance score of local communities in the radius, relative to null expectation	Mean pairwise functional distance score of local communities in the radius, relative to null expectation
	Beta (turnover)	Mean pairwise dissimilarity of local communities in the radius, logit-transformed	Mean pairwise phylogenetic distance among communities in the radius, relative to null expectation	Mean pairwise functional distance among communities in the radius, relative to null expectation
	Gamma (regional)	Richness of all communities in the radius, pooled to a single community	Mean pairwise phylogenetic distance of all communities in the radius, pooled to a single community, relative to null expectation	Mean pairwise functional distance of all communities in the radius, pooled to a single community, relative to null expectation

Table S2: This table shows model fit statistics for each response variable for each model. The RMSE is the root mean squared error of the model fit with all the data. The CV RMSE is the root mean squared error of the holdout data points in spatially blocked cross-validation. Both RMSEs are divided by the range of the data to produce a relative RMSE value that is comparable among models. Lower RMSE values indicate better model performance. The R^2 is calculated using the method of Gelman *et al.*. For all fit statistics, mean value as well as upper and lower bounds of 95% credible intervals are shown.

Warning: package 'knitr' was built under R version 3.6.1

taxon	biodiversity level	biodiversity dimension	model	RMSE	CV RMSE	R^2
birds	alpha	taxonomic	space only	0.13 [0.13,0.14]	0.16 [0.15,0.18]	0.5 [0.48,0.52]
birds	alpha	taxonomic	space + climate	0.12 [0.11,0.12]	0.21 [0.19,0.24]	0.62 [0.6,0.63]
birds	alpha	taxonomic	space + geodiversity	0.11 [0.11,0.12]	0.21 [0.18,0.25]	0.63 [0.61,0.64]
birds	alpha	taxonomic	space + climate + geodiversity	0.11 [0.1,0.11]	0.23 [0.19,0.26]	0.68 [0.67,0.69]
birds	alpha	phylogenetic	space only	0.15 [0.15,0.16]	0.23 [0.21,0.25]	0.67 [0.66,0.68]
birds	alpha	phylogenetic	space + climate	0.13 [0.13,0.13]	0.32 [0.27,0.37]	0.76 [0.75,0.77]
birds	alpha	phylogenetic	space + geodiversity	0.13 [0.13,0.14]	0.26 [0.23,0.3]	0.75 [0.74,0.76]
birds	alpha	phylogenetic	space + climate + geodiversity	0.12 [0.12,0.12]	0.32 [0.27,0.38]	0.8 [0.79,0.81]
birds	alpha	functional	space only	0.15 [0.15,0.15]	0.2 [0.19,0.22]	0.62 [0.61,0.64]
birds	alpha	functional	space + climate	0.13 [0.12,0.13]	0.33 [0.28,0.39]	0.73 [0.72,0.74]
birds	alpha	functional	space + geodiversity	0.13 [0.12,0.13]	0.25 [0.22,0.29]	0.72 [0.71,0.73]
birds	alpha	functional	space + climate + geodiversity	0.11 [0.11,0.12]	0.32 [0.27,0.37]	0.78 [0.77,0.79]
birds	beta	taxonomic	space only	0.12 [0.12,0.13]	0.14 [0.13,0.15]	0.64 [0.62,0.65]
birds	beta	taxonomic	space + climate	0.12 [0.11,0.12]	0.17 [0.16,0.19]	0.67 [0.66,0.69]
birds	beta	taxonomic	space + geodiversity	0.11 [0.11,0.12]	0.16 [0.15,0.18]	0.68 [0.67,0.7]
birds	beta	taxonomic	space + climate + geodiversity	0.11 [0.11,0.11]	0.19 [0.17,0.22]	0.71 [0.7,0.73]
birds	beta	phylogenetic	space only	0.15 [0.14,0.15]	0.22 [0.2,0.25]	0.69 [0.68,0.7]
birds	beta	phylogenetic	space + climate	0.12 [0.12,0.13]	0.33 [0.28,0.39]	0.78 [0.77,0.79]
birds	beta	phylogenetic	space + geodiversity	0.13 [0.12,0.13]	0.24 [0.21,0.28]	0.77 [0.76,0.78]
birds	beta	phylogenetic	space + climate + geodiversity	0.11 [0.11,0.11]	0.33 [0.28,0.39]	0.83 [0.82,0.83]
birds	beta	functional	space only	0.14 [0.14,0.15]	0.2 [0.19,0.22]	0.64 [0.62,0.65]
birds	beta	functional	space + climate	0.12 [0.12,0.13]	0.33 [0.28,0.38]	0.74 [0.73,0.75]
birds	beta	functional	space + geodiversity	0.12 [0.12,0.13]	0.22 [0.2,0.25]	0.73 [0.72,0.74]
birds	beta	functional	space + climate + geodiversity	0.11 [0.11,0.11]	0.31 [0.26,0.37]	0.79 [0.78,0.8]
birds	gamma	taxonomic	space only	0.14 [0.13,0.14]	0.17 [0.16,0.18]	0.46 [0.43,0.48]
birds	gamma	taxonomic	space + climate	0.12 [0.12,0.13]	0.21 [0.19,0.24]	0.55 [0.53,0.57]
birds	gamma	taxonomic	space + geodiversity	0.12 [0.12,0.12]	0.21 [0.18,0.25]	0.58 [0.57,0.6]
birds	gamma	taxonomic	space + climate + geodiversity	0.12 [0.11,0.12]	0.2 [0.18,0.24]	0.62 [0.6,0.63]
birds	gamma	phylogenetic	space only	0.17 [0.16,0.17]	0.24 [0.22,0.26]	0.65 [0.64,0.66]
birds	gamma	phylogenetic	space + climate	0.15 [0.14,0.15]	0.35 [0.3,0.41]	0.73 [0.72,0.74]
birds	gamma	phylogenetic	space + geodiversity	0.14 [0.14,0.15]	0.27 [0.23,0.3]	0.74 [0.73,0.75]
birds	gamma	phylogenetic	space + climate + geodiversity	0.13 [0.13,0.13]	0.37 [0.31,0.44]	0.79 [0.78,0.8]

(continued)

	taxon	biodiversity level	biodiversity dimension	model	RMSE	CV RMSE	R²
7	birds	gamma	functional	space only	0.15 [0.15,0.16]	0.2 [0.18,0.22]	0.57 [0.55,0.59]
8	birds	gamma	functional	space + climate	0.13 [0.13,0.13]	0.35 [0.3,0.41]	0.68 [0.67,0.69]
9	birds	gamma	functional	space + geodiversity	0.13 [0.13,0.13]	0.25 [0.22,0.28]	0.69 [0.68,0.7]
10	birds	gamma	functional	space + climate + geodiversity	0.12 [0.11,0.12]	0.35 [0.29,0.41]	0.75 [0.74,0.76]
11							
12	trees	alpha	taxonomic	space only	0.12 [0.12,0.13]	0.18 [0.16,0.2]	0.89 [0.88,0.89]
13	trees	alpha	taxonomic	space + climate	0.09 [0.09,0.1]	0.36 [0.3,0.43]	0.94 [0.93,0.94]
14	trees	alpha	taxonomic	space + geodiversity	0.1 [0.1,0.1]	0.37 [0.3,0.46]	0.93 [0.92,0.93]
15	trees	alpha	taxonomic	space + climate + geodiversity	0.09 [0.08,0.09]	0.35 [0.28,0.41]	0.95 [0.94,0.95]
16							
17							
18	trees	alpha	phylogenetic	space only	0.2 [0.2,0.21]	0.27 [0.25,0.29]	0.76 [0.75,0.77]
19	trees	alpha	phylogenetic	space + climate	0.15 [0.15,0.16]	0.57 [0.48,0.68]	0.86 [0.86,0.86]
20	trees	alpha	phylogenetic	space + geodiversity	0.17 [0.17,0.18]	0.38 [0.32,0.45]	0.82 [0.82,0.83]
21	trees	alpha	phylogenetic	space + climate + geodiversity	0.14 [0.14,0.14]	0.54 [0.46,0.64]	0.88 [0.88,0.89]
22							
23	trees	alpha	functional	space only	0.09 [0.09,0.09]	0.12 [0.11,0.14]	0.73 [0.72,0.74]
24	trees	alpha	functional	space + climate	0.08 [0.08,0.08]	0.21 [0.18,0.25]	0.79 [0.79,0.8]
25	trees	alpha	functional	space + geodiversity	0.08 [0.07,0.08]	0.17 [0.14,0.21]	0.8 [0.8,0.81]
26	trees	alpha	functional	space + climate + geodiversity	0.07 [0.07,0.07]	0.24 [0.19,0.28]	0.84 [0.83,0.84]
27							
28							
29	trees	beta	taxonomic	space only	0.3 [0.29,0.3]	0.32 [0.31,0.34]	0.16 [0.14,0.19]
30	trees	beta	taxonomic	space + climate	0.29 [0.28,0.3]	0.33 [0.32,0.35]	0.2 [0.17,0.23]
31	trees	beta	taxonomic	space + geodiversity	0.29 [0.28,0.3]	0.34 [0.32,0.36]	0.2 [0.17,0.23]
32	trees	beta	taxonomic	space + climate + geodiversity	0.29 [0.28,0.29]	0.34 [0.32,0.36]	0.22 [0.2,0.25]
33							
34	trees	beta	phylogenetic	space only	0.18 [0.18,0.19]	0.22 [0.21,0.24]	0.63 [0.62,0.64]
35	trees	beta	phylogenetic	space + climate	0.16 [0.16,0.17]	0.36 [0.3,0.41]	0.71 [0.7,0.72]
36	trees	beta	phylogenetic	space + geodiversity	0.17 [0.17,0.18]	0.26 [0.23,0.28]	0.68 [0.67,0.69]
37	trees	beta	phylogenetic	space + climate + geodiversity	0.16 [0.15,0.16]	0.32 [0.28,0.38]	0.73 [0.72,0.74]
38							
39							
40	trees	beta	functional	space only	0.1 [0.1,0.11]	0.12 [0.11,0.12]	0.51 [0.49,0.52]
41	trees	beta	functional	space + climate	0.1 [0.1,0.1]	0.14 [0.13,0.15]	0.54 [0.52,0.56]
42	trees	beta	functional	space + geodiversity	0.1 [0.1,0.1]	0.13 [0.12,0.14]	0.54 [0.52,0.55]
43	trees	beta	functional	space + climate + geodiversity	0.1 [0.09,0.1]	0.14 [0.13,0.16]	0.56 [0.54,0.58]
44							
45	trees	gamma	taxonomic	space only	0.12 [0.12,0.13]	0.19 [0.17,0.21]	0.9 [0.9,0.91]
46	trees	gamma	taxonomic	space + climate	0.09 [0.09,0.09]	0.42 [0.35,0.5]	0.95 [0.95,0.95]
47	trees	gamma	taxonomic	space + geodiversity	0.09 [0.09,0.1]	0.29 [0.24,0.35]	0.94 [0.94,0.95]
48	trees	gamma	taxonomic	space + climate + geodiversity	0.08 [0.07,0.08]	0.38 [0.31,0.46]	0.96 [0.96,0.96]
49							
50	trees	gamma	phylogenetic	space only	0.12 [0.11,0.12]	0.17 [0.15,0.19]	0.89 [0.89,0.9]
51	trees	gamma	phylogenetic	space + climate	0.08 [0.08,0.09]	0.36 [0.29,0.43]	0.94 [0.94,0.95]
52	trees	gamma	phylogenetic	space + geodiversity	0.1 [0.09,0.1]	0.27 [0.22,0.31]	0.93 [0.93,0.93]
53	trees	gamma	phylogenetic	space + climate + geodiversity	0.08 [0.07,0.08]	0.32 [0.26,0.37]	0.95 [0.95,0.96]
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(continued)

taxon	biodiversity level	biodiversity dimension	model	RMSE	CV RMSE	R^2
trees	gamma	functional	space only	0.13 [0.13,0.13]	0.17 [0.16,0.19]	0.65 [0.64,0.67]
trees	gamma	functional	space + climate	0.11 [0.11,0.11]	0.28 [0.24,0.33]	0.75 [0.74,0.76]
trees	gamma	functional	space + geodiversity	0.12 [0.11,0.12]	0.21 [0.18,0.24]	0.73 [0.71,0.74]
trees	gamma	functional	space + climate + geodiversity	0.1 [0.1,0.11]	0.28 [0.24,0.33]	0.78 [0.77,0.79]

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Table S3: This table shows the Widely Available Information Criterion (WAIC) for each model, along with the standard error of the WAIC. Lower WAIC values indicate a more parsimonious fit.

taxon	biodiversity level	model	WAIC	standard error of WAIC
birds	alpha	space only	15278.9	230.6
birds	alpha	space + climate	13189.6	259.3
birds	alpha	space + geodiversity	13307.8	246.9
birds	alpha	space + climate + geodiversity	11922.8	256.1
birds	beta	space only	13245.3	197.8
birds	beta	space + climate	11525.5	214.9
birds	beta	space + geodiversity	11698.0	203.9
birds	beta	space + climate + geodiversity	10407.8	213.2
birds	gamma	space only	16016.9	215.8
birds	gamma	space + climate	14375.7	243.3
birds	gamma	space + geodiversity	14053.7	231.8
birds	gamma	space + climate + geodiversity	12908.8	240.4
trees	alpha	space only	10308.1	205.6
trees	alpha	space + climate	6737.0	236.5
trees	alpha	space + geodiversity	7810.7	226.4
trees	alpha	space + climate + geodiversity	5412.5	248.2
trees	beta	space only	18052.9	257.3
trees	beta	space + climate	17223.2	276.8
trees	beta	space + geodiversity	17545.7	262.8
trees	beta	space + climate + geodiversity	16957.1	278.8
trees	gamma	space only	8349.6	205.3
trees	gamma	space + climate	4009.5	228.0
trees	gamma	space + geodiversity	5444.2	220.2
trees	gamma	space + climate + geodiversity	2541.7	245.6

Supplementary Figures

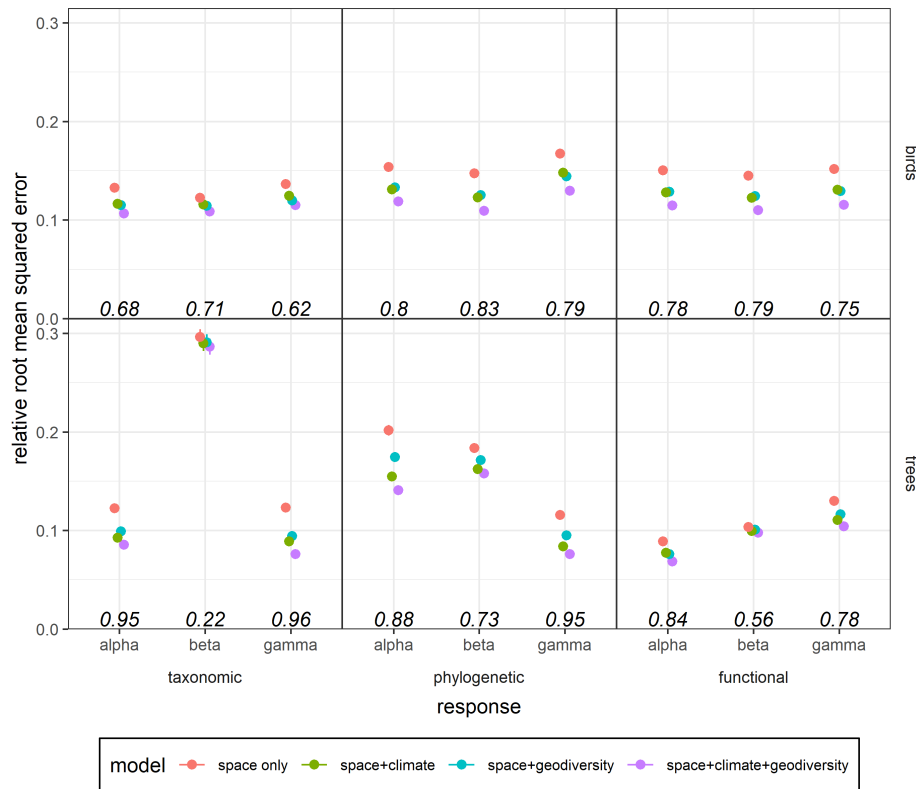


Figure S1: Model performance assessed with standard evaluation

Figure S1: This figure shows the relative root mean squared errors obtained from standard resubstitution evaluation, in which the models are fit using all data and the predicted and observed values compared. The raw errors are divided by the range of the observed data to produce a relative value comparable among models. A lower value represents better performance of the model predicting biodiversity. Error bars are 95% credible intervals. Here, we not only compare taxa but also the four types of model: space only (null), space + climate, space + geodiversity, and space + climate + geodiversity (full model). The Bayesian R-squared values for the full models are also shown. For most biodiversity variables, tree biodiversity is better predicted by a combination of space, climate, and geodiversity, compared to bird biodiversity. The exceptions are taxonomic and phylogenetic beta-diversity and phylogenetic alpha-diversity, which are predicted relatively poorly for trees.

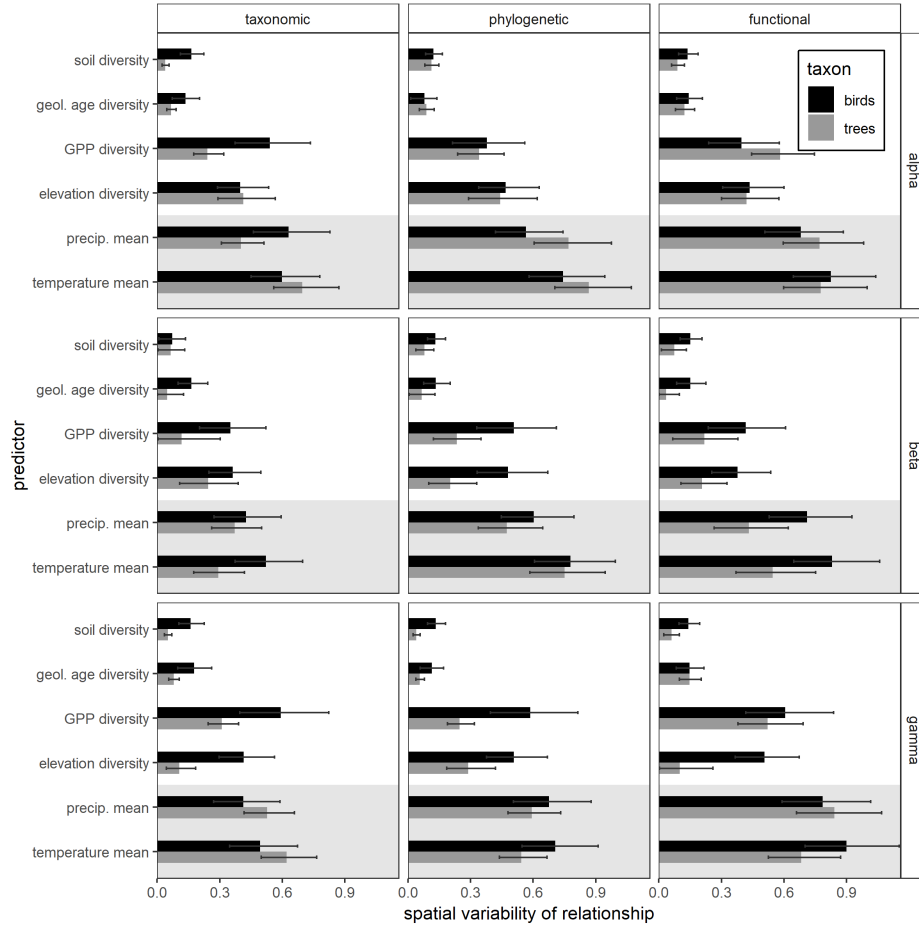


Figure S2: Spatial variation in geodiversity-biodiversity relationships

Figure S2: The spatial variability of the relationship between each predictor and each response, by taxon. The spatial variability is measured by the standard deviation of each coefficient value among ecoregions. Error bars represent the 95% credible interval of the standard deviation parameter. Higher values represent relationships that vary more spatially.

Supplementary Figures S3-S14

The following figures are maps of the coefficient on each climate or geodiversity predictor from the full multivariate models predicting alpha, beta, and gamma diversity for birds and for trees. Each figure shows the coefficients from the alpha, beta, and gamma models for each of the three biodiversity dimensions (taxonomic, phylogenetic, and functional) for one taxonomic group. Figures 3 through 8 show the coefficients for birds separately for each predictor, and figures 9 through 14 show the coefficients for trees.

In figures S3a, S4a, etc. below, the color of each TNC ecoregion is the region-level coefficient estimate from the model (USA-wide fixed-effect slope + random-effect slope from that region). The colors are scaled so that darker red ecoregions have more positive coefficients, and darker blue ecoregions have negative coefficients. White ecoregions have coefficients approximating zero, and dark gray ecoregions have coefficients that could not be estimated.

In figures S3b, S4b, etc., below, the ecoregions are shaded based on whether the 95% credible interval around the coefficient overlaps zero. Red shaded regions have entirely positive nonzero 95% credible intervals, while blue shaded regions have entirely negative nonzero 95% credible intervals. Dark gray shaded regions have 95% credible intervals that contain zero.

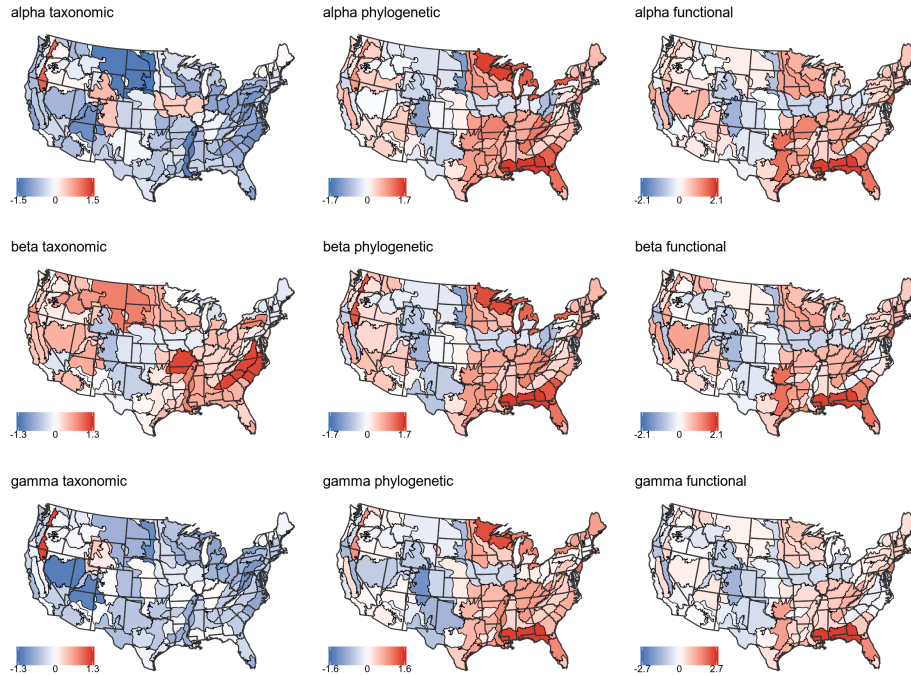


Figure S3a: Coefficients of mean annual temperature on bird diversity, values shown

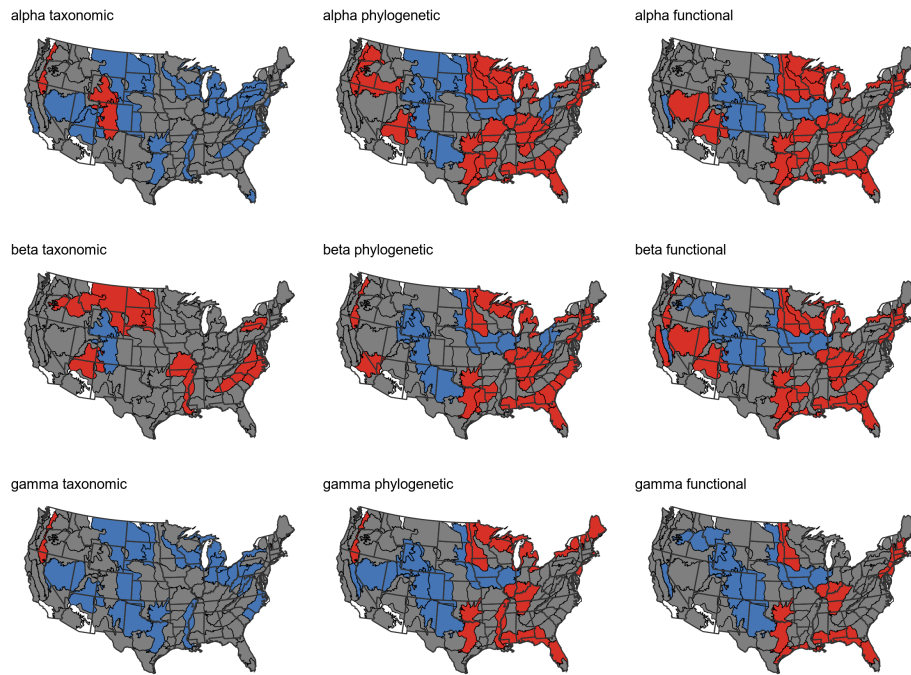


Figure S3b: Coefficients of mean annual temperature on bird diversity, nonzero regions shown

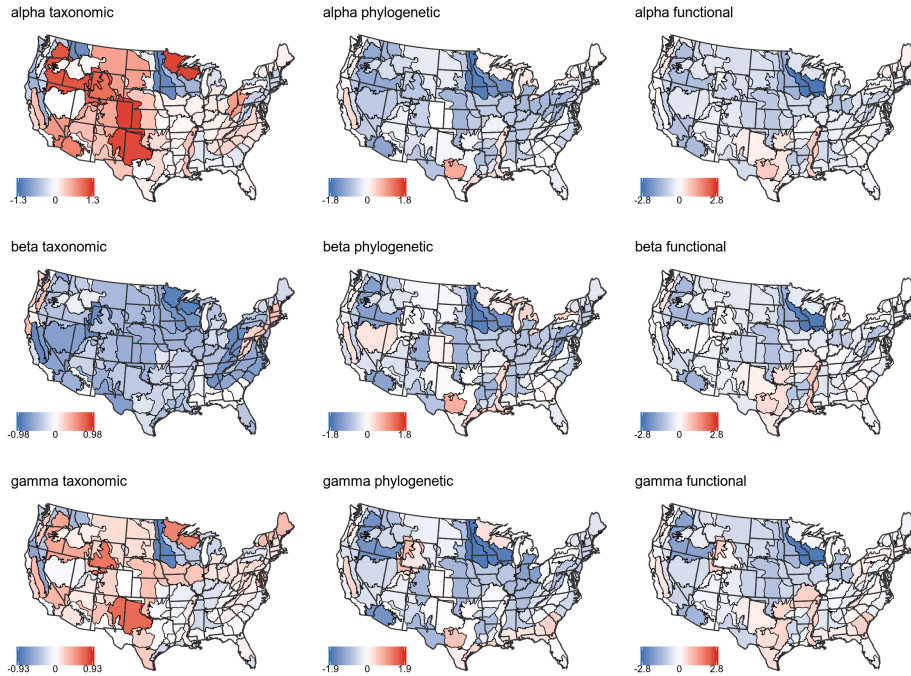


Figure S4a: Coefficients of mean annual precipitation on bird diversity, values shown

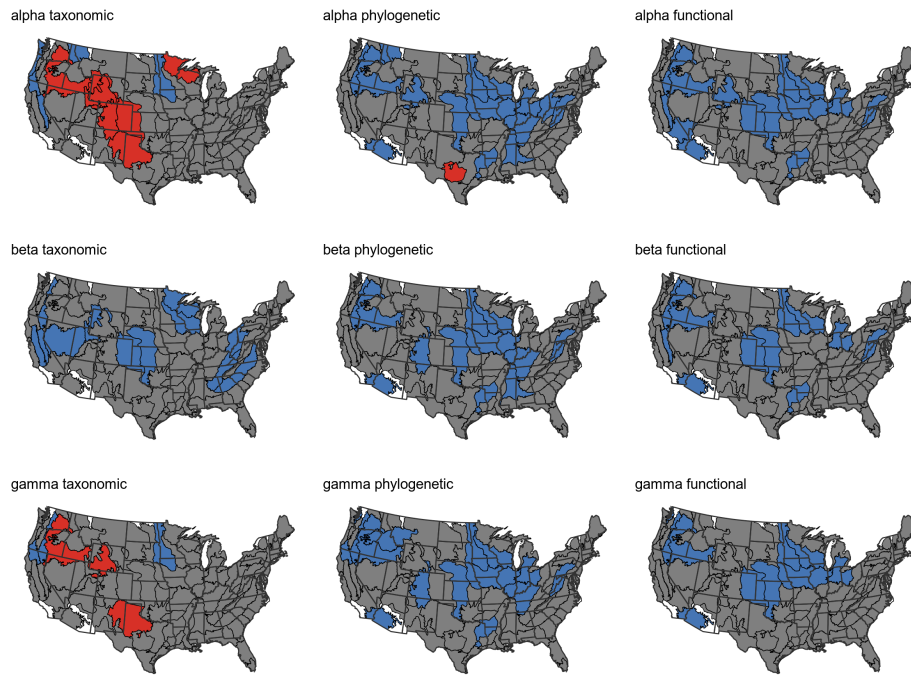


Figure S4b: Coefficients of mean annual precipitation on bird diversity, nonzero regions shown

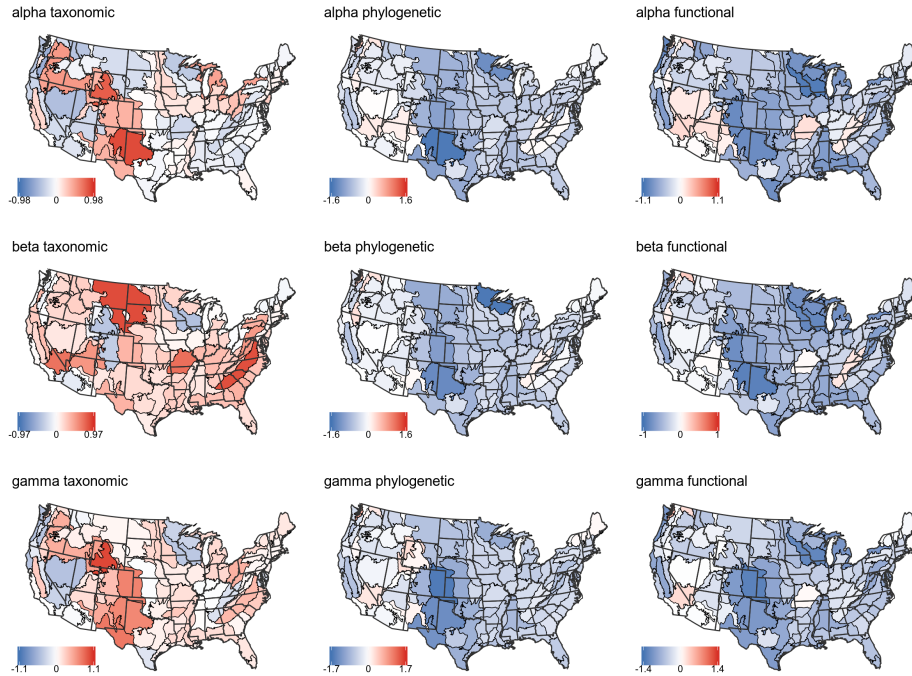


Figure S5a: Coefficients of elevation variability on bird diversity, values shown

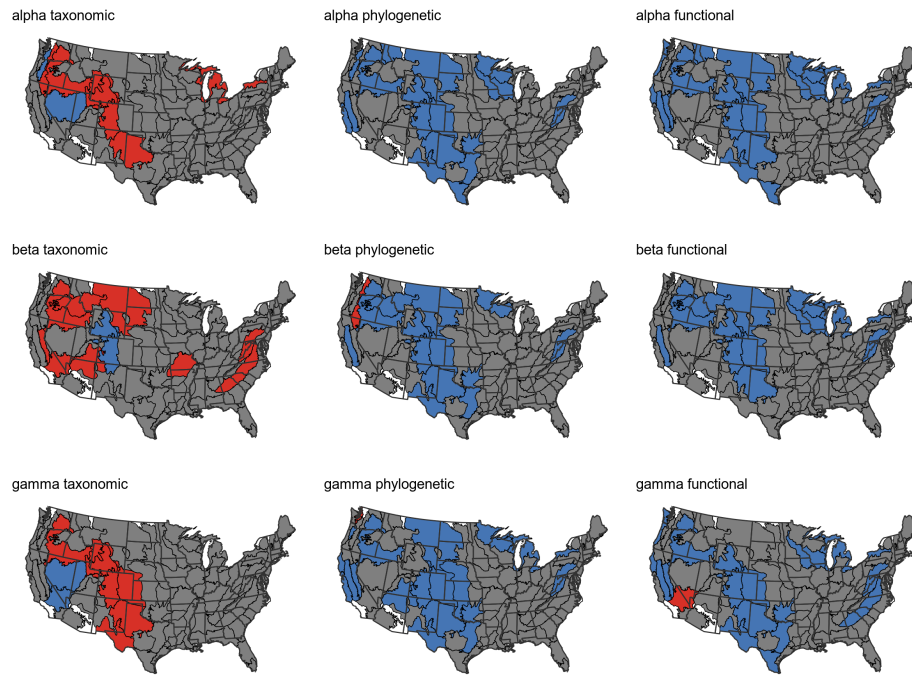


Figure S5b: Coefficients of elevation variability on bird diversity, nonzero regions shown

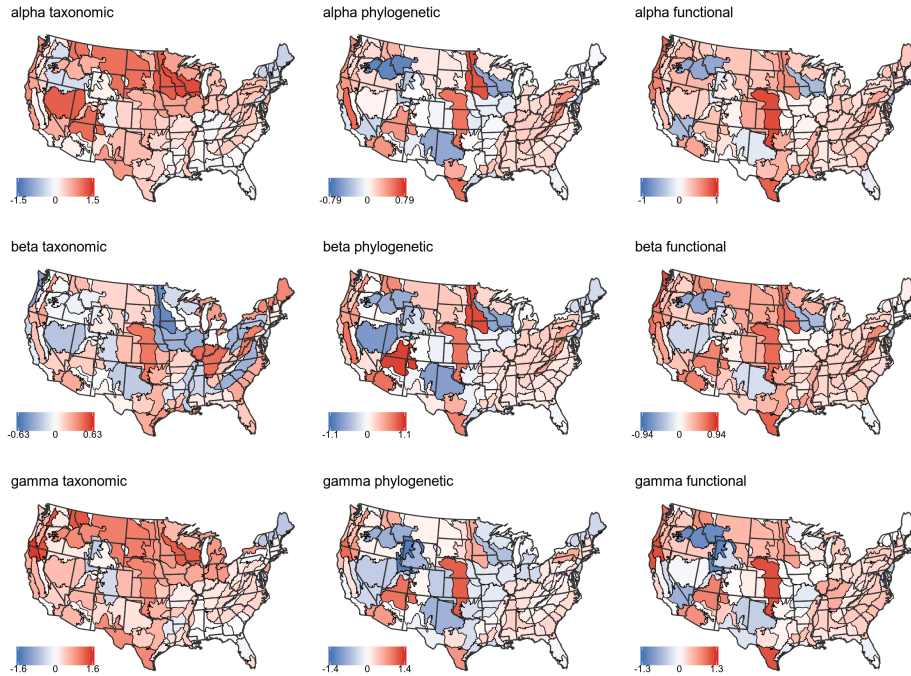


Figure S6a: Coefficients of GDP variability on bird diversity, values shown

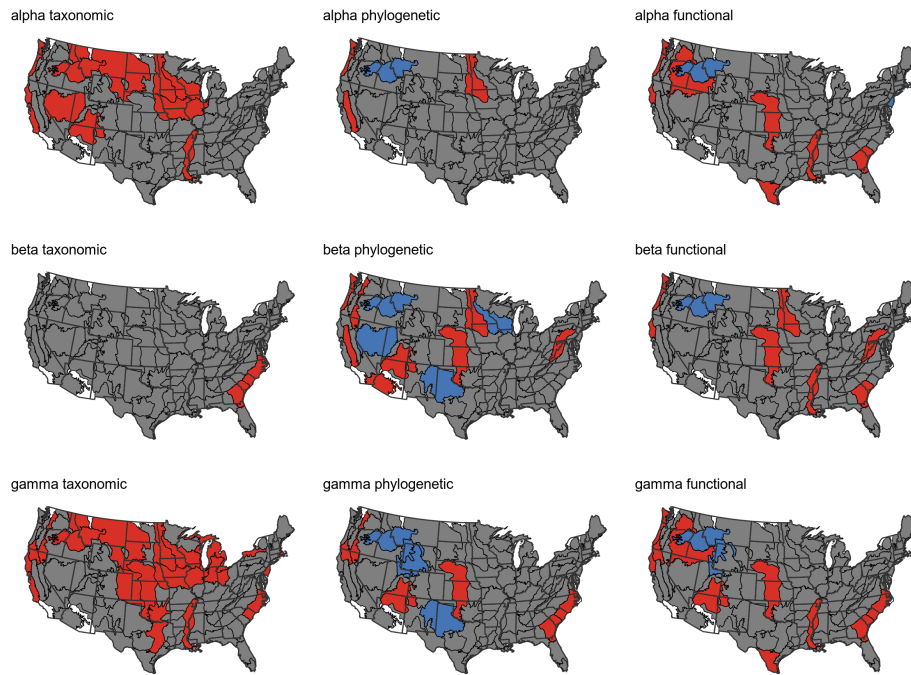


Figure S6b: Coefficients of GDP variability on bird diversity, nonzero regions shown

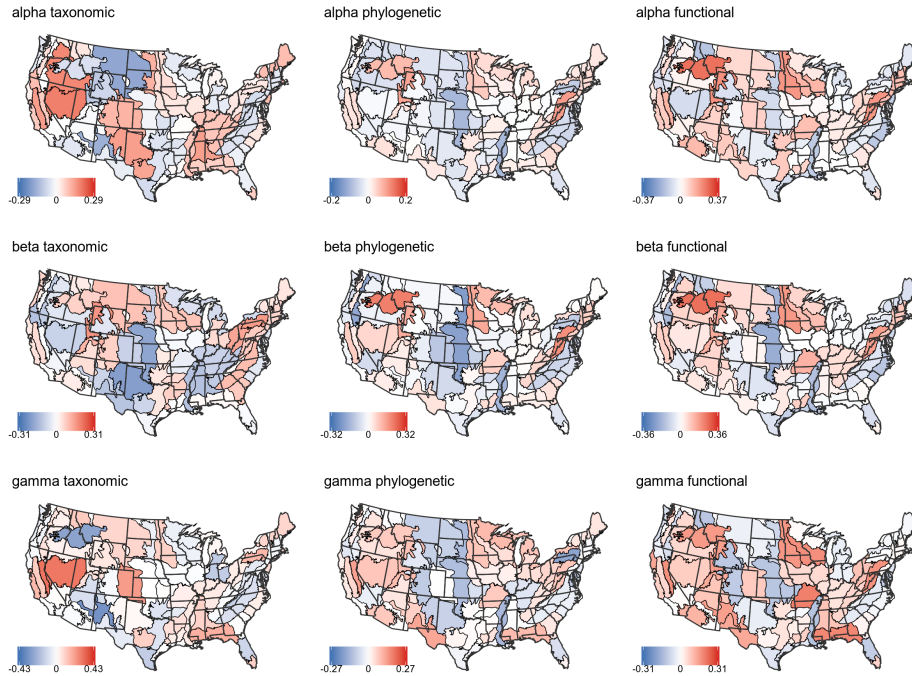


Figure S7a: Coefficients of geological age diversity on bird diversity, values shown

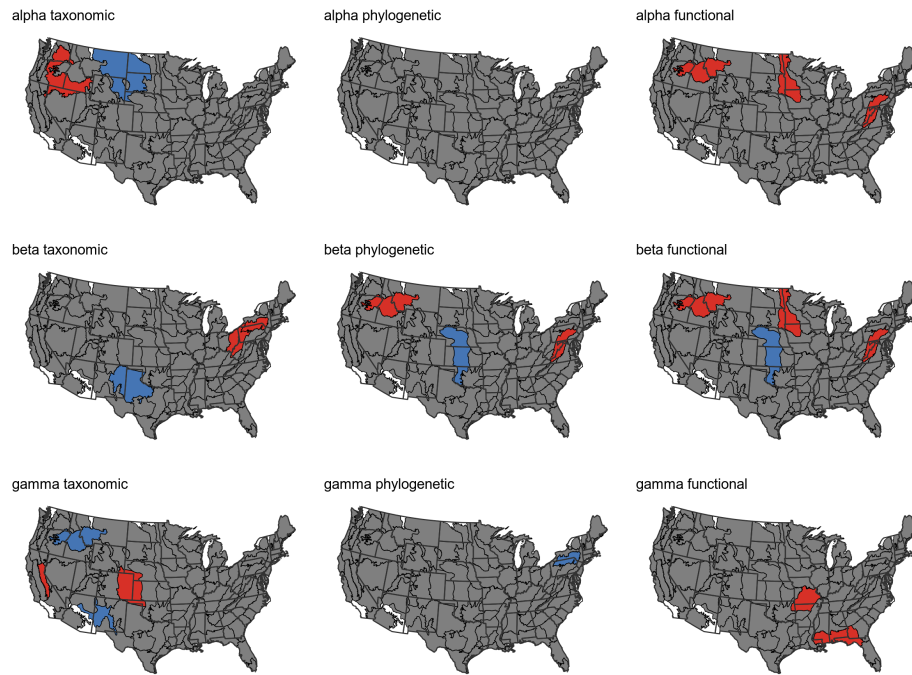


Figure S7b: Coefficients of geological age diversity on bird diversity, nonzero regions shown

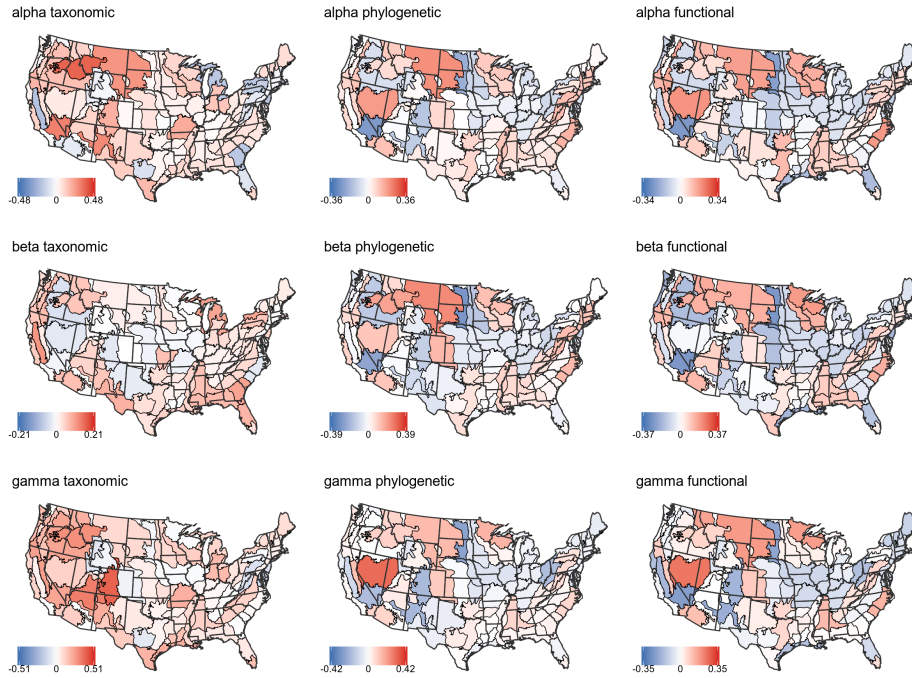


Figure S8a: Coefficients of soil type diversity on bird diversity, values shown

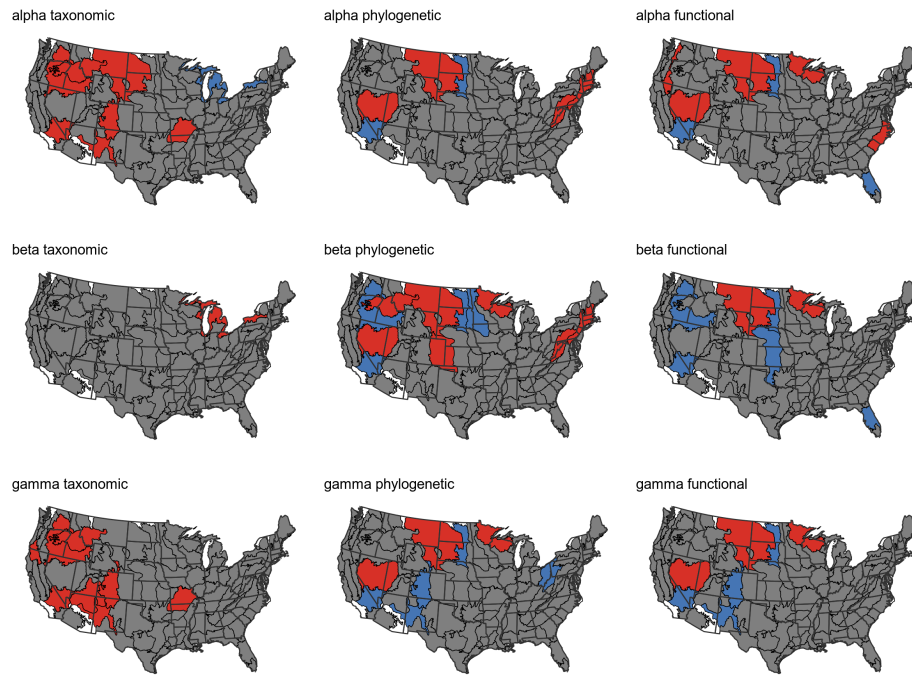


Figure S8b: Coefficients of soil type diversity on bird diversity, nonzero regions shown

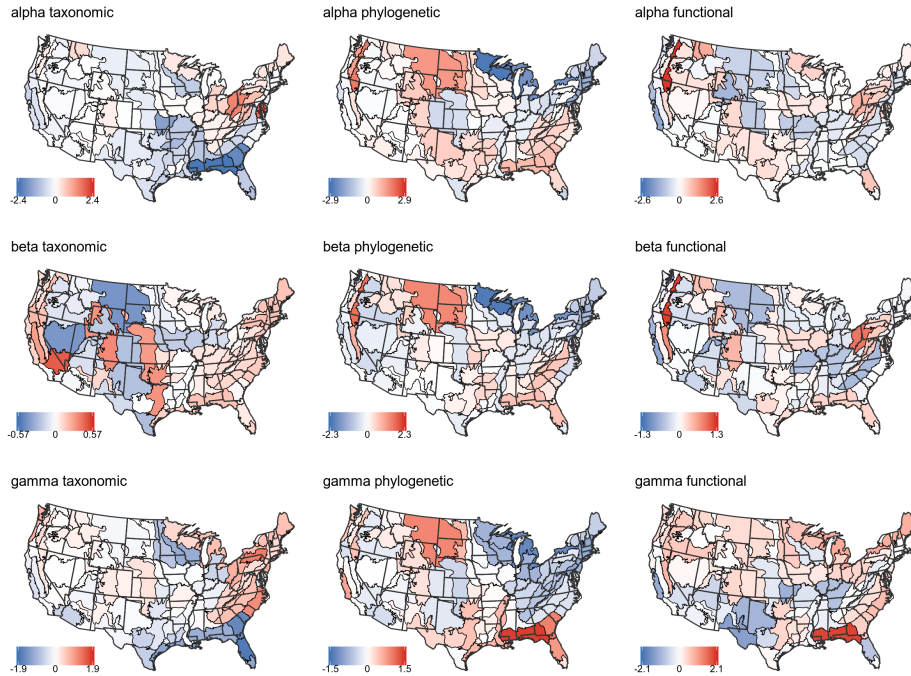


Figure S9a: Coefficients of mean annual temperature on tree diversity, values shown

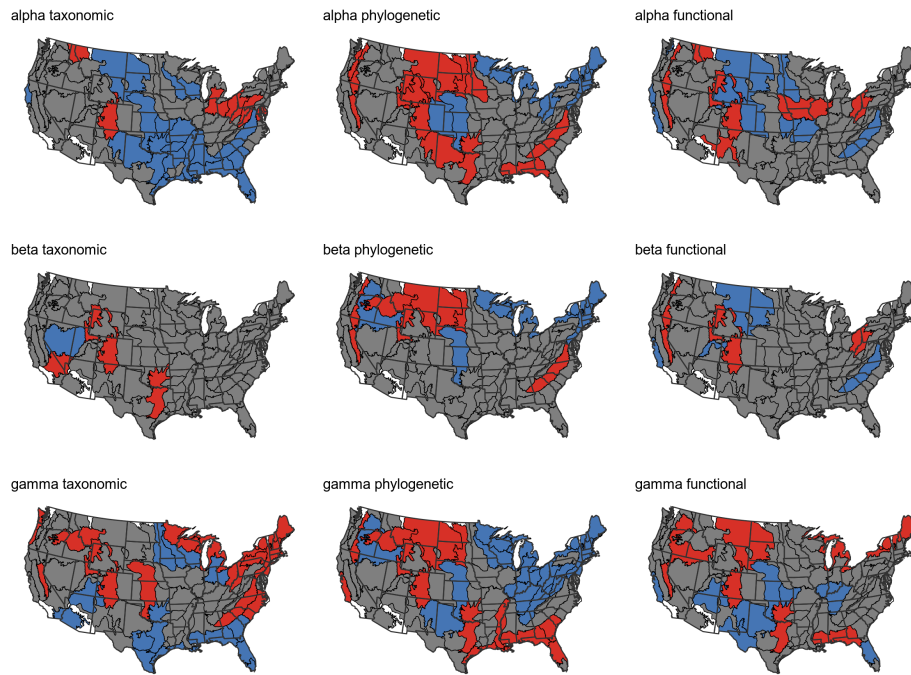


Figure S9b: Coefficients of mean annual temperature on tree diversity, nonzero regions shown

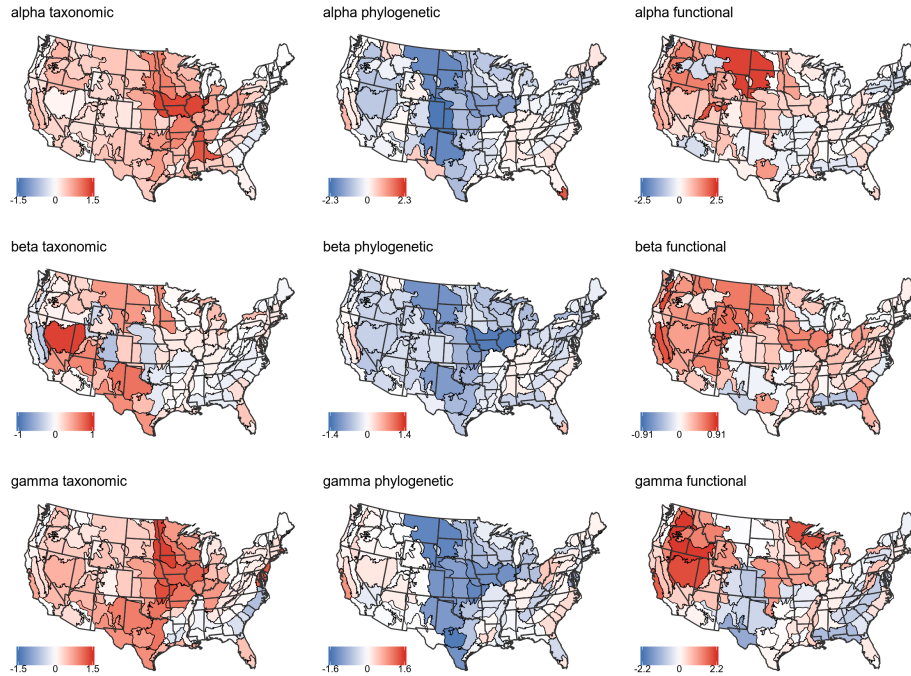


Figure S10a: Coefficients of mean annual precipitation on tree diversity, values shown

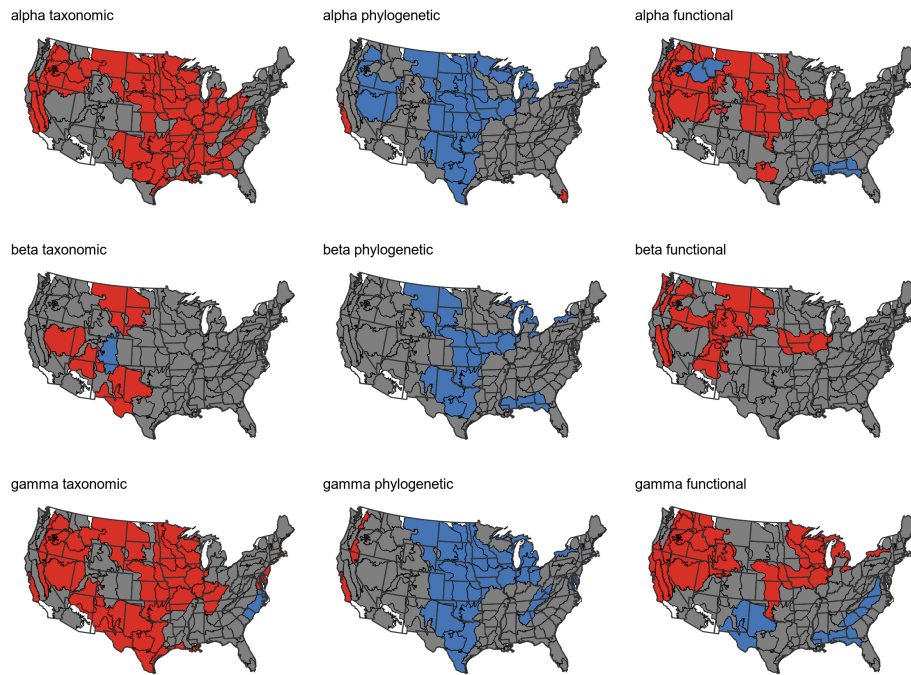


Figure S10b: Coefficients of mean annual precipitation on tree diversity, nonzero regions shown

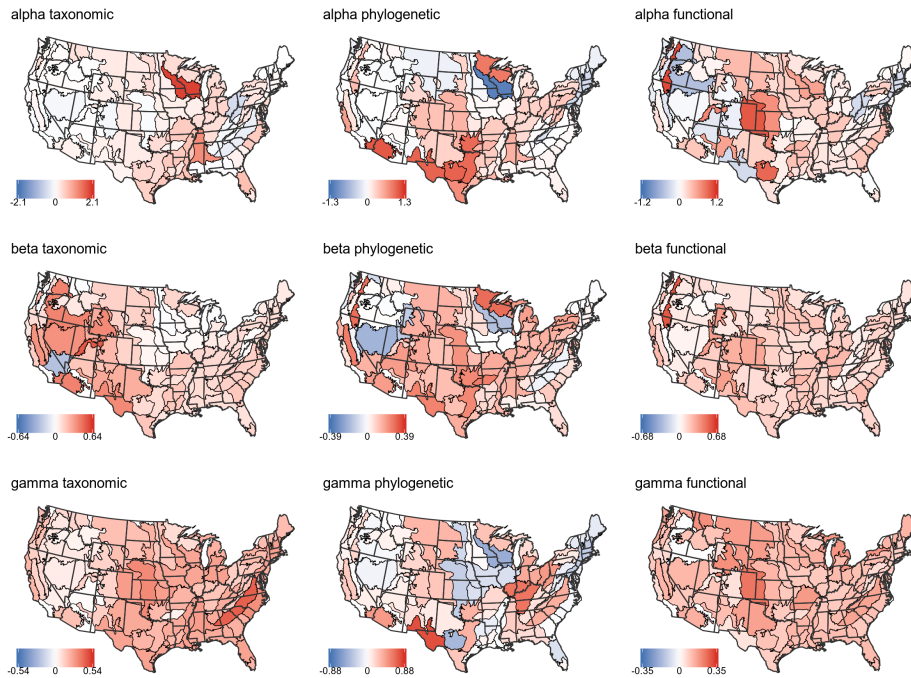


Figure S11a: Coefficients of elevation variability on tree diversity, values shown

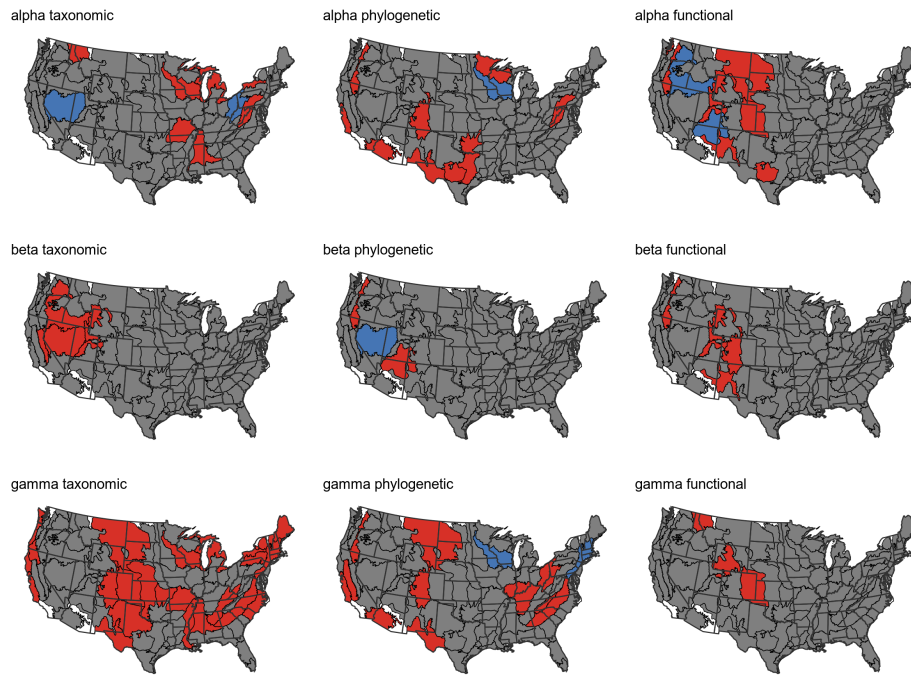


Figure S11b: Coefficients of elevation variability on tree diversity, nonzero regions shown

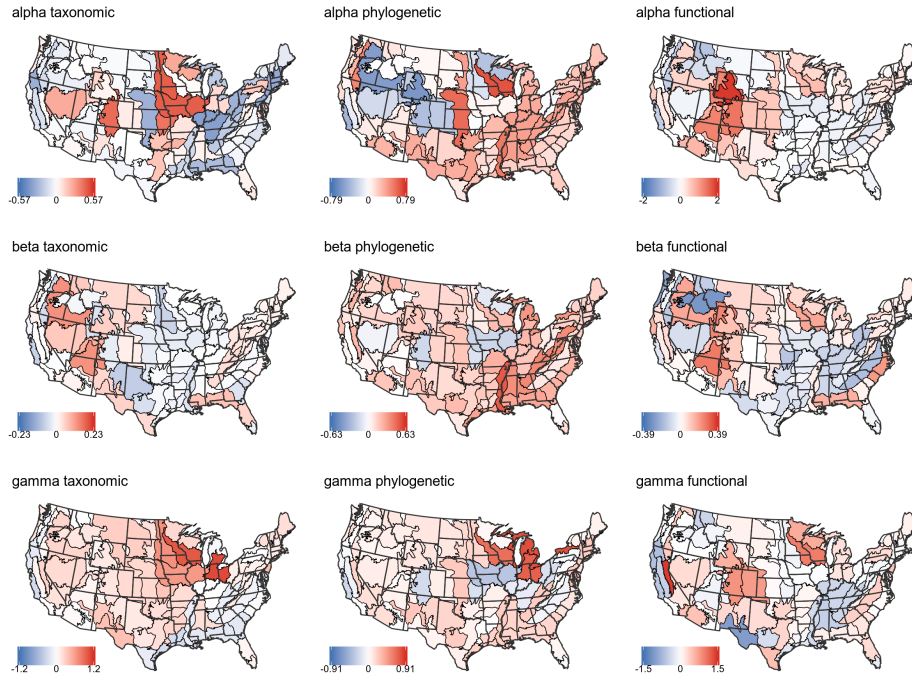


Figure S12a: Coefficients of GDP variability on tree diversity, values shown

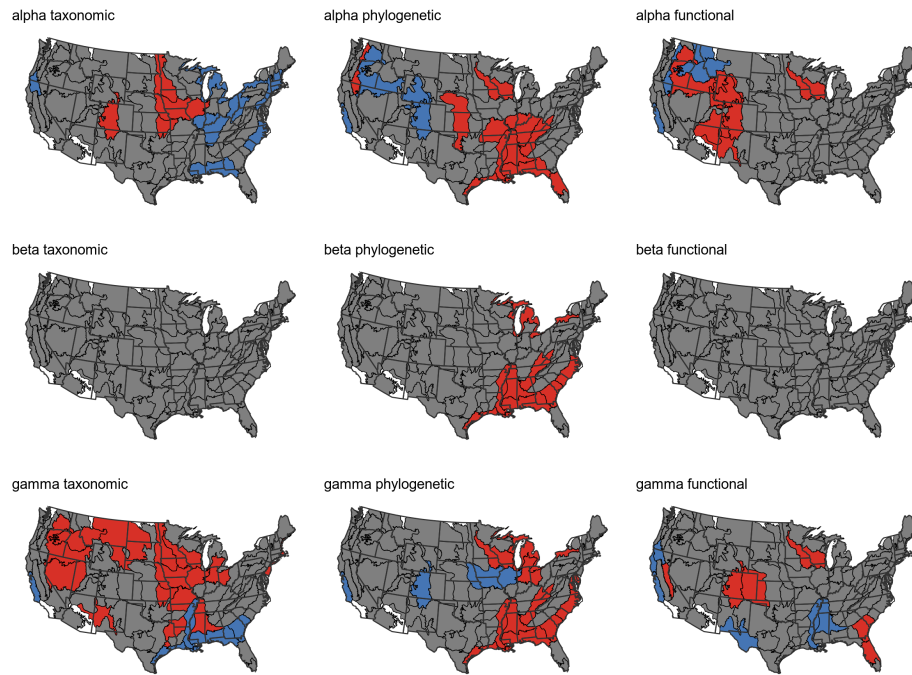


Figure S12b: Coefficients of GDP variability on tree diversity, nonzero regions shown

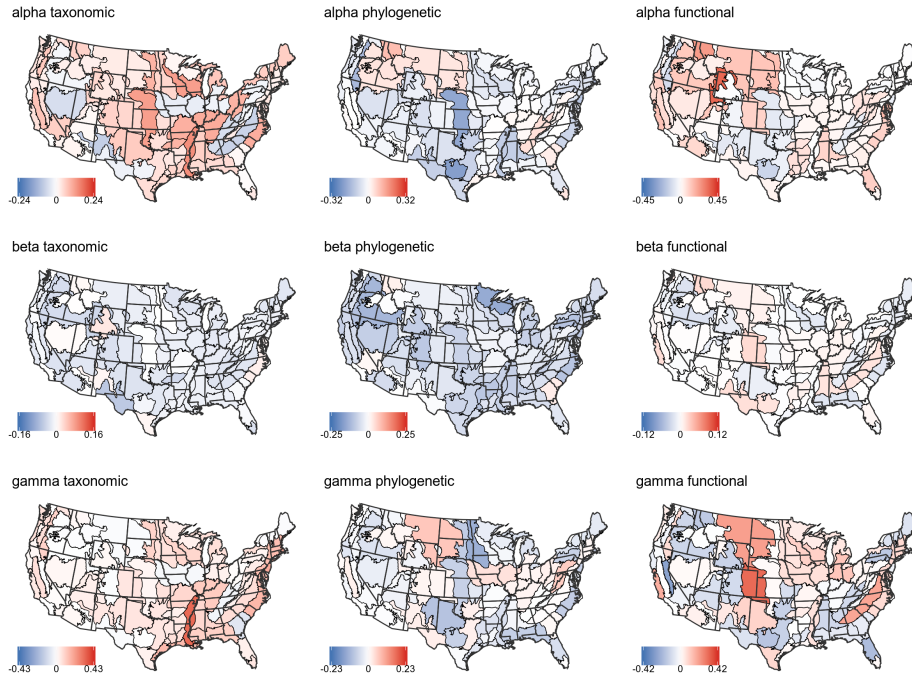


Figure S13a: Coefficients of geological age diversity on tree diversity, values shown

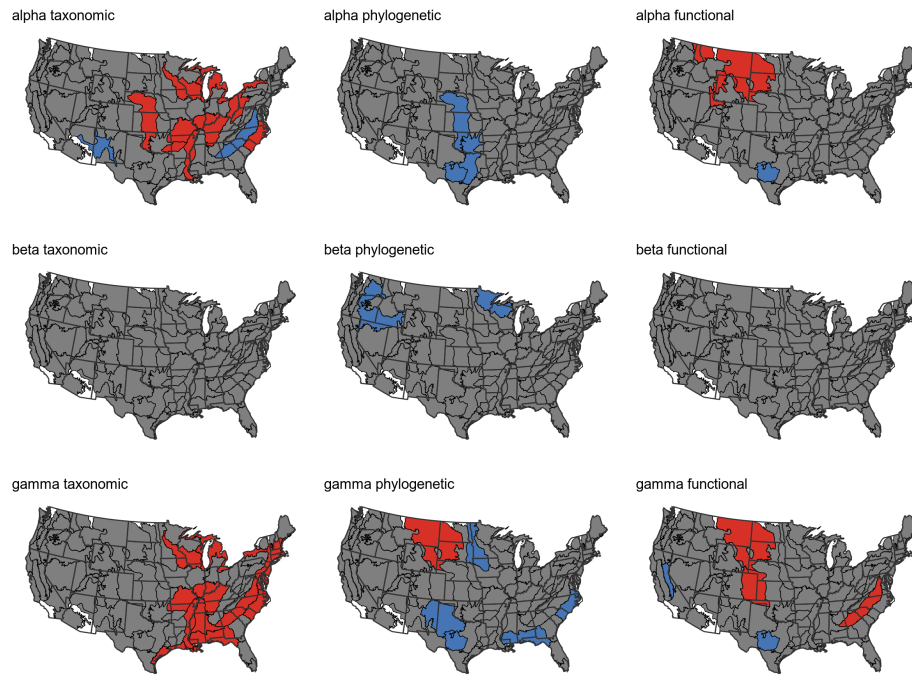


Figure S13b: Coefficients of geological age diversity on tree diversity, nonzero regions shown

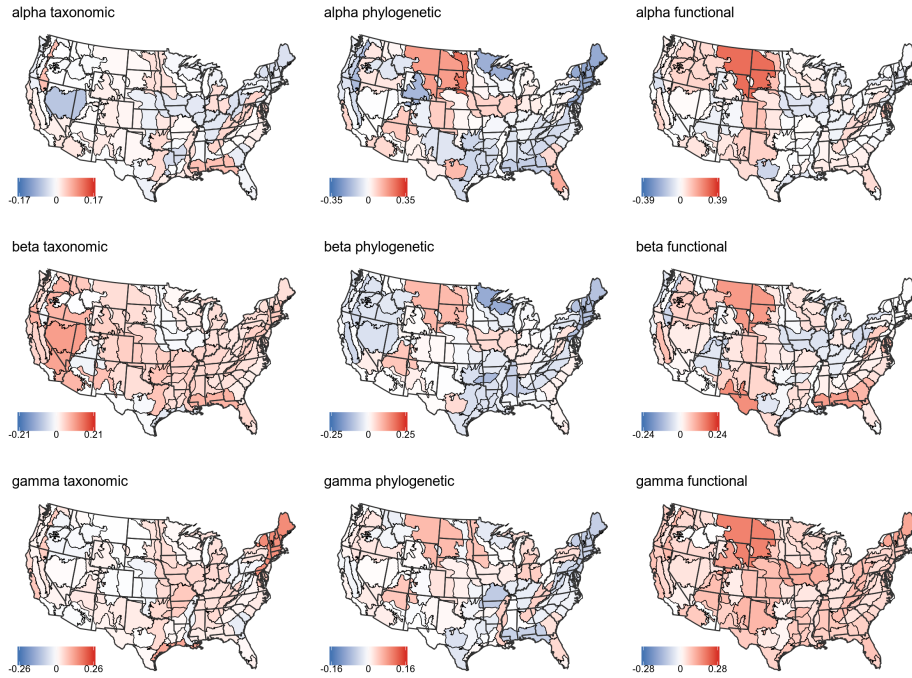


Figure S14a: Coefficients of soil type diversity on tree diversity, values shown

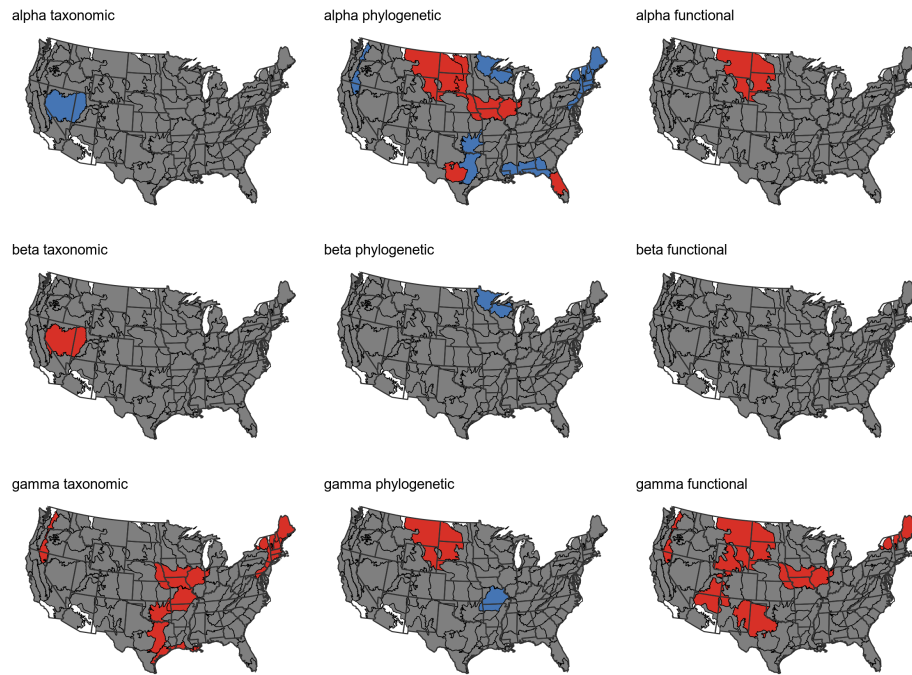


Figure S14b: Coefficients of soil type diversity on tree diversity, nonzero regions shown

Response to reviewers

***** Below we reproduce the reviewers' comments from the most recent round of peer review, with our responses to each individual comment printed in bold and preceded with ***.**

EDITOR'S COMMENTS TO AUTHORS

Editor: Bahn, Volker

Comments to the Author:

Thank you for your thorough revisions. You addressed most points well. Reviewer 1 only has some minor requests for changes in figures. Reviewer 2 and I are inclined to say that you did enough for a publishable manuscript but we both still have some reservations on the rigor and how you present your methodology and results. Please read over reviewer 2's comments carefully and see how far you can address them with reasonable effort.

To me one semantic issue remains (and I apologize if I didn't comment on that last iteration).

You use the terms "predictive power" and "explanatory power" loosely, maybe even interchangeably, when really they are strong terms with important, somewhat distinct meanings. Predictive power means the ability of a model to predict onto independent, new data (here locations). In a spatial model, this can only be tested on locations that were held out and are outside the reach of spatial autocorrelation to training locations. The blocked CV achieves that partly (there can still be some autocorrelated test locations close to the borders). However, using that technique you actually find that you don't have any predictive power. Explanatory power implies a causal relationship. To prove such a relationship again requires that you apply the claimed relationships in a new context. Resubstitution (training data = test data) does not allow to evaluate explanatory power. What you find out with resubstitution is goodness of fit. Or in other words, correlation does not imply causation. I'm not dogmatic about this. I think that simple models with low risk of overfitting paired with much data make a correlation free of any causation pretty unlikely. Unfortunately, it has been shown repeatedly that in particular in spatial data correlation without causation is not only possible, but has an elevated probability to happen because of coincidence of spatial structure. Therefore, to me the much more parsimonious interpretation of your results (see your great summary at the beginning of the Discussion starting L 380) is that there is little functional relationship between environmental variables and the different measures of diversity. The goodness-of-fit achieved in resubstitution models would then be a reflection of coincidence in spatial structure in these variables. This interpretation much more parsimoniously explains your "intriguingly context-dependent" relationships that vary so much among regions and dependent variables and the lack of predictive power as evaluated on independent test data than that all functional relationships happen to be idiosyncratic to ecoregions and measures of diversity.

I personally think that we are about to see a paradigm shift toward finding very little functional relationship between coarse environmental variables and diversity, and that your study is a strong contribution toward that paradigm shift, but you are trying to interpret it according to the old paradigm, that is propped up by countless studies correlating diversity (and distributions) with environmental variables. I will not abuse my power as editor to enforce that view upon you, and you have already made some space in the discussion for that viewpoint. I will leave it up to you to think about this one more time and do as you see fit with this thought. The same goes for the comments of reviewer 2.

1
2
3 ***** Thanks for your thoughts and interpretation. We agree that the body of work exploring**
4 **the relationship between biodiversity and environmental variables is top-heavy with**
5 **correlational studies and that there are few convincing demonstrations of mechanism.**
6 **Our work is no exception. However we do not agree that the explanation that there is**
7 **little or no functional relationship between coarse-scale environmental variables and**
8 **biodiversity is most parsimonious. From what we know about biology, we can derive**
9 **mechanistic hypotheses for large-scale environmentally-driven biodiversity trends from**
10 **first principles, and the many correlational studies support those hypotheses.**
11 **Furthermore, in noisy systems it is possible to mask true effects with conservative**
12 **statistical tests designed primarily to minimize Type I error.**
13

14
15 L 81: here you use explanatory power. In the abstract it was predictive power. Most of your
16 approaches don't evaluate either one. Explanatory power should be tested in a mechanistic
17 sense, ie the predictors need to be shown to have a process-based relationship to the
18 dependent variable. Predictive power needs to be evaluated by predicting onto independent
19 data, ie locations outside of SAC distance of training locations. What you are looking at is
20 goodness-of-fit.

21 L 303 That is actually assessing predictive performance and by implication explanatory power.

22 L 310 This only assesses goodness-of-fit, which need not be (but can be) related to explanatory
23 power. It can be purely correlational.

24 L 358 Again, fit best rather than explained most
25

26 Dr. Volker Bahn, Editor
27

28
29 ***** Thank you for your careful reading of the text. We have modified the text in the**
30 **abstract and at the four places in the main text that you noted to more carefully**
31 **distinguish between tests of predictive power and tests of goodness-of-fit.**
32

33 -----
34 REVIEWER COMMENTS TO AUTHORS
35

36 Referee: 1
37

38 Comments to the Author

39 Thank you for addressing my comments. I have gone through the revisions that the authors
40 have made and I am now satisfied with the manuscript. The only suggestion I would like to
41 make is to make small changes to some figures. Specifically, please increase the font in figures
42 2-4 because the scales are not legible.
43

44
45 ***** We increased the legend font size on Figures 2-4.**
46

47 Referee: 2
48

49 Comments to the Author

50 The authors made some efforts to respond to some of my concerns. Nevertheless, I am not
51 really convinced to some of the responses.
52

53 First, obviously my suggestion to use an additive response was not as simple as it appeared to
54 me. I understand that additive beta is correlated to gamma. But what happens if this beta is
55 scaled by gamma? What is the difference compared to a simple Sorensen-Index? From a
56
57
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59
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biological perspective, I want to know what is measured by the Sorensen-Index or any other index?

*** Thank you for your suggestion. We further tested our taxonomic beta-diversity model on the bird community data using the additive partition beta-diversity scaled by gamma-diversity (regional richness). The coefficients all had the same sign as the original Sorensen dissimilarity metric (see the figure below). The only difference in interpretation was that the credible intervals of the coefficients on elevation diversity and mean precipitation overlapped zero when the scaled additive beta-diversity was used for the response variable, though they did not for the dissimilarity beta-diversity. The broad overall similarity between the two sets of coefficients reassuringly indicates that the dissimilarity and additive partitioning metrics (when correctly scaled to remove dependence on gamma-diversity) are likely measuring the same latent variable -- the among-community variation. Therefore, we feel that we have thoroughly investigated the possibility of using additive partition beta-diversity and that it would not yield additional insight to include in the manuscript.

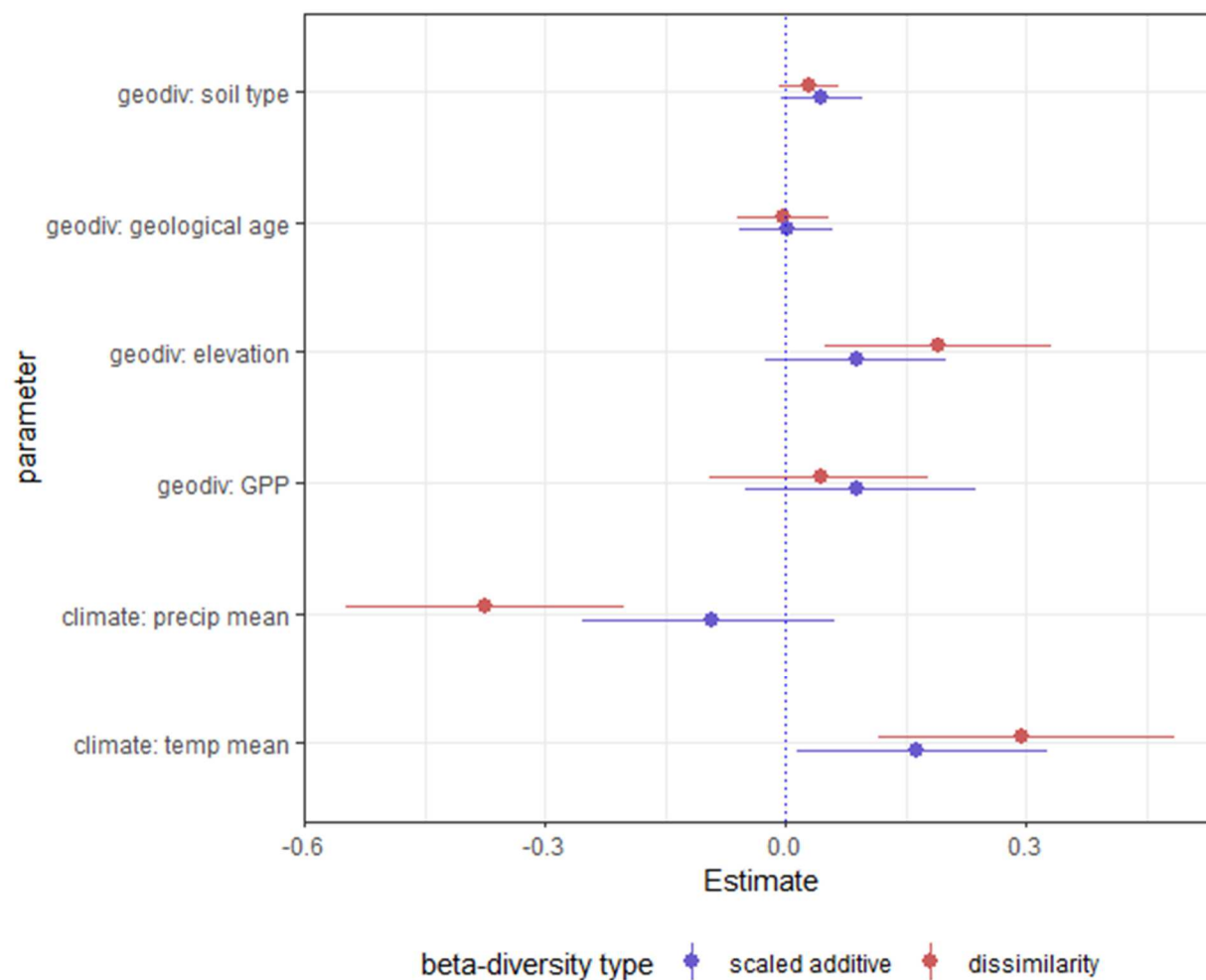


Figure: Comparison of standardized regression coefficients on predictors of taxonomic bird beta-diversity, using two different types of beta-diversity. The dissimilarity type is

1
2
3 *the one used in the manuscript. Error bars represent 95% credible intervals around the*
4 *parameter estimates.*
5

6 To explain the biological meaning of our chosen beta-diversity index, we added text at
7 line 193 as follows:
8

9
10 **“The Sørensen dissimilarity index represents the degree to which pairs of**
11 **communities differ from one another in their species composition, independent of**
12 **their species richness, and encompasses both species turnover and nestedness**
13 **components of beta-diversity. This contrasts with beta-diversity indices based on**
14 **multiplicative or additive partitions of alpha- and gamma-diversity (Anderson et al.**
15 **2011).”**
16

17 Furthermore, I am still not happy of replacing zeros and ones of the beta-diversity in the tree
18 data. It is very difficult to evaluate the effect of the arbitrary decision. 16 % of all tree sites have
19 values of zero and 1. That's a lot! What happens if we exclude such zeros and ones from the
20 analysis? One might argue, if you have no beta-diversity at all (zeros) we have nothing to
21 predict.
22

23
24 ***** Thank you for your comment. As you suspect, since there are a large proportion of 0**
25 **and 1 values for tree beta-diversity, the model results are indeed sensitive to whether we**
26 **exclude the values or adjust them. However, we disagree with the statement that no beta-**
27 **diversity means that there is nothing to predict. A zero value of beta-diversity means that**
28 **there is no species turnover among the focal plot and its neighbors, and a value of one**
29 **indicates that no species are shared among the plots (complete turnover). It is important**
30 **to note that 0 beta-diversity does not mean no species were present, it simply means the**
31 **species are identical among the communities under consideration. FIA plots with no**
32 **trees were not considered in our analysis. Because the 0 and 1 values represent true**
33 **biological phenomena, extreme points on the continuum between no turnover and**
34 **complete turnover, we were also interested in understanding which environmental**
35 **factors are associated with locations where no turnover or complete turnover occurs.**
36 **Therefore, we determined that adjusting the 0 and 1 values was the best of the imperfect**
37 **options available to us.**
38

39
40 Second, I am still not happy about the procedures to estimate functional diversity. It was clear to
41 me that morphological data of relevant traits are not available in books or data banks. But I am
42 convinced that it would have been possible (of course with a little bit of effort) to measure the
43 relevant traits of bill, legs, tail and wings at museum specimen. With such data at hand the
44 authors would have the possibility to retrieve a rich picture of the functional diversity.
45

46 ***** Thank you for your suggestion. Unfortunately collecting bird morphological trait data**
47 **spanning the United States was outside the scope of our study, but we agree that this**
48 **would be a fascinating avenue for future research that would yield a better**
49 **understanding of patterns of variation in relevant bird functional traits.**
50

51 Furthermore, the author checked the impact of the correlation of several of their data used to
52 estimate functional diversity with body size by correlating a distance matrix using a reduced set
53 of variables to the original matrix. They found a high matrix correlation. To my opinion this is not
54 the test needed; to my feeling this test shows only that these traits do not measure new aspects
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of the functional diversity. Why using them at all? An appropriate way of removing body size is to regress these variables on body size and to use the residuals for further calculations.

***** While we agree with the sentiment behind this comment, we feel that the test we ran in response to your comments on the previous revision adequately addresses this point. (In that previous document, we compared the pairwise Gower functional distance matrices for all birds with and without the traits that were highly correlated with body size. A Mantel test shows that the two distance matrices were very highly correlated, with $r = 0.979$). While we agree that this could be interpreted as justification for removing the traits, we intended our functional diversity metrics to include all traits for which we had adequate data for most of the bird species in our dataset. Our functional diversity metrics appear to be robust to the inclusion or exclusion of a small number of correlated traits among the set of possible traits, so we do not feel that any additional insight into important biological patterns can be gained by continuing to test out other possible trait combinations or scaling the morphological traits by body size.**

Nevertheless, after the revisions the paper has matured to an interesting contribution, although I am not always convinced by the theoretical predictions, data, procedures and results. Particularly some of the predictions in the introduction are not really informative. For example, that different measures of biodiversity have different relationships to geodiversity is to my opinion a bit empty. Different measures are different by definition and should have different relationships. But the finding that the relationships between biodiversity and climate as well as geodiversity is context dependent is an important message that might caution the increasing tendency to rely too much on remote sensing to predict biodiversity.

***** Thank you for your comment. We agree that the prediction that different dimensions of biodiversity should have different relationships with geodiversity may seem trivial. Our motivation for including this prediction was essentially rhetorical: we noticed that many conservation organizations are advancing the idea that “we must conserve geodiversity to conserve biodiversity.” However, it is probable that focusing conservation efforts on geodiversity would only have a positive effect on conserving some aspects of biodiversity, and a neutral or even negative effect on other aspects. As you note, the various dimensions of biodiversity are inherently different by definition, and many of them are orthogonal to one another. In summary, we included this prediction primarily to underscore the context-dependence for readers and to make the point that this context-dependence has consequences for conservation such that the blanket statement that “geodiversity = biodiversity” is inadequate.**

We added text to the introduction section of the manuscript to emphasize this point (lines 79-83):

“Furthermore, conservation frameworks, including CNS, typically advance the idea that conserving geodiversity will result in positive outcomes for biodiversity writ large (Beier & de Albuquerque 2015). This assumption must be tested empirically, especially given potential tradeoffs among orthogonal dimensions of biodiversity within and among taxa: conserving one aspect of biodiversity might have a neutral or even negative effect on other aspects.”

Beyond counts and averages: relating geodiversity to dimensions of biodiversity

Running title: Geodiversity across dimensions of biodiversity

Abstract

Aim

We may be able to buffer biodiversity against the effects of ongoing climate change by prioritizing the protection of habitat with diverse physical features (high geodiversity) associated with ecological and evolutionary mechanisms that maintain high biodiversity. Yet, the relationships between biodiversity and habitat vary with spatial and biological context. In this study we compare how well habitat geodiversity — spatial variation in abiotic processes and features — and climate explain biodiversity patterns of birds and trees. We also evaluate the consistency of biodiversity-geodiversity relationships across ecoregions.

Location

Contiguous United States

Time period

2007-2016

Major taxa studied

Birds, trees

Methods

We quantified geodiversity with spatially-continuous remotely-sensed data and generated biodiversity maps from the Forest Inventory and Analysis and Breeding Bird Survey datasets. We fit separate multivariate regressions to alpha-, beta-, and gamma-diversity, accounting for

23 spatial autocorrelation among Nature Conservancy ecoregions and relationships among. ~~The~~
24 ~~response variables for each model were~~ taxonomic, phylogenetic, and functional biodiversity.
25 We fit models including climate alone (temperature, precipitation), geodiversity alone
26 (topography, soil, geology), and climate + geodiversity.

27 Results

28 A combination of geodiversity and climate ~~predicted predictor variables fit~~ most forms of bird
29 and tree biodiversity with less than 10% relative error. Models using geodiversity and climate
30 performed better for local (alpha) and regional (gamma) diversity than turnover-based (beta)
31 diversity. Among geodiversity predictors, variability of elevation ~~predicted fit~~ biodiversity best;
32 interestingly, topographically diverse places tended to have higher tree diversity but lower bird
33 diversity.

34 Main conclusions

35 Although climatic predictors tended to have larger individual effects than geodiversity, adding
36 geodiversity improved climate-only models of biodiversity ~~for both taxa~~. Geodiversity ~~predicted~~
37 was correlated with biodiversity more consistently than climate across ecoregions, but models
38 tended to have poor ~~predictive accuracy fit~~ in ecoregions held out of the training dataset. ~~With~~
39 ~~ongoing climate change, ecoregion-scale geodiversity could help prioritize conservation regions~~
40 ~~for U.S. tree and bird biodiversity~~ Patterns of geodiversity could help prioritize conservation
41 efforts within ecoregions. However, we need to understand the underlying mechanisms more
42 fully before we can build models transferable across ecoregions.

43 Keywords

44 biodiversity, geodiversity, Breeding Bird Survey (BBS), Forest Inventory and Analysis (FIA),
45 alpha-diversity, beta-diversity, gamma-diversity, ~~phylogenetic diversity, functional diversity,~~
46 richness conservation

47 Introduction

48 In the face of an ongoing sixth mass extinction, society is challenged to minimize biodiversity
49 loss through conservation efforts (Ceballos *et al.* 2015). While many conservation policies and
50 strategies focus on conserving particular species (e.g., the United States Endangered Species
51 Act, the International Union for Conservation of Nature Red List), there is growing interest in
52 broadening conservation to include preserving parcels of Earth's surface that promote diversity
53 even as species shift their ranges in response to climate change (Beier & de Albuquerque
54 2015). For example, The Nature Conservancy (TNC) prioritizes preserving areas with high
55 geodiversity — variation in Earth's abiotic processes and features — through their 'Conserving
56 Nature's Stage' (CNS) campaign (Beier & de Albuquerque 2015). Conserving nature's stage
57 requires a firm understanding of biodiversity-geodiversity relationships, yet we know little about
58 how these relationships vary across space, among taxa, and across different dimensions of
59 biodiversity (Zarnetske *et al.* 2019). Addressing this knowledge gap is key to advancing
60 conservation prioritization.

61 Geodiversity represents natural variation in geologic, geomorphic, and soil features (Gray 2004,
62 2008) and can be measured in a variety of ways. Most studies focus on elements of topography
63 (roughness, elevation, slope and aspect), geology (geologic diversity, landscape complexity),
64 soils (pH, organic matter, nutrient availability), or hydrology (variation of hydrological features
65 such as rivers, ponds and lakes; Hjort *et al.* 2012; Wang *et al.* 2013; Kaskela *et al.* 2017). Some
66 geodiversity definitions include climate, using variables such as temperature, precipitation,
67 evapotranspiration, water balance, and solar radiation, while others explicitly exclude climate
68 from their definition (Gray 2004; Parks & Mulligan 2010; Tukiainen *et al.* 2017). A
69 comprehensive definition of geodiversity includes all abiotic features and processes found within
70 Earth's atmosphere, lithosphere, hydrosphere, and cryosphere (Record *et al.* in press;
71 Zarnetske *et al.* 2019).

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3 72 Abiotic variation may promote increased variety of available niches for organisms (Tews *et al.*
4
5 73 2004), and high geodiversity is likely to indicate biodiversity hotspots (Lawler *et al.* 2015, but
6
7 74 see Noss *et al.* 2014). However, little is known about how geodiversity of Earth's surface
8
9 75 compares to climate in explaining variation in biodiversity, whether relationships generalize
10
11 76 across geographic locations, and what types of biodiversity have the closest relationship with
12
13 77 geodiversity. Despite the potential importance of geodiversity for explaining patterns of
14
15 78 biodiversity, models explaining patterns of biodiversity rarely include geodiversity (Bailey *et al.*
16
17 79 2018). Furthermore, conservation frameworks, including CNS, typically advance the idea that
18
19 80 conserving geodiversity will result in positive outcomes for biodiversity writ large (Beier & de
20
21 81 Albuquerque 2015). This assumption must be tested empirically, especially given potential
22
23 82 tradeoffs among orthogonal dimensions of biodiversity within and among taxa: conserving one
24
25 83 aspect of biodiversity might have a neutral or even negative effect on other aspects. In this
26
27 84 study, we use bird and tree occurrence data and remotely-sensed environmental data from
28
29 85 across the United States to increase our understanding of biodiversity-geodiversity
30
31 86 relationships. Geodiversity, in conjunction with climate, predicts patterns of species diversity of
32
33 87 plants (Tukiainen *et al.* 2017; Bailey *et al.* 2018) and animals (Parks & Mulligan 2010; Alahuhta
34
35 88 *et al.* 2018) across disparate biomes. Informed by these previously documented patterns, our
36
37 89 **Prediction 1** is that combining geodiversity and climate predictors will significantly **increase**
38
39 90 **improve** the ~~explanatory power~~goodness-of-fit of models explaining biodiversity of birds and
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41 91 trees.
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45

46 92 Recent work shows that the biodiversity-geodiversity relationship depends on spatial grain and
47
48 93 extent (Bailey *et al.* 2017; Zarnetske *et al.* 2019). Nevertheless, most studies have focused on
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50 94 alpha-diversity (local diversity) measured within a plot. In contrast, most large-scale mapping
51
52 95 studies characterizing diversity have equated diversity with gamma-diversity, or the size of the
53
54 96 regional species pool (Currie & Paquin 1987; Jenkins *et al.* 2015). Only a few have accounted
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1
2
3 97 for the three *levels* of biodiversity: alpha-diversity, beta-diversity (turnover among plots) and
4
5 98 gamma-diversity (Meynard *et al.* 2011; Gossner *et al.* 2013). Beta-diversity represents
6
7 99 compositional turnover among local communities, linking local diversity (alpha-diversity) to
8
9 100 regional species pools (gamma-diversity). We expect that the relationship between geodiversity
10
11 101 and beta- and gamma-diversity will be stronger than alpha-diversity, because high geodiversity
12
13 102 often reflects high diversity of habitats within regions and therefore more unique local species
14
15 103 assemblages (Stein *et al.* 2014). This leads to **Prediction 2**: Geodiversity will explain more
16
17 104 variability in the beta and gamma levels of biodiversity than alpha-diversity.
18
19

20
21 105 The relationship between geodiversity and biodiversity may also vary with the *dimensions* of
22
23 106 biodiversity (taxonomic, functional and phylogenetic diversity). Targeting functional and
24
25 107 phylogenetic diversity is especially important for conserving unique ecological function (Steudel
26
27 108 *et al.* 2016) and evolutionary history (Davis *et al.* 2018) in the face of the current biodiversity
28
29 109 crisis. Because phylogenetic (Winter *et al.* 2012) and functional (Lamanna *et al.* 2014)
30
31 110 biodiversity are explicitly linked to different ecological and evolutionary mechanisms, they may
32
33 111 provide deeper insight into ecological and evolutionary processes that underlie regional
34
35 112 variation in diversity. However, few studies of geodiversity have investigated these multiple
36
37 113 dimensions of biodiversity (Meynard *et al.* 2011); most studies have considered only taxonomic
38
39 114 diversity (e.g., Safi *et al.* 2011; Stevens & Gavilanez 2015). Because each dimension of
40
41 115 biodiversity represents a unique mechanistic connection with the environment, we predict
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43 116 **(Prediction 3)** that the different dimensions of biodiversity will have different relationships with
44
45 117 geodiversity.
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49 118 Relationships between dimensions of biodiversity and geodiversity vary across geographic and
50
51 119 environmental space. In some areas and environmental contexts, one form of geodiversity
52
53 120 might be a more reliable predictor of biodiversity than elsewhere. For example, topographic
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55 121 complexity generates a diversity of climatic conditions at small to intermediate spatial scales
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3 122 ranging from meters (Bennie *et al.* 2008) to tens of kilometres (Badgley *et al.* 2017), which may
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5 123 buffer species against local extinctions as climate warms (Dobrowski 2011; Lenoir *et al.* 2013).
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7 124 Such buffering is, however, conditional on climatic context: if an entire landscape is far outside
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9 125 of the physiological range of tolerance for some taxonomic or functional groups, geodiversity is
10
11 126 likely to be unimportant for maintaining local biodiversity. For example, along the central
12
13 127 California coast, land and ocean surface temperatures contrast strongly and there is high
14
15 128 heterogeneity in topography and associated cloud and fog patterns. Such conditions support
16
17 129 relatively high local richness of tree species (Barbour *et al.* 2007). Inland, in contrast, the
18
19 130 average climate of the Coast Range is more arid and fog is absent (Ackerly *et al.* 2010), so only
20
21 131 the coolest facets of the landscape support any level of tree cover. In this context, topographic
22
23 132 heterogeneity is still associated with higher tree diversity, but the relationship is likely to be
24
25 133 weaker. For these reasons, we predict (**Prediction 4**) that the influence of different geodiversity
26
27 134 predictors on biodiversity will vary across ecoregions. In particular, mountainous ecoregions
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29 135 with more mesic climates will have more positive relationships between topographic diversity
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31 136 and biodiversity than more arid mountain ranges.
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36 137 In this study, we use bird and tree occurrence data and remotely-sensed environmental data
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38 138 from across the United States to increase our understanding of biodiversity-geodiversity
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40 139 relationships. We make the following predictions:

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42 140 (1) Geodiversity will significantly increase the explanatory power of models explaining
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44 141 biodiversity of birds and trees.
- 45
46 142 (2) Geodiversity will explain more variability in beta- and gamma-diversity than alpha-
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48 143 diversity.
- 49
50 144 (3) The different dimensions of biodiversity will have different relationships with geodiversity.
- 51
52 145 (4) The influence of different geodiversity predictors on biodiversity will vary across
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54 146 ecoregions.
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147 Methods

148 We used multivariate linear mixed models with spatial random effects to determine which
149 geodiversity predictors explain the most variation across the levels and dimensions of bird and
150 tree biodiversity in the contiguous U.S. We used biodiversity and geodiversity data collected
151 from 2007-2016.

152 Breeding Bird Survey (BBS)

153 The North American Breeding Bird Survey (BBS, <https://www.pwrc.usgs.gov/bbs/>) is an annual
154 survey of breeding birds across the U.S. and Canada begun in 1966. Volunteer observers report
155 species and counts of birds seen or heard during 3-minute observations at 50 stops spaced
156 every ~800 m along routes ~39.4 km in length (Sauer *et al.* 2013). There are ~3480 active
157 routes in the contiguous U.S. with continuous yearly stop-level data. We excluded any routes
158 with an ambiguous midpoint coordinate (discontinuous transects), leaving 3089 routes. We
159 included only the surveys conducted under the standard protocol, discarding repeat surveys and
160 any observations recorded by trainees.

161 Forest Inventory and Analysis (FIA)

162 The U.S. Department of Agriculture Forest Service's Forest Inventory and Analysis program
163 (FIA) surveys the composition and status of forests throughout the United States, with data
164 collected annually (Bechtold *et al.* 2005). Each FIA plot consists of four 7.2-m fixed radius
165 subplots. Plots are spaced roughly on a 5-km grid across forested land. Each plot is surveyed
166 approximately every 5 years (Bechtold *et al.* 2005). Each tree is identified to species. We
167 obtained the most recent survey from all forested, non-plantation FIA plots in the contiguous
168 United States (119,177 plots). Some plots in the Pacific Northwest Region included a larger

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3 169 “macroplot” around the central subplots; we excluded any trees outside the subplot boundary.
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5 170 The year of the most recent survey varied between 2012 and 2016.
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8 171 Phylogenetic and Trait Data 9

10
11 172 We obtained phylogenetic trees and compiled trait information for all bird and tree species in the
12
13 173 BBS and FIA databases, respectively, and used them to calculate the distance-based
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15 174 phylogenetic and functional diversity indices described below. See Appendix 1 for additional
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17 175 details.
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20 21 176 Calculation of Biodiversity Metrics 22

23
24 177 For both tree and bird communities, we calculated biodiversity metrics based on species
25
26 178 presence at the site level (here defined as a single FIA plot or BBS route). For trees in FIA, we
27
28 179 used the most recent survey as a single time point for each site, as there is little turnover in
29
30 180 species composition between surveys and the probability of imperfect detection is low. To
31
32 181 minimize the effects of imperfect bird detection in the BBS survey, we pooled observations from
33
34 182 all stops in each route and pooled all surveys from 2007-2016. See Appendix 2 for additional
35
36 183 details.
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40 184 We calculated alpha-, beta-, and gamma-diversity (referred to as *levels* of biodiversity) within a
41
42 185 circle of 50 km radius around each site, originating at the centre of the FIA plot or midpoint of
43
44 186 the BBS route. We defined any BBS route whose midpoint fell within the 50-km circle around
45
46 187 the focal route midpoint to be a neighbour route (see Appendix 2). We took (1) the median
47
48 188 diversity of all sites in the radius, including the focal site (alpha), (2) the median pairwise
49
50 189 diversity of all pairs of sites in the radius, including the focal sites (beta), and (3) the aggregated
51
52 190 diversity of all sites in the radius (gamma). Each diversity *level* has three *dimensions*:
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54 191 taxonomic, phylogenetic, and functional (Table S1). For taxonomic diversity, alpha-diversity and
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3 192 gamma-diversity were represented by species richness and beta-diversity by pairwise Sørensen
4
5 193 dissimilarity. The Sørensen dissimilarity index represents the degree to which pairs of
6
7 194 communities differ from one another in their species composition, independent of their species
8
9 195 richness, and encompasses both species turnover and nestedness components of beta-
10
11 196 diversity. This contrasts with beta-diversity indices based on multiplicative or additive partitions
12
13 197 of alpha- and gamma-diversity (Anderson et al. 2011). To quantify phylogenetic diversity, we
14
15 198 calculated mean pairwise phylogenetic distance (MPD) of each community with the R package
16
17 199 *picante* (Kembel *et al.* 2018). We randomized the phylogenetic distance matrix 999 times and
18
19 200 calculated the z-score of the observed phylogenetic distances relative to the distribution of
20
21 201 phylogenetic distances of the randomized matrices to remove dependence on richness.
22
23 202 Similarly, we calculated a distance-based metric of functional diversity by finding the Gower
24
25 203 distance between the trait values for all possible species pairs, and then calculating the mean
26
27 204 pairwise distance among all pairs of species in each community and its z-score. Because the
28
29 205 BBS surveys poorly estimate abundances of some species, we calculated incidence-based
30
31 206 biodiversity metrics for both birds and trees so that metrics are comparable between the two
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33 207 taxa.

34 35 36 37 38 208 Geodiversity Data Sources and Processing

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41 209 We obtained and processed remotely-sensed data for the contiguous United States to generate
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43 210 geodiversity and climate data layers. Remotely-sensed geodiversity variables are particularly
44
45 211 valuable in disentangling the independent effects of climate and geodiversity. Many biodiversity
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47 212 analyses use climatic data products that interpolate weather station data using elevation, e.g.
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49 213 Worldclim v.1 (Hijmans *et al.* 2005). Using elevation to derive temperature values makes it
50
51 214 difficult to evaluate independent contributions from climate and topography (Körner 2007).
52
53 215 Remotely-sensed temperature represents the temperature of the land surface, in contrast with
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55 216 weather stations that measure air temperature several meters above ground level (Bechtel

1
2
3 217 2015). In areas with very sparse coverage of meteorological stations and/or complex
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5 218 topography, the error introduced by interpolating between ground stations may be large. In
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7 219 many regions, especially grasslands, shrublands, and croplands, surface temperature shows
8
9 220 large systematic deviations from air temperature (Mildrexler *et al.* 2011). What is more, studies
10
11 221 have shown that surface temperature may be more ecologically relevant than air temperature
12
13 222 (Pau *et al.* 2013; Still *et al.* 2014). The thermodynamic temperature of an organism, which drives
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15 223 its respiration rate and vapor pressure deficit, is more closely related to the surface temperature
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17 224 than the surrounding air temperature. Remotely-sensed data products provide spatially
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19 225 continuous, independent, and direct measures of climate and geodiversity for use in biodiversity
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21 226 models.

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25 227 We generated predictors from the following remotely-sensed data products: elevation from
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27 228 SRTM (Farr *et al.* 2007), land surface temperature from MODIS MOD11A2 (Wan *et al.* 2015),
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29 229 precipitation from CHIRPS (Funk *et al.* 2015), and gross primary productivity (GPP) dynamic
30
31 230 habitat index from MODIS (Hobi *et al.* 2017). We generated additional predictors from non-
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33 231 remotely-sensed products including soil type category from SoilGrids (Hengl *et al.* 2017), which
34
35 232 uses remotely-sensed data to interpolate ground-based measurements, and geologic age
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37 233 category from USGS International Surface Geology. We included GPP because spatial
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39 234 variability in GPP integrates many geodiversity variables known to influence biodiversity via
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41 235 resource availability (Austin & Smith 1989; Alahuhta *et al.* 2018). GPP spatial variability is
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43 236 moderately correlated with mean annual precipitation but largely orthogonal to the other
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45 237 geodiversity variables we chose (Figure 1), indicating that it may capture additional spatial
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47 238 variation not accounted for by the other three geodiversity variables. See Appendix 3 for
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49 239 additional details.

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53 240 We coarsened all environmental data layers by calculating the means within 25 km² pixels to
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55 241 equal the coarsest resolution of any layer, then we aggregated all geodiversity and biodiversity

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3 242 variables within a 50-km radius around the centre of each FIA plot and the midpoint of each
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5 243 BBS route. The 50-km scale of aggregation averages over a wide range of microhabitats and
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7 244 microclimates, capturing the geodiversity-biodiversity relationship at a coarse spatial grain; it is
8
9 245 possible that a smaller grain of analysis would reveal different patterns (Zarnetske *et al.* 2019).
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11 246 For continuous predictors, we calculated the mean of all pixels partially or wholly in the 50-km
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13 247 radius, and we used the mean terrain ruggedness index (TRI; Wilson *et al.* 2007) of the 3×3
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15 248 pixel neighbourhood around all pixels to represent spatial variability. For discrete predictors, we
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17 249 used Shannon entropy of all pixels in the radius to represent spatial variability. Shannon entropy
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19 250 has been shown to monotonically increase with increasing number of landscape patch types, to
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21 251 behave consistently in both real and simulated landscapes, and to correlate positively with many
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23 252 other measures of landscape heterogeneity (Peng *et al.* 2010). Importantly, while many past
24
25 253 studies have used variables extracted from spatially continuous layers at points to characterize
26
27 254 environmental variation, we explicitly consider spatial variation in the regions around the points
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29 255 where biodiversity was measured. Defining geodiversity in terms of this variation is critical for
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31 256 fully explaining biodiversity because a single point value cannot capture the diversity of niche
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33 257 space that may determine biodiversity (Lawler *et al.* 2015).
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37 258 Finally, we spatially grouped geodiversity and biodiversity observations using TNC's terrestrial
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39 259 ecoregions (Olson & Dinerstein 2002) to account for spatial autocorrelation in response
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41 260 variables. We selected this classification scheme over alternatives because the regions are
42
43 261 defined based on biodiversity analyses conducted across many taxa, and because the number
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45 262 of ecoregions in the contiguous USA (63 after excluding 6 border regions with insufficient data)
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47 263 is high enough to adequately account for spatial autocorrelation in biodiversity responses within
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49 264 the study area without overfitting.
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265 Selection of Predictor Variables

266 We selected six predictor variables for our models: two climate variables to describe the climate
267 norms inside the radius (mean annual temperature and mean annual precipitation), and four
268 predictors to describe geodiversity or environmental heterogeneity (mean TRI of elevation and
269 GPP, Shannon diversities of geological age category and soil type). Together, the six variables
270 encompass most of the variation in geodiversity and climate among locations in the contiguous
271 United States and are only modestly correlated with one another (Figure 1), meeting model
272 assumptions. Based on our *a priori* hypothesis that geodiversity is related to biodiversity, we
273 included one predictor to represent each of the unique geodiversity data sources available to us
274 (elevation, soil type, and geological age category). In addition, we selected GPP diversity to
275 represent other aspects of geodiversity not captured by the first three variables. Our choice of
276 mean annual temperature and mean annual precipitation to represent long-run climate norms is
277 reasonable because the two variables have no relationship to one another at our scale of
278 observation (Figure 1).

279 Final Data Processing

280 First, we excluded any site within 50 km of the Canada or Mexico borders because the 50-km
281 radius around those sites contained areas without biodiversity measurements. We logit-
282 transformed the taxonomic beta-diversity variable, which is a raw dissimilarity metric varying
283 between 0 and 1 in the model. No bird sites had a taxonomic beta-diversity of exactly 0 or 1, but
284 ~16% of tree sites had taxonomic beta-diversity of exactly 0 or 1, which is outside the domain of
285 the logit function. Thus, we replaced zeroes with 0.001 and ones with 0.999. We took a spatially
286 stratified random sample of tree sites where each sampled site was a minimum of 20 km from
287 any other site, to minimize spatial autocorrelation not captured by our model. This process left

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3 288 ~3000 sites, so that sample sizes were comparable between the datasets used to fit each
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5 289 model.
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8 290 Model Fitting 9

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11 291 We fit spatial multivariate mixed models with the following fixed predictors: (1) all six predictor
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13 292 variables as fixed effects, (2) only the four geodiversity predictors as fixed effects, (3) only the
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15 293 two climate predictors as fixed effects, and (4) no fixed effects (null model with only spatial
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17 294 random effects). We fit multivariate models for each diversity level (alpha, beta, and gamma)
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19 295 and each taxon (birds, trees), totalling 24 models (4 predictor sets \times 3 diversity levels \times 2 taxa =
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21 296 24). Each model had three response variables corresponding to the three dimensions of
22
23 297 biodiversity (taxonomic, phylogenetic, and functional). We used the null model z-scores to
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25 298 represent phylogenetic and functional biodiversity in all the models.
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29 299 We fit a random intercept and slope for each predictor in each TNC ecoregion. We excluded
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31 300 ecoregions with <5 sites, because random effects estimated with <5 data points are not robust.
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33 301 The excluded ecoregions were primarily in Canada or Mexico and only have a small area inside
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35 302 the contiguous United States that is at least 50 km from a land border. After excluding these
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37 303 ecoregions, 63 ecoregions remained. We estimated random slopes and intercepts for each
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39 304 ecoregion with a multilevel conditional autoregressive (CAR) structure to model the spatial
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41 305 variability in the biodiversity-geodiversity relationship among ecoregions (Besag & Kooperberg
42
43 306 1995). We specified the neighbourhood structure with an adjacency matrix identifying all pairs of
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45 307 regions that share a border. The ecoregion random effects in the model were therefore spatially
46
47 308 structured, accounting for spatial autocorrelation in the biodiversity values of neighbouring
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49 309 regions. We chose to model spatial dependence using discrete regions because of better out-of-
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51 310 sample prediction performance than simultaneous autoregressive models (Kress, unpublished).
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3 311 We fit the models in a hierarchical Bayesian framework using the R package *brms* (Bürkner
4 312 2017). We modelled error in response variables as normally distributed. Finally, we
5 313 standardized both predictor and response variables before fitting the models so that we could
6 314 compare effect sizes across predictors and responses. The standard deviation of each
7 315 coefficient represents the among-region variability of each predictor-response relationship.
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15 316 Model Validation

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17 317 To assess model predictive performance, we performed spatially blocked leave-one-location-
18 318 out cross-validation (Roberts *et al.* 2017). We refit each of the models 63 times, each time
19 319 holding out all data points from one of the 63 ecoregions. We found the root mean squared error
20 320 (RMSE) of the predicted values of the withheld data from each fold to get a cross-validation
21 321 RMSE for each model. We also calculated the RMSE of the models fit to all the data. We
22 322 divided all RMSE values by the range of the observed data to yield relative values that can be
23 323 compared among models. We also calculated RMSEs using resubstitution evaluation, in which
24 324 no data points were held out in model fitting. This procedure assesses the explanatory
25 325 powergoodness-of-fit of models across the entire contiguous U.S. but does not fully correct for
26 326 spatial autocorrelation.
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39 327 We calculated the Bayesian R-squared (Gelman *et al.* 2018) for each model to quantify the
40 328 proportion of variation in the response explained by fixed and spatial random effects combined.
41 329 Finally, we calculated the widely applicable information criterion (WAIC; Watanabe 2010) for
42 330 each model.
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331 Results

332 Description of geodiversity and biodiversity variables

333 Correlations among geodiversity predictor variables were relatively low (Figure 1a). The
334 pairwise correlation between elevation diversity and geologic age diversity was relatively high (r
335 = 0.52), indicating that geodiversity measured as topographic variability is correlated with
336 geodiversity measured as the variety of geologic substrate ages. Notably, the correlation
337 between elevation diversity and mean annual temperature was low ($r = -0.20$). In both birds
338 (Figure 1b) and trees (Figure 1c), taxonomic and phylogenetic diversity were positively
339 correlated with one another at all levels; this relationship was strongest for birds. However, local
340 (α) and regional (γ) functional diversity tended to correlate negatively with other forms
341 of biodiversity in both birds and trees.

342 Geodiversity variables (Figure 2) had unique patterns and spatial grains of variability. Climate
343 variables varied at broad scales, while geologic and topographic variables varied at scales
344 corresponding to major land features such as mountain ranges (Figure 2). Biogeographic
345 patterns were disparate across dimensions of biodiversity for birds (Figure 3) and trees (Figure
346 4). Bird diversity patterns were spatially idiosyncratic (Figure 3), while tree diversity showed a
347 strong longitudinal pattern, with taxonomic diversity highest in the east and functional and
348 phylogenetic diversity highest in the west (Figure 4).

349 Effects of climate and geodiversity across taxa and components of biodiversity

350 Among geodiversity variables, elevation variability tended to be the strongest predictor of
351 biodiversity (Figure 5). Elevation variability was associated with increased bird taxonomic beta-
352 diversity but with decreased bird phylogenetic and functional diversity at all levels. Interestingly,
353 it had a positive effect across all levels and dimensions of tree biodiversity; it was the only

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3 354 predictor with such a consistently positive relationship. Higher mean annual temperature was
4
5 355 associated with lower taxonomic diversity but higher phylogenetic and functional diversity in
6
7 356 birds. In contrast, for trees, precipitation was a much more important climate driver than
8
9 357 temperature (Figure 5). The effect size for temperature was not distinguishable from zero for
10
11 358 most levels and dimensions of tree diversity. For birds, taxonomic alpha-diversity (local
12
13 359 richness) was highest in colder and wetter areas, but most other levels and dimensions of
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15 360 biodiversity showed the opposite pattern. For trees, taxonomic and functional diversity were
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17 361 higher in wetter areas, but phylogenetic diversity was higher in drier areas.

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21 362 The effects of geologic age variability and soil type variability tended to be relatively weak,
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23 363 although for birds, soil type variability positively affected taxonomic diversity, and for trees,
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25 364 geologic age variability positively affected taxonomic diversity. Spatial variability in GPP had a
26
27 365 positive relationship with bird taxonomic and functional diversity and a positive relationship with
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29 366 tree turnover and regional diversity across the three dimensions of biodiversity.

30 31 32 367 Overall model performance

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36 368 The spatially blocked cross-validation showed that the models with climate or geodiversity
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38 369 predictors performed no better than the null model when predicting all biodiversity values from
39
40 370 an entire ecoregion held out during model fitting (Figure 6). However, cross-validation prediction
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42 371 error for models including climate tended to be higher than for models including geodiversity.

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44 372 Model evaluation using the full dataset without holding out any locations showed that models
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46 373 including the six fixed predictors and the random ecoregion spatial effect were the best fit for
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48 374 biodiversity of trees and birds explained most of the spatial variation in biodiversity of trees and
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50 375 birds, as shown by the RMSEs, WAIC values, and Bayesian R-squared values (Figure S1;
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52 376 Table S2). Geodiversity explained a consistent proportion of variation in most forms of bird
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55 377 biodiversity. For trees, the explanatory power of geodiversity depended on the level of
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3 378 biodiversity considered: geodiversity explained local (alpha) and regional (gamma) biodiversity
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5 379 better than turnover (beta).
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8 380 Spatially varying biodiversity-geodiversity relationships

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11 381 The strength of biodiversity-climate relationships varied more across ecoregions than the
12
13 382 strength of biodiversity-geodiversity relationships (Figure S2). Interestingly, the relationship
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15 383 between mean annual precipitation and tree taxonomic and functional biodiversity tended to be
16
17 384 more strongly positive in drier western ecoregions where precipitation is limiting (Figure S10).
18
19 385 Phylogenetic diversity showed an opposite spatial pattern: drier areas in the west had higher
20
21 386 tree phylogenetic diversity. In those ecoregions, we observed high phylogenetic diversity at sites
22
23 387 dominated by gymnosperms (*Pinus* and *Juniperus* spp.) with a few associated angiosperm
24
25 388 species, notably *Cercocarpus ledifolius* and *Populus tremuloides*. These dry sites, which tended
26
27 389 to have low to intermediate taxonomic and functional diversity, may be driving the negative
28
29 390 relationship between precipitation and phylogenetic diversity in the western USA. Notably, the
30
31 391 relationship between elevation variability and biodiversity was relatively consistent across
32
33 392 ecoregions, being generally positive for trees, positive for bird taxonomic diversity, and negative
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35 393 for bird functional and phylogenetic diversity. Other geodiversity-biodiversity relationships varied
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37 394 idiosyncratically across space (Figures S2-S14).
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43 395 Discussion

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46 396 The magnitude and direction of the relationships between environmental variability and
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48 397 biodiversity were intriguingly context-dependent, varying between birds and trees, by diversity
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50 398 level (alpha, beta, and gamma), by diversity dimension (taxonomic, phylogenetic, and
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52 399 functional), and by ecoregion. Below we explore potential reasons for this context-dependence
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54 400 as they relate to the predictions we made initially.
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3 401 Effects of climate and geodiversity across components of biodiversity
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6 402 A combination of geodiversity and climate predictors predicted biodiversity within 10% relative
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8 403 error for most forms of biodiversity for both birds and trees (Figure S1). However, these more
9
10 404 complex models performed worse than the null models in spatially blocked cross-validation,
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12 405 when predicting biodiversity values in ecoregions not used to fit the model (Figure 6). The poor
13
14 406 performance of models outside the training dataset may indicate that similarity among
15
16 407 neighboring communities of birds and trees explains the majority of variation in biodiversity, with
17
18 408 deterministic effects of geodiversity and climate playing a smaller role. Alternatively this
19
20 409 suggests that a large proportion of the relationship between geodiversity and bird and tree
21
22 410 biodiversity is spatially context-dependent, providing only weak support for our prediction that
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24 411 geodiversity and climate together explain variation in biodiversity among ecoregions (Prediction
25
26 412 1). The high level of spatial autocorrelation and high variability in relationships among
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28 413 ecoregions prevented the statistical models from identifying spatially transferable relationships
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30 414 between geodiversity and biodiversity. Nevertheless, geodiversity variables performed relatively
31
32 415 better than climate variables at out-of-sample prediction (Figure 6), suggesting a potential use of
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34 416 geodiversity to identify biodiversity hotspots at local to regional scales. The poor performance of
35
36 417 the models relative to null models reveals the difficulty of disentangling environmental drivers of
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38 418 biodiversity from biogeographical and historical contingency and caution against relying heavily
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40 419 on geodiversity or climate to predict biodiversity in regions far from where models are fit.
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45 420 Temperature and precipitation means had the strongest effects on diversity, across taxa and
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47 421 across the levels and dimensions of biodiversity. However, adding geodiversity predictors
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49 422 significantly increased explanatory power when evaluating models trained on the full dataset
50
51 423 (Figure S1), although neither climate nor geodiversity predictors increased prediction accuracy
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53 424 in spatially blocked cross-validation (Figure 6). Among geodiversity predictors, topographic
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55 425 variability had the largest effect on biodiversity. Interestingly, topographic variability had a
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3 426 positive relationship with tree diversity across levels, but was associated with lower bird
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5 427 diversity. This may be because breeding bird diversity is driven by highly mobile migratory bird
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7 428 species seeking out high-productivity regions for breeding sites (Anderson & Shugart 1974;
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9 429 Cody 1981). ~~The tendency of topographic variability to promote microclimate variability may be~~
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11 430 ~~less important for bird diversity relative to tree diversity.~~ The diversity of niche opportunities
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13 431 available to trees may depend on the microhabitats created by topographic variation. Niche
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15 432 diversity for birds may be driven more by the diversity of food sources, which could be reduced
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17 433 in more topographically rugged regions. In contrast with topographic variability, geologic age
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19 434 and soil type diversity tended to have little or no effect on biodiversity in the regions and taxa we
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21 435 studied.

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25 436 We found that geodiversity has significant effects on all diversity levels. Gamma-diversity, which
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27 437 integrates the alpha and beta levels, is best predicted by a combination of geodiversity and
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29 438 climate. This finding contrasts with Prediction 2, that geodiversity's effect would be strongest on
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31 439 turnover (beta) and regional diversity (gamma). For trees in particular, geodiversity combined
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33 440 with climate predicted beta-diversity less well than alpha- and gamma-diversity. This result may
34
35 441 be due to incomplete sampling of the local community by single FIA plots. If trees have patchy
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37 442 distributions at local scales, the small-sized FIA plots may overestimate beta-diversity because
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39 443 some species that are present throughout the region will be absent from a random subset of
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41 444 plots within the focal region (Figure 4). Therefore, local sampling might obscure the true pattern
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43 445 of turnover among plots, but not the regional diversity, which integrates over many plots. We
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45 446 show that familiar maps of biodiversity, which are commonly created using species range maps
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47 447 (Currie & Paquin 1987; Brown & Lomolino 1998; Jenkins *et al.* 2015), represent gamma-
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49 448 diversity patterns, but not necessarily other forms of biodiversity. Our results show that these
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51 449 different levels of biodiversity (Figures 3 and 4) exhibit different relationships with environmental
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3 450 gradients. Our maps promote a more nuanced view of biodiversity and emphasize that each
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5 451 level and dimension has a different relationship with spatial variability in the environment.
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8 452 Although we found generally similar responses across biodiversity dimensions, differences may
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10 453 indicate ecologically or evolutionarily meaningful relationships. In general, we found similar
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12 454 responses across biodiversity dimensions because they tend to correlate positively with one
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14 455 another (Figure 1). This finding partially contradicts Prediction 3 that patterns would differ across
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16 456 dimensions. However, in support of Prediction 3, some environmental drivers had opposite
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18 457 effects on different dimensions of biodiversity (Jarzyna & Jetz 2016). This result parallels
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20 458 contrasting patterns across biodiversity dimensions previously documented in mammals (Davies
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22 459 & Buckley 2011). For example, areas with ~~increased-greater~~ topographic variability tended to
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24 460 have higher bird taxonomic diversity but lower phylogenetic and functional diversity. Birds'
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26 461 taxonomic diversity might not have the same signal as phylogenetic or functional diversity
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28 462 because both the functional guilds and the phylogenetic lineages of birds differ greatly from one
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30 463 another in species richness (De Graaf *et al.* 1985). For example, there are many functionally
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32 464 similar and closely related species within the guild of small insectivorous songbirds. An increase
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34 465 of species richness in the insectivore guild would result in increased taxonomic diversity without
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36 466 influencing the other dimensions of diversity. The high numbers of bird species harboured by
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38 467 geodiverse regions likely reflects increased taxonomic diversity within speciose guilds.
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43 468 The discrepancy in relationships we observed among the dimensions of biodiversity we
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45 469 examined mirror that of a previous study examining biodiversity change over time. Increases in
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47 470 taxonomic diversity without corresponding changes in phylogenetic or functional diversity may
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49 471 indicate biotic homogenization of assemblages; 40 years of BBS surveys show a homogenizing
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51 472 trend over time (Jarzyna & Jetz 2017). While our study does not address change over time, the
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53 473 discrepancy between taxonomic and functional/phylogenetic diversity patterns with topographic
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55 474 variability and with temperature is notable. Jarzyna and Jetz also observed that the greatest

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3 475 temporal changes in diversity occurred at higher elevations and latitudes, ascribing this pattern
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5 476 to climate change. We documented a positive association between temperature and beta-
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7 477 diversity for all dimensions, but we found lower phylogenetic and functional diversity in
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9 478 topographically diverse regions (Figure 5). This result echoes the temporal pattern documented
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11 479 by Jarzyna and Jetz, suggesting that bird communities at high elevations and in cold regions
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13 480 may be relatively homogeneous and thus relatively more vulnerable to changing climate. In the
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15 481 case of breeding birds in the United States, topographically diverse regions may in fact be the
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17 482 most sensitive to environmental change.

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21 483 Phylogenetic and functional diversity have similar patterns with respect to most predictor
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23 484 variables. This finding makes sense given that many, though not all, traits are phylogenetically
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25 485 conserved (Devictor *et al.* 2010), such that phylogenetic diversity roughly approximates
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27 486 functional diversity (Winter *et al.* 2012). However, tree phylogenetic diversity increases with
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29 487 decreasing precipitation, while functional diversity and taxonomic diversity decrease. This
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31 488 suggests that the angiosperm and gymnosperm species that contribute to high phylogenetic
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33 489 diversity in low-precipitation regions may have convergently evolved suites of adaptations to dry
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35 490 environments (Méndez-Alonzo *et al.* 2012), resulting in low functional diversity at those sites.

39 491 Spatially varying biodiversity-geodiversity relationships

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42 492 The relationship between geodiversity variables and biodiversity variables varied in direction
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44 493 and magnitude across the ecoregions of the United States. For example, elevational variability
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46 494 had a greater effect on tree biodiversity in the central and eastern United States, providing
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48 495 support for Prediction 4. In the west, climatic factors and a smaller regional species pool set
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50 496 upper bounds on richness, so the opportunity for increased richness with increased geodiversity
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52 497 is reduced relative to the east (Figure S11). In contrast, the effect of elevational variability on
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54 498 bird taxonomic diversity was more likely to be non-zero in regions of high topographic relief,
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3 499 such as the Appalachian ecoregion and the northern Rocky Mountains (Figure S5). For trees,
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5 500 the effect of precipitation on biodiversity was more likely to be significant in the drier central and
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7 501 western United States (Figure S10), where water tends to be limiting. This suggests that in
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9 502 regions where climatic factors strongly control species diversity, the influence of geodiversity on
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11 503 biodiversity is weaker. However, this result may depend on spatial extent of the study region; a
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13 504 similar model fit only for trees in the Pacific Northwest region shows a strong positive correlation
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15 505 between elevational variability and tree alpha- and gamma-diversity (Record *et al.* in press).

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18 506 The form of the geodiversity-biodiversity relationship and the particular variables that are the
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20 507 best predictors of biodiversity may not be transferable across ecoregions. This may present a
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22 508 conundrum for organisms that are migrating to track climate conditions and may encounter
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24 509 novel geological features. The Nature Conservancy documented a similar pattern: when they
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26 510 initially developed the Conserving Nature's Stage framework, they identified geological variables
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28 511 as the best predictors of biodiversity in the Northeast U.S. (Anderson & Ferree 2010). Those
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30 512 variables did not predict biodiversity well when they extended the approach to the Southeast
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32 513 (Anderson *et al.* 2014), where geologically homogeneous regions of the Coastal Plain host high
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34 514 biodiversity.

35 36 37 38 39 515 Conclusions and future directions

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42 516 Our study found that topographic variability was related to biodiversity independently from, and
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44 517 in different ways than, climatic means. This result suggests that using remotely-sensed
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46 518 temperature data, rather than values interpolated between weather stations using local
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48 519 elevation, may improve our ability to distinguish between the effects of climate and of
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50 520 topographic variability (Pau *et al.* 2013; Still *et al.* 2014). Remotely-sensed temperature has
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52 521 broader spatial coverage than interpolated temperature and is not inherently dependent on
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3 522 elevation. Therefore, it would be valuable to confirm whether remotely-sensed temperature is
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5 523 biologically relevant across a range of taxa (Heft-Neal *et al.* 2017).
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8 524 With the increasing intensity of global change threatening biodiversity and ecological integrity, it
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10 525 is vital to conserve nature's stage and create refugia for organisms moving to track their optimal
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12 526 climatic conditions. While past ecological research and the results of this study show that
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14 527 climate explains much of the spatial variation in biodiversity of trees and birds, geodiversity is
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16 528 related to biodiversity independently of climate. To disentangle the effects of climatic and
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18 529 topographic drivers, spatially continuous remotely-sensed data are necessary. Biodiversity-
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20 530 geodiversity relationships depend on taxonomic group, spatial location, the level and dimension
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22 531 of biodiversity considered, and the grain of analysis (Zarnetske *et al.* 2019): there is no single
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24 532 relationship valid for all conditions. To date, biodiversity-geodiversity relationships have primarily
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26 533 been characterized in a few well-studied taxa (Meynard *et al.* 2011; Hjort *et al.* 2012; Wang *et*
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28 534 *al.* 2013; but see Kaskela *et al.* 2017; Tukiainen *et al.* 2017); our study of birds and trees only
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30 535 hints at potential mechanisms underlying differences in relationships among taxonomic groups.
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32 536 Future work across a wider range of taxa would allow us to identify the mechanisms behind the
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34 537 differences. Although we need to understand the underlying mechanisms more fully before we
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36 538 can build models that are transferable across ecoregions, globally available geodiversity
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38 539 predictors can inform conservation practitioners working at a local scale to conserve different
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40 540 dimensions of biodiversity in the face of climate change.
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3 728 **Data Accessibility Statement**
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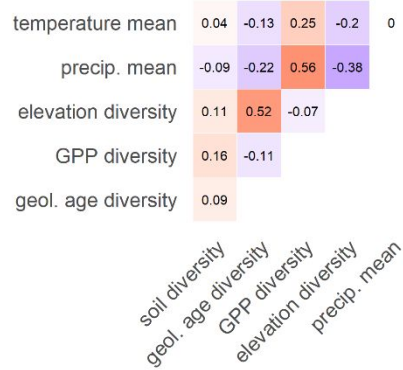
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7 729 Data and code for reviewers to reproduce all the model fitting and analysis presented in this
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9 730 manuscript is archived on FigShare at doi.org/10.6084/m9.figshare.7680083.v1 (draft version).
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11 731 Code to replicate the data preparation and cleaning stages described in the methods is also
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13 732 archived on the FigShare repository.
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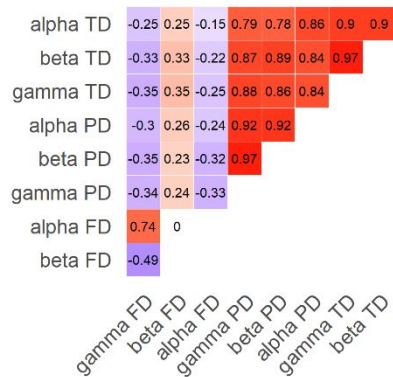
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734 Figures

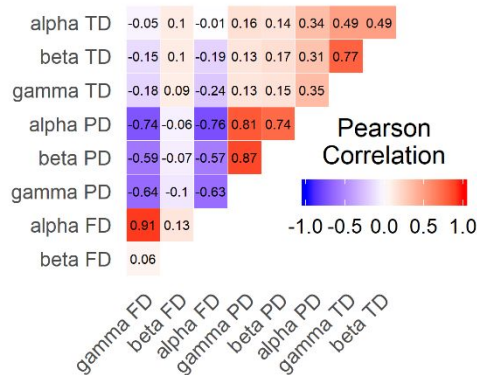
(a) environmental correlations



(b) bird biodiversity correlations



(c) tree biodiversity correlations

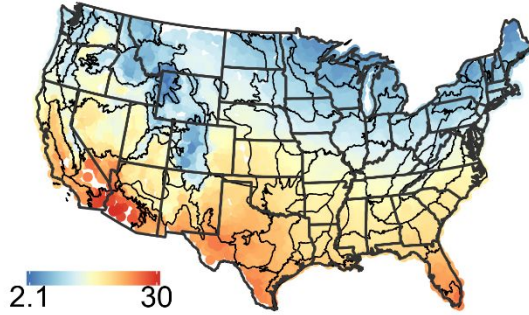


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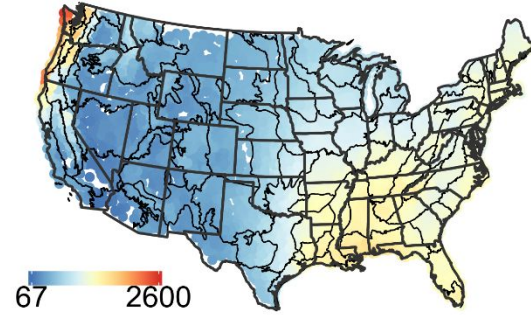
736 Figure 1. Heat maps showing correlations between pairs of environmental predictor variables
 737 including geodiversity and climate (a), bird biodiversity variables (b), and tree biodiversity
 738 variables (c). Pearson correlation coefficients are shown, along with colours showing the

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3 739 magnitude of the correlation coefficients. TD = taxonomic diversity; PD = phylogenetic diversity;
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5 740 FD = functional diversity.
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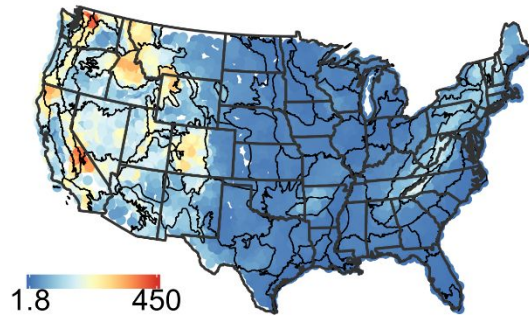
temperature mean



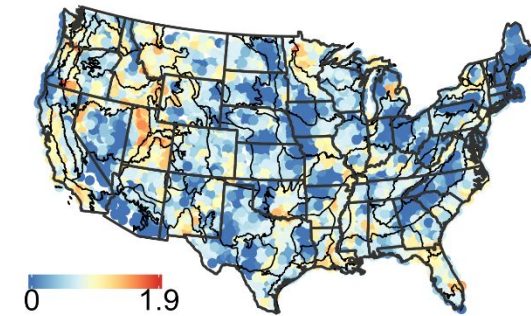
precipitation mean



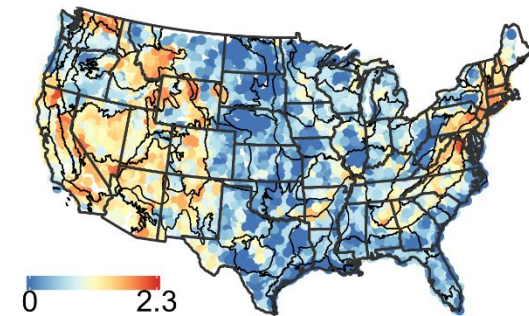
elevation diversity



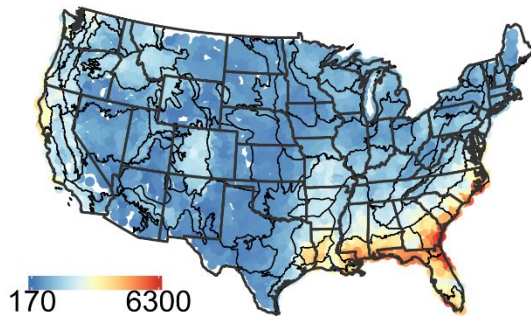
soil diversity



geological age diversity

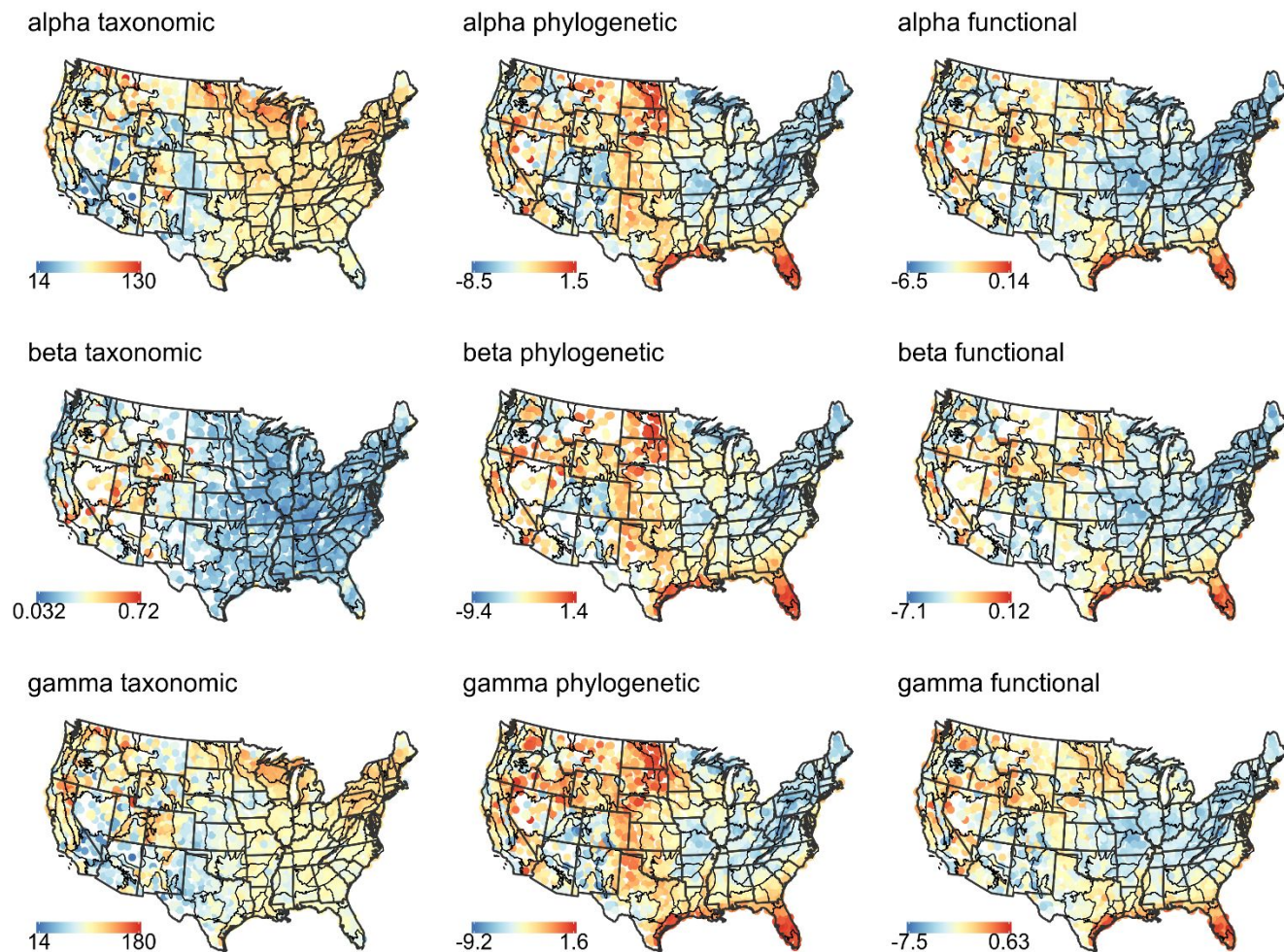


GPP diversity



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743 Figure 2: Maps of climate and geodiversity predictor variables across the contiguous United
744 States, centred on BBS route midpoints and FIA plots (fuzzed locations shown).



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746 Figure 3: Maps of bird biodiversity at BBS routes, across 3 levels and 3 dimensions of

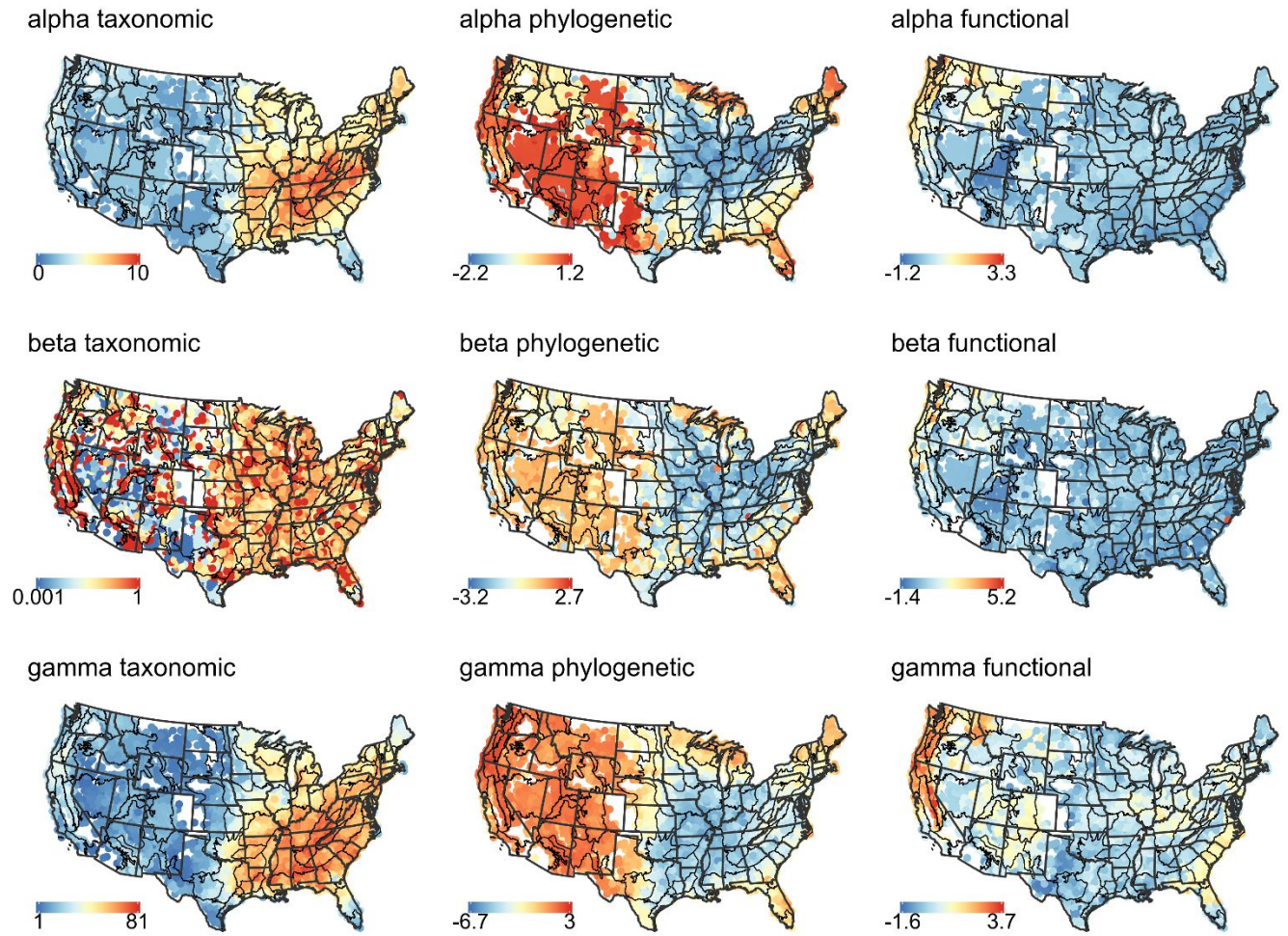
747 biodiversity. For taxonomic diversity, richness is plotted for alpha- and gamma-diversity, and

748 pairwise dissimilarity score is plotted for beta-diversity. For phylogenetic and functional diversity,

749 z-scores are plotted for all levels. Midpoints of each route are shown on the map.

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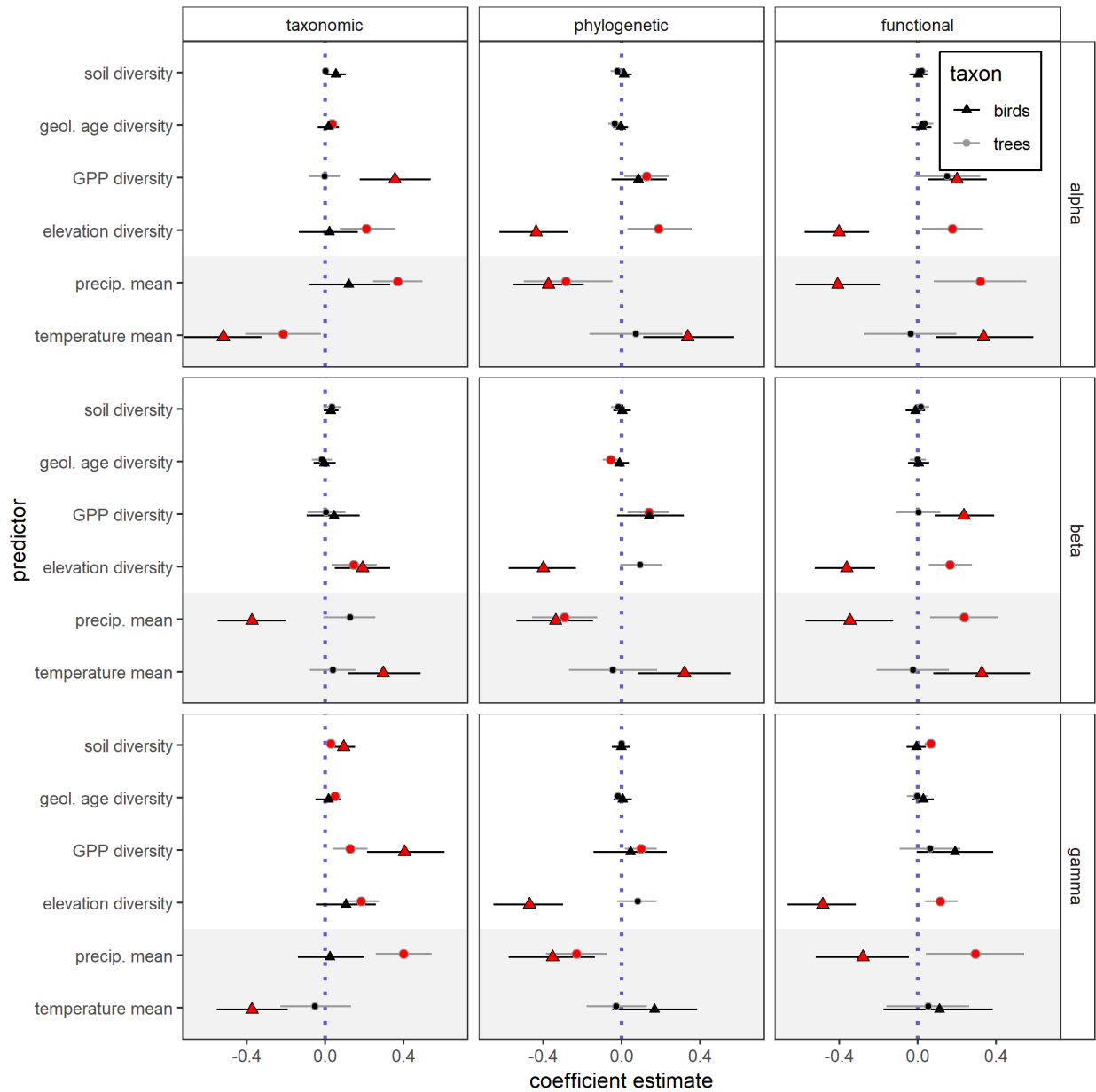
753 Figure 4: Maps of tree biodiversity at FIA plots, across 3 levels and 3 dimensions of biodiversity.

754 The same biodiversity metrics are shown as in Figure 3. Fuzzed locations of each FIA plot are

755 shown on the map.

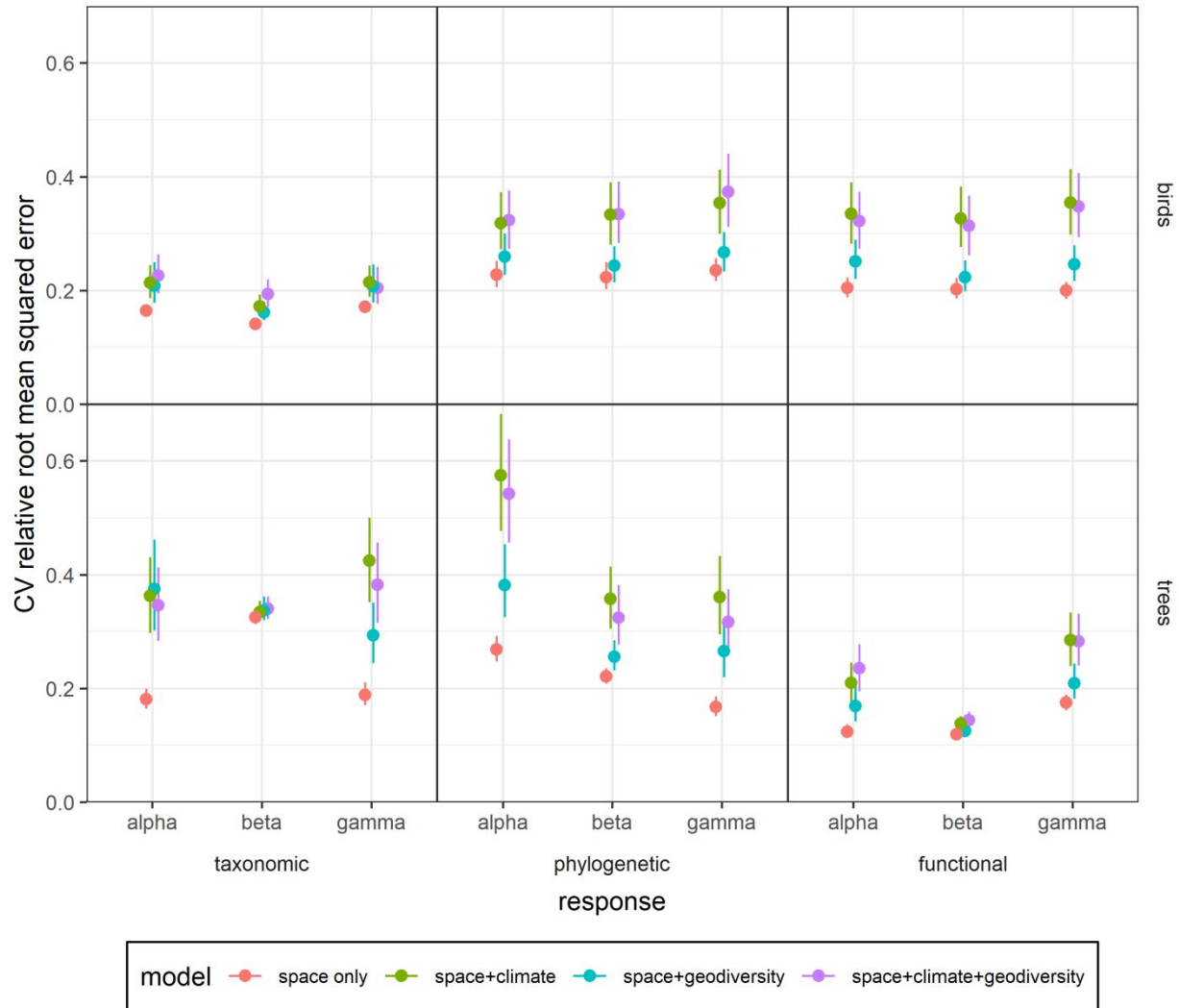
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759 Figure 5: Scaled coefficients of fixed effects for birds and trees. Error bars show 95% credible
 760 interval around parameter estimate. Parameters with credible intervals that do not overlap zero
 761 are shown in red. Within each model, predictors are scaled so that coefficients can be
 762 compared across variables within the model. Predictors representing mean climate are shaded
 763 in grey; the other predictors represent geodiversity.



764

765 Figure 6: Model performance for bird biodiversity and tree biodiversity, assessed with spatially
 766 blocked leave-one-location-out cross-validation. This figure shows the root mean squared errors
 767 from the space-only or null models (red), models with climate predictors (green), models with
 768 geodiversity predictors (blue), and full models (purple) for each taxon and each response
 769 variable. Individual models were fit holding out all data points from one ecoregion, then the
 770 holdout data points were predicted and root mean squared error calculated across all
 771 ecoregions. The raw errors are divided by the range of the observed data to produce a relative
 772 value comparable among models. A lower value represents better performance of the model.
 773 Error bars are 95% credible intervals. Because each cross-validation fold excludes an entire

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3 774 region, the null model including only the spatial random effect tends to predict the held out
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5 775 values as well or better than the models including climate and geodiversity predictors. However,
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7 776 models including geodiversity predictors tend to perform as well or better than the models
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9 777 including climate predictors, especially for phylogenetic and functional diversity.
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