Title: Protected area planning to conserve biodiversity in an uncertain world

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Abstract:

Protected areas are a key instrument for conservation. Despite this, they are vulnerable to risks associated with weak governance, land use intensification, and climate change. Using a novel hierarchical optimization approach, we identified priority areas for expanding the global protected area system to explicitly account for such risks whilst maximizing protection of all known terrestrial vertebrate species. We illustrate how reducing exposure to these risks only requires expanding the area of the global protected area system by 1.6% while still meeting conservation targets. Incorporating risks from weak governance drove the greatest changes in spatial priorities for protection, while incorporating risks from climate change required the largest increase in global protected area. Conserving wide-ranging species required countries with relatively strong governance to protect more land when bordering nations with comparatively weak governance. Our results underscore the need for cross-jurisdictional coordination and demonstrate how risk can be efficiently incorporated into conservation planning.

Introduction

Protecting land is one of the best strategies to stem the biodiversity crisis (Watson et al. 2014) and a cornerstone of international agreements to safeguard biodiversity (Convention on Biological Diversity (CBD) 2017; CBD 2020). The effectiveness of a global network of protected areas depends upon the identification of areas that will both meet the needs of species and provide the greatest return on conservation investments. Yet most spatial planning efforts base decisions heavily upon the estimated ecological value of land (Brooks et al. 2006; Venter et al. 2014; CBD 2017; CBD 2020) and carry the tacit, but often incorrect, assumption that protection will be enforced, effective, and permanent. Despite evidence that protected areas are subject to risks associated with weak governance (e.g., political instability and corruption; Schulze et al. 2018), land use intensification (e.g., deforestation and degazetting of parks; Tesfaw et al. 2018), and climate change (e.g., extreme weather events; Maxwell et al. 2019), few plans have explicitly considered these risks (McBride et al. 2007; Alagador et al. 2014). Here we demonstrate how we can expand the planning lens to include risks as well as ecological value, with the goal of improving the resilience and performance of protected areas.

We considered the following three broad categories of risk, which we defined as factors likely to diminish the long-term effectiveness of protected areas: (i) governance, (ii) land use, and (iii) climate. We then generated plans for establishing protected areas ("prioritizations") based on scenarios for different risk factors. Our framework provides a flexible approach for incorporating multiple risk metrics into conservation decision making.

Methods

We considered the influence of risk categories on allocating protection decisions at a global scale in suitable habitat for all 29,350 vertebrate species from the IUCN Red List of

Threatened Species (IUCN 2019) using a multi-objective optimization approach. To incorporate

risk categories, we built on the minimum set problem, where the objective is to reach species

distribution protection targets while accounting for one constraint such as land cost or area

(Margules & Pressey 2000; Moilanen et al. 2009). We expanded this approach to include

multiple objectives accounting for risk in the problem formulation, by treating each risk layer as

a separate objective in the problem formulation (Deb 2014).

Biodiversity Data

We produced area of habitat (AOH) estimates for 10,774 species of birds, 5,219

mammals, 4,462 reptiles and 6,254 amphibians with available IUCN range polygon data

following the procedure outlined in (Brooks et al. 2019). Species range polygons obtained from

the IUCN Red List spatial data (https://www.iucnredlist.org/) and Birdlife International

(http://datazone.birdlife.org/species/requestdis) were first filtered for 'extant' range then

rasterized to a global 1 km grid in the Eckert IV equal area projection. Individual species range

rasters were then modified to only include land cover classes that match the habitat associations

for each species. Habitat associations were obtained from the IUCN Red List species habitat

classification scheme and were matched to ESA land cover classes for the year 2018 following

Santini et al. 2019. ESA land cover classification data was aggregated from 300 m resolution to

match the global 1 km grid using a majority rule. Species ranges were additionally filtered so

that only areas within a species' accepted elevational range were included. Global elevation data

derived from SRTM was obtained from WorldClim v. 2 (Fick & Hijmans 2017). For bird species

with multiple seasonal distributions, data for resident, breeding, and non-breeding ranges were

processed separately.

Basic administrative delineations

National boundaries were derived from the Global Administrative Areas database

(http://gadm.org). We obtained protected area boundaries from the World Database on Protected

Areas (https://www.protectedplanet.net). Following standard procedures for cleaning the

protected area dataset (Butchart et al. 2015), we (i) projected the data to an equal-area coordinate

system (World Behrman), (ii) excluded reserves with unknown or proposed designations, (iii)

excluded UNESCO Biosphere Reserves (Coetzer et al. 2014), (iv) buffered sites represented as

point localities to their reported area, (v) dissolved boundaries to prevent issues with overlapping

areas, and (vi) removed slivers (code available at https://github.com/jeffreyhanson/global-

protected-areas). After the protected area data were modified as described above, we overlaid the

protected area boundaries with a 10 x 10 km grid covering the Earth. These spatial data

procedures were implemented using ArcMap (version 10.3.1) and python (version 2.7.8).

Governance risk

We used worldwide governance indicators from the World Bank to capture governance

risk (Kaufmann et al. 2011). The indicators include six scaled measures: voice and

accountability; political stability and absence of violence; government effectiveness; regulatory

quality; rule of law; and control of corruption (see Table S4 for definitions). We chose these

indicators because evidence suggests that they reliably predict protected area effectiveness

(Barnes et al. 2016) and state investment and efforts for biodiversity conservation (Coetzer et al.

2014). For each country, we used a mean of annual averages of all six measures (Baynham-Herd

et al. 2018) (Figure S1).

Land use risk

117   We used a global land systems map produced by Kehoe et al. (2017) to incorporate the

118   risk of land-use change. This map is based on a global land systems map for the year 2000

119   (Asselen & Verburg 2012) at a 9.25 km^2 spatial resolution but is refined based on recent land-

120   cover and land-use datasets to a spatial resolution of 1 km^2. Kehoe et al. (2017) further estimated

121   the impact of land use and land use intensity on biodiversity, with data originating from the

122   PREDICTS project (Hudson et al. 2014). They first matched their land-systems classes to

123   varying intensity levels for each land use type (for detailed conversion table, see Asselen &

124   Verburg 2012). This allowed Kehoe et al. (2017) to calculate average biodiversity loss per land

125   system (relative to an unimpacted baseline) by taking the mean model estimates of biodiversity

126   loss per land use intensity class from previous work (Hudson et al. 2014). The result gives

127   average relative biodiversity gain or loss per land-system class. Here, we used their modelled

128   mean estimates (following Newbold et al. (2015)) of relative percent biodiversity change for

129   each land-system class for species abundance as a measure of the land use pressure (Figure S2).

130

131   <u>Climate risk</u>

132   We used, velocity of climate change, which is an instantaneous measurement of how

133   projected temperature increases translate to horizontal climate velocity on the landscape (Loarie

134   et al. 2009). It is an integration of both the rate of change in average climate and landscape

135   properties that govern how bands of similar temperature redistribute spatially as climate changes.

136   For example, in a region with high topographic diversity, a species may be able to track its

137   climatic niche through relatively small dispersal distances (e.g. 10s or 100s of meters) upslope or

138   downslope. By contrast, keeping pace with preferred climate under the same magnitude of

139   temperature rise in the plains may require much larger dispersal distances – 100s or 1000s of

140   kilometers. Velocity of future temperature change used here follows the method of Loarie et al.

141 (2009), and is essentially the ratio of the projected temporal rate of change (C/year) to the spatial

142 rate of change (C/km). Projected temporal rate of change was based on the 20-year mean (2040-

143 2060) projection for mean annual temperature from the HadGEM2-ES model (CMIP5) and the

144 baseline (1960-1990) temperature available from Worldclim v1.4. Spatial rate of change was

145 derived from 30 arc second elevation data and calculated with the 'terrain' function from the R

146 'raster' package.

147 We also explored an alternative measure of climate risk: exposure to extreme events.

148 Detailed methods and results for this alternative measure are provided in the online Supporting

149 Information.

150

151 Multi-objective optimization of risk reduction

152 We created 16 planning scenarios, such that solutions accounted for all possible

153 combinations of risk categories within each hierarchical level (Table S1). We then compared

154 these risk-based solutions to those produced with a null scenario that adopted the traditional area-

155 minimizing approach to optimization without considering risk.

156 We processed all data described previously to a 10 x 10 km resolution and clipped data to

157 the extent of land based on the global administrative areas database. Our multi-objective

158 approach uses a hierarchical (lexicographic) framework that assigns a priority to each objective,

159 and sequentially optimizes for the objectives in order of decreasing priority. At each step, it finds

160 the best solution for the current objective, but only from among those that would not degrade the

161 solution quality for higher-priority objectives. We considered up to three objectives in our

162 prioritization scenarios, i) governance risk, ii) land use risk, and iii) climate risk. To compare

163 different scenarios, we calculated solutions for each unique objective combination (n = 15), as

164 well as one where we use a constant objective function as the null scenario, as the order of the

165   hierarchy can influence the results. For a detailed mathematical exploration of this method, see

166   the online Supporting Information.

167   For all scenarios we locked in current protected areas. Following Hanson et al. (2020),

168   we used flexible targets for suitable habitat based on species' ranges. Species with less than

169   1,000 km^2 of suitable habitat were assigned a 100% target (1,802 amphibians, 893 avian and 645

170   mammalian species), species with more than 250,000 km2 of suitable habitat were assigned a

171   10% target (712 amphibians, 4,518 avian and 1,868 mammalian species) and species with an

172   intermediate amount of suitable habitat were assigned a target by log-linearly interpolating

173   values between the previous two thresholds (2,683 amphibians, 5,190 avian and 2,557

174   mammalian species). Migratory bird species were assigned targets for each seasonal distribution

175   separately. Additionally, to prevent species with very large suitable habitats from requiring

176   excessively large amounts of area to be protected, the targets for species' distributions larger

177   than 10,000,000 km^2 were capped at 1,000,000 km^2. This upper limit affected only 206 (1%)

178   species, and sensitivity analyses showed that it had negligible effect on our results. We

179   acknowledge that these targets are arbitrary; however, they are more precise than previous

180   targets based on species' ranges (which can contain a large amount of unsuitable habitat), and

181   account for the increased vulnerability of species with smaller range sizes (Pimm & Raven

182   2000), as well as the difficulty in conserving all habitat for species that occur over large areas.

183

184   **Results**

185   Surprisingly, scenarios that incorporated combinations of the three risk categories

186   increased the priority area by only 1.6% on average (0.08 – 2.52%) compared to the null scenario

187   based solely on ecological value to species. Among single-risk scenarios, accommodating risks

188   due to climate change velocity required the greatest increase in global protected area, compared

189   to scenarios including only governance or land use intensification risks (Table S1).

190   Scenarios shared many overlapping spatial priorities, which can be considered as reliably

191   good investments in terms of both ecological value and risk management. Most notably, all 15

192   scenarios prioritized the same 8.5 million km^2 (5.8% of global land area) ("no regrets" areas, Fig.

193   2), much of which was located in Canada, Kenya and Peru (Figure S4). There also was

194   substantial overlap among the priorities across scenarios within Conservation International's

195   global biodiversity hotspots (Myers et al. 2000), but many high overlap areas lie either outside of

196   (53.3%) or in small areas within hotspots (Figure S5).

197   At the same time, risk scenarios elicited several prominent shifts in spatial priorities

198   among areas varying in risk exposure (Fig. 3; Table S2). In some cases, high risks to protected

199   areas in weakly-governed countries could be compensated by expanding protected areas in well-

200   governed neighboring nations (Fig S6). For example, challenges to the transborder conservation

201   of the wide-ranging and IUCN-vulnerable caribou (*Rangifer tarandus*) due to weak governance

202   in Russia (Table S3) were mitigated by increasing the land area protected by Finland from 16.2%

203   to 36.4% (Fig. 4). High exposure to risks from land use change could be offset in a similar

204   fashion, such as by protecting more land in Liberia (32% rather than 22.5% in null scenario) than

205   in the agriculturally intensifying nation of Sierra Leone (Fig. 4). Likewise, climate-associated

206   risks in Hungary and Serbia (Figure S3) might be tempered by protecting twice as much land

207   (20.4% from 10.2% in null) in nearby Kosovo, which has lower predicted climate velocity (Fig.

208   4). Addressing risks from extreme weather events (La Sorte et al. 2021) (Figures S7 – S9) also

209   required shifting some priority areas to less climatically volatile locations.

210

211   **Discussion**

212   Although a growing body of literature shows that protected areas are seldom effective if

213   subject to unmitigated risks from land use change, weak governance and climate change

214   (Schulze et al. 2018; Tesfaw et al. 2018; Maxwell et al. 2019), most systematic conservation

215   planning efforts prioritize land based on ecological value and some measure of cost. We show

216   how only small (1.6%) increases in land area, but importantly a change in the spatial

217   configuration of where protected areas are places, may reduce the vulnerability of protected areas

218   to future threats if risk are explicitly considered during planning stages (Fig. 1). Across all

219   planning scenarios, we identified 8.5 million km^2 of priority lands that either uniquely

220   contributed to conservation targets (e.g., high endemism) or were resilient to the risks we

221   modeled. Countries with large proportions of land already in protection (e.g., Brazil with >30%)

222   also had similar priorities for risk vs. null scenarios. Such shared priority areas across planning

223   scenarios are likely to provide good return on conservation investments.

224   Despite modest differences across scenarios in the global land area required to conserve

225   terrestrial vertebrates, shifts in the locations of priority areas sometimes resulted in substantial

226   increases within any given nation. These asymmetries highlight the importance of cross-

227   jurisdictional coordination to promote collaboration and improve the effectiveness of protected

228   area systems (Dallimer & Strange 2015). In regions where nations vary widely in exposure to

229   risks, coordination may provide opportunity to offset or otherwise mitigate risks by adjusting the

230   geographic locations and/or boundaries of protected areas. Cooperative governance frameworks

231   (Miller et al. 2019) are especially important for countries supporting wide-ranging species that

232   are expected to be impacted by climate, land use, and governance risk across borders (Fig. 3).

233   These governance frameworks, both within and among countries, would need to be developed in

234   an environmentally just and equitable way to deliver benefits to biodiversity and local

235   communities (Martin et al. 2013).

236 A novel contribution of our framework is that it explicitly incorporates multiple risk

237 factors at the same time. Previous work has incorporated single risk factors analogous to those

238 we used, including governance (Mascia & Pailler 2011; Eklund & Cabeza-Jaimejuan 2017),

239 climate change (Hoffmann et al. 2019) and land use change (Pouzols et al. 2014; Di Minin et al.

240 2016) demonstrating the importance of each type of risk in protected area planning. Our results

241 similarly demonstrate that protected area expansion decisions can be profoundly influenced by

242 all three risk factors combined, yet they also show that relatively little additional protected area is

243 required to account for these risks.

244 Our flexible framework and methods can also allow conservation agencies to set their

245 own priorities from local to global scales and incorporate different metrics to assess the relevance

246 of different forms and levels of risk. Indeed, our risk metrics were chosen as reasonable

247 examples, rather than definitive recommendations. Our alternative climate risk framework

248 (presented in the Supporting Information) illustrates the importance of metric choice. The

249 difference between our climate risk scenarios highlights the need for agencies to carefully

250 consider their choices of risk metrics and suggests that smaller-scale planning exercises should

251 choose metrics that are most relevant for each region.

252 The conservation community has traditionally neglected to estimate how future changes

253 in climate (Kelly et al. 2020), land use (Di Minin et al. 2016), and governance risk might

254 compromise the effectiveness of protected areas. Yet, as we work towards an ambitious new plan

255 to curb biodiversity loss (CBD 2020) in a rapidly changing world, we show that incorporating

256 future risk has profound implications for the spatial distribution of protected areas. The risk of

257 weak governance was particularly influential. Surprisingly, incorporating risk into decision-

258 making adds <2% to the total global area required to meet biodiversity targets. Thus, accounting

259 for risk comes at limited extra cost which is likely outweighed by increased likelihood of

260   achieving global biodiversity targets. Our results also emphasize the importance of cross-

261   jurisdictional conservation initiatives, especially in adjacent countries sharing wide-ranging

262   species where risk varies considerably from country to country. Considering risk in conservation

263   decision-making will result in more resilient and effective conservation plans into the future to

264   help safeguard our planet's biodiversity in the face of the current extinction crisis.

265

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Competing interests: The authors declare no competing interests.

Data and materials availability: All data, scripts and full results are available on Open Science Framework (OSF) and will be assigned a DOI once the manuscript is in print:

https://osf.io/e2fuw/?view_only=46eb2e525daf42d29df318a92762d885
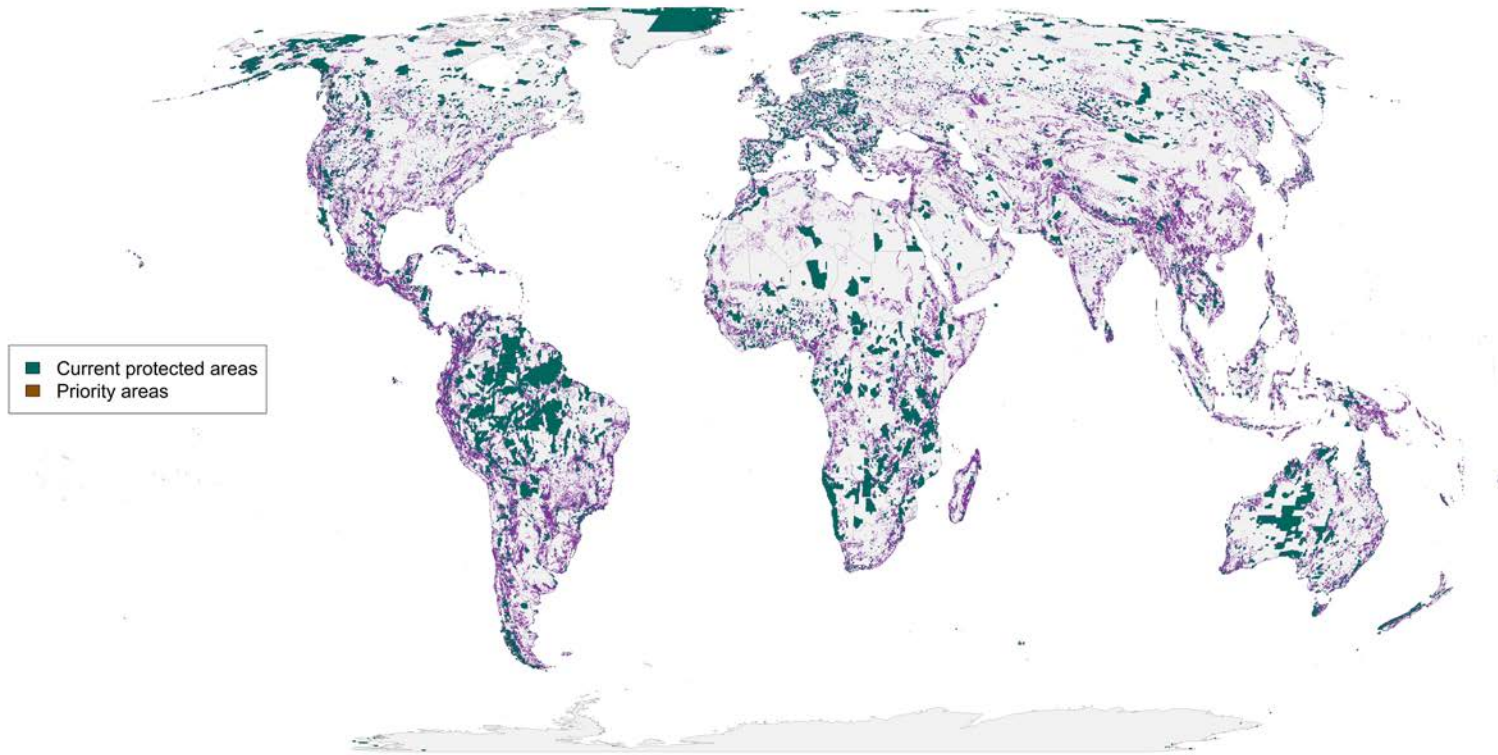
434 **Figure 1:** Spatial representation of priority areas for protection to account for governance, land use and climate risk. Accounting for

435 these risks to protected area effectiveness to produce more resilient conservation networks would require 23.5% of land surface to reach

436 suitable habitat protection goals (*26*) for vertebrate species from the IUCN Red List of Threatened Species (*20*).
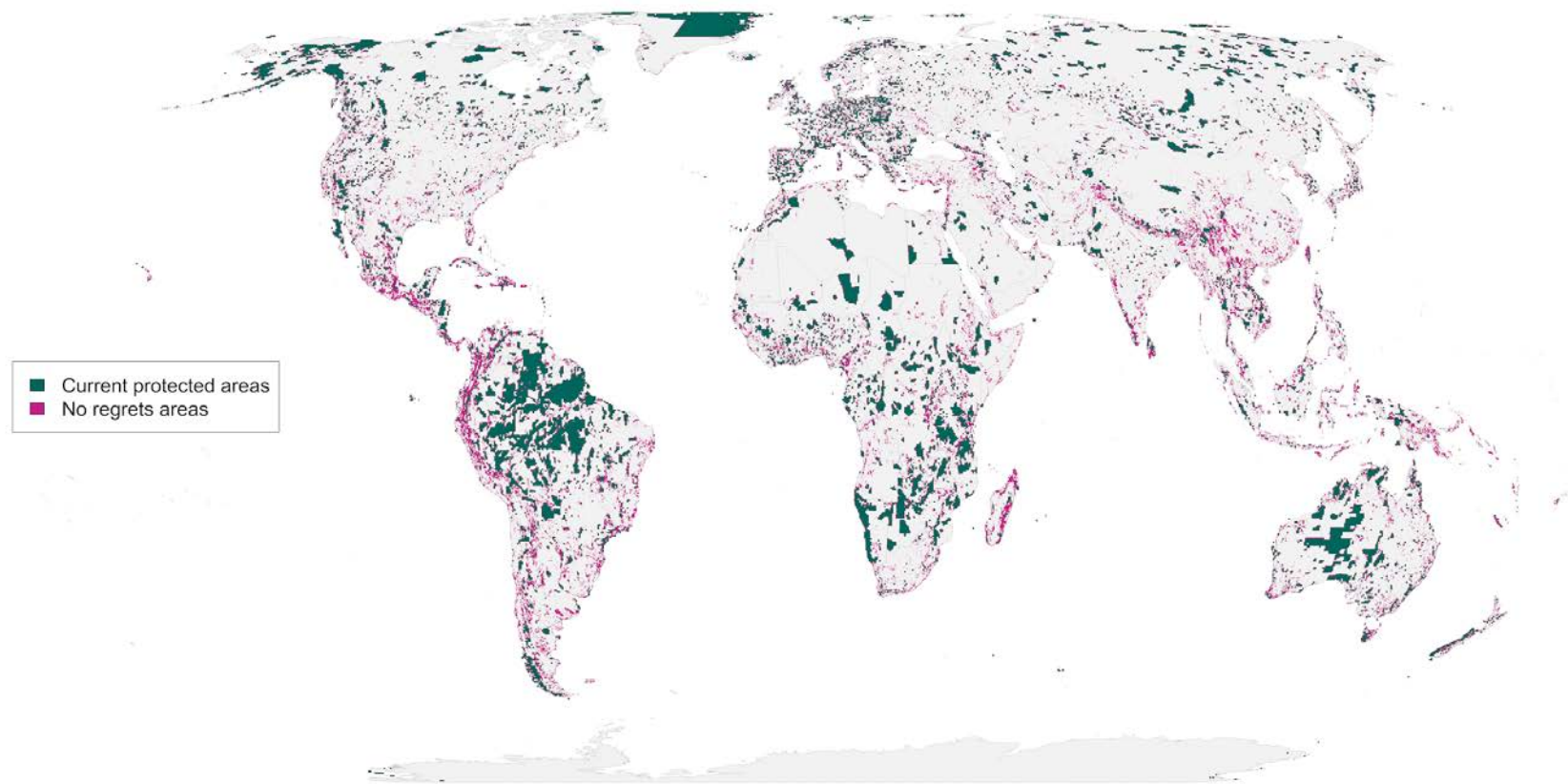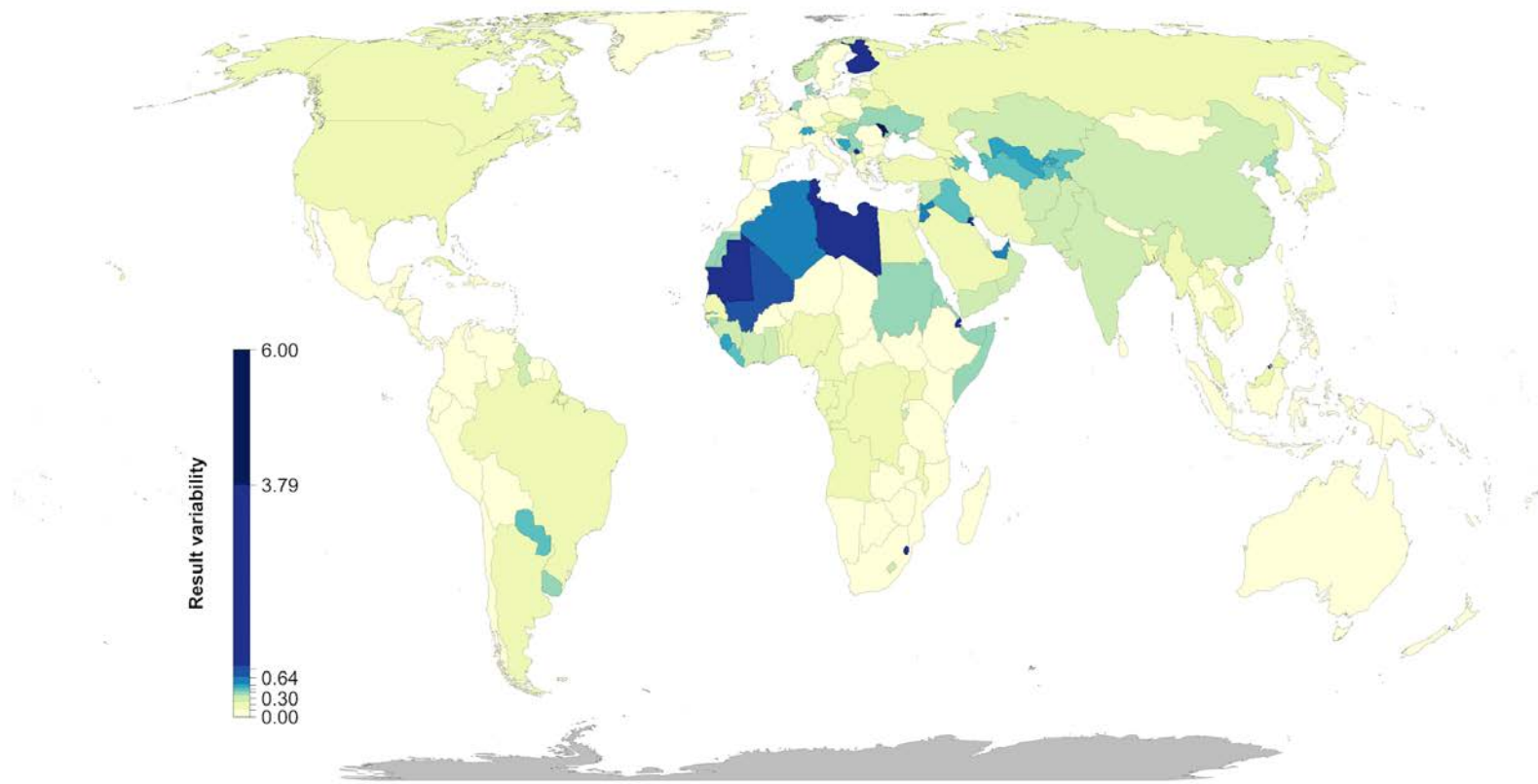
437

Figure 2: "No regrets" areas comprising 8.5 million km^2 of land that was identified as priority habitat for protection regardless of the
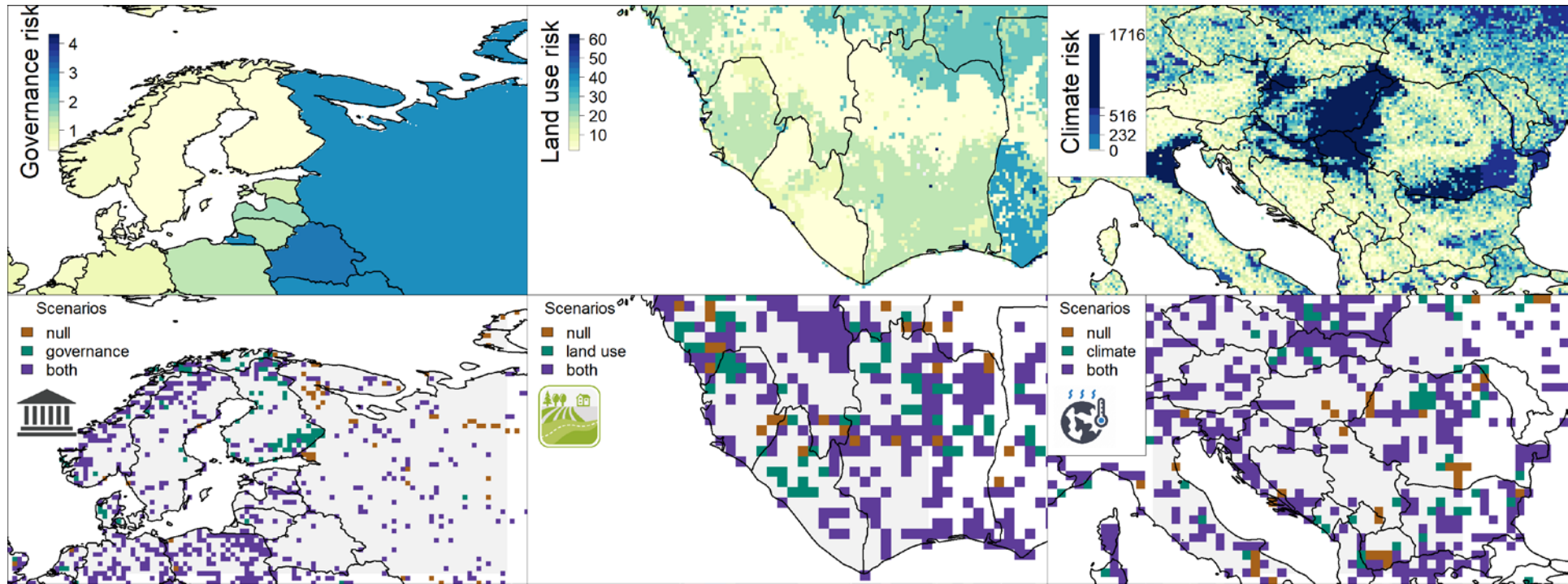
439   risks included in our analysis.

440

Figure 3: Percent country-level variation between the null scenario and the 15 scenarios including risk. Countries whose results are consistent across the 15 scenarios (e.g., Mexico) have low variation, while countries whose results are less consistent across the 15 scenarios (e.g., Finland) have high variation.

Figure 4: Contrast of using individual risk objectives (governance, land use, climate) to the null scenario of uniform objective structure. The top panels represent the individual risk data for the focal regions. In the bottom panels brown shows null, green the specific risk objective scenario results, and purple where both scenarios agree. The figures show how the spatial configuration of the solutions changes when risk is considered in a scenario. Governance focus is on Finland and Russia, land use risk on Sierra Leone and Liberia, and climate risk on Serbia, Hungary and Kosovo.