Comments from reviewer

I appreciate that the authors ran another prioritization with an alternative scenario on climate metrics. However, I have not seen why velocity of climate change is preferred as the main metric than exposure to extreme events. I think that some areas are more vulnerable to the latter. For example, the rainforest at my study site was heavily impacted by ENSO in 1997, 2015, and 2019, damaging much of wildlife habitat, causing wildlife mortality, increasing chance of disease outbreak, etc. Maybe in the other region, the former climate metric is more important. So I suggest the authors to add 1-2 sentences on why the former metric (velocity of climate change) is chosen for the main result (could add in line 126).

- Regarding unclear comment for Line 183-185 in the first manuscript, I was referring to how much area do we need to add to existing protected area network in order to cover all priority areas identified in this study, i.e. how much area in km2 are purple vs. green in Figure 1?

- Figure 4: I agree that country names might make the figure busier. But not all readers are familiar with the regions being shown. Perhaps add inset maps showing which part of the continent the pictures are from? (For me personally, I am not familiar with southern Europe).

- Supplementary materials Table S2: I still somehow see the notations A, S, L, and C in the first column of the csv spreadsheet. I am not sure if these are supposed to correspond with N, G, L, and C in the Table S2?

- Please change all “null” to “baseline” in the supplementary materials too. (good idea)

- Line 84: Capital P for Python

- Line 180: superscript km2

- Line 184: add space between 2,160reptile

**SSG=see style guide**

**Protected area planning to conserve biodiversity in an uncertain future**

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**Keywords:** biodiversity, protected areas, optimization, risk, governance, land use, climate change

**Article Impact Statement:** Accounting for governance, land use and climate risks will result in more resilient and effective conservation effort for biodiversity.

I read the abstract and tables and figures carefully and spotchecked the rest of the manuscript for factors that should be addressed before copyediting and typesetting. In most cases, only the first or first few instances of a particular point are marked.

**Abstract:**

use an entire page for your abstract to provide a miniversion of the paper

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. We used a novel hierarchical optimization approach to identify priority areas for expanding the global protected area system that explicitly accounted for such risks while maximizing protection of all known terrestrial vertebrate species. xxx Reducing exposure to these risks required 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, and 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 they bordered 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 (CBD 2010, 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; CBD 2010, 2020; Venter et al. 2014) and carry the tacit, but often incorrect, assumption that protection will be enforced, effective, and permanent. However, 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). Patterns in protected area vulnerability vary spatially, with some regions and jurisdictions being more vulnerable to protected area degazettement or degradation than others (Mascia & Pailler 2011; Leberger et al. 2020). Few conservation plans have explicitly considered these risks (McBride et al. 2007; Alagador et al. 2014). We examined how the planning lens can be expanded to include risks as well as ecological value with the goal of improving the resilience and performance of protected areas.

We considered the following 3 (copyeditor will change numbers to style during copyediting) broad categories of risk, which we defined as factors likely to diminish the long-term effectiveness of protected areas: governance, land use, and 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 the 3 risk categories on allocation of protection decisions at a global scale in habitat for all 29,350 vertebrate species on the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (IUCN 2019) (SSG, using) with a multiobjective 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 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 include only land-cover classes that matched (SSG, tense) the habitat associations for each species. Habitat associations were obtained from the IUCN Red List species habitat classification scheme and were matched to xxx (spell out) land-cover classes for the year 2018 following Santini et al. (2019). Classifications of suitable’ and ‘marginal’ were used and included those identified as of major importance. xxx (spell out) land-cover classification data were aggregated from 30- m resolution to match the global 1-km grid with (SSG, using) a majority rule. Species’ ranges were additionally filtered so that only areas within a species’ accepted elevational range were included. Elevation limits were obtained from IUCN Red List entries for each species. Global elevation data derived from SRTM were obtained from WorldClim 2 (Fick & Hijmans 2017). For bird species with multiple seasonal distributions, data for resident, breeding, and nonbreeding ranges were processed separately. For each AOH data set, we calculated the proportion of habitat at a 10 x 10 km resolution, which was the resolution used in the optimization analyses.

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 (UNEP-WCMC & IUCN 2020)). Following standard procedures for cleaning the protected area dataset (Butchart et al. 2015), we projected the data to an equal-area coordinate system (World Behrman), excluded reserves with unknown or proposed designations, excluded UNESCO Biosphere Reserves (Coetzer et al. 2014), buffered sites represented as point localities according to their reported area in the database (see UNEP-WCMC & IUCN (2020) for buffer sizes), dissolved boundaries to prevent problems with overlapping areas, and removed slivers (code available from 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 Earth and coded grid cells as protected if the protected area covered >50% of the cell, following common practice (e.g., Hanson et al. 2020). These spatial data procedures were implemented using ArcMap 10.3.1 and python 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 (definitions in Appendix S?). We chose these indicators because they reliably predict protected area effectiveness (Barnes et al. 2016) and state investment in 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) (Appendix S?).

Land-use risk

We used a global land systems map produced by Kehoe et al. (2017) to incorporate the risk of land-use change. This map is based on a global land systems map for the year 2000 (Asselen & Verburg 2012) at a 9.25-km2 spatial resolution, but we refined it based on recent land-cover and land-use datasets to a spatial resolution of 1 km2. Kehoe et al. (2017) further estimated the impact of land use and land-use intensity on biodiversity with data originating from the PREDICTS project (Hudson et al. 2014). They matched their land-systems classes to varying intensity levels for each land-use type (detailed conversion table in Asselen and Verburg [2012]). This allowed Kehoe et al. (2017) to calculate average biodiversity loss per land system (relative to an unaffected standard) by taking the mean model estimates of biodiversity loss per land-use-intensity class from previous work (Hudson et al. 2014). The result gives average relative biodiversity gain or loss per land-system class. We used their modeled mean estimates (following Newbold et al. [2015]) of relative percent biodiversity change for each land-system class for species abundance as a measure of the land-use pressure (Appendix S?).

Climate risk

We used velocity of climate change, which is an instantaneous measurement of how projected temperature increases translate to horizontal climate velocity on the landscape (Loarie et al. 2009). It is an integration of the rate of change in average climate and landscape properties that govern how bands of similar temperature redistribute spatially as climate changes. For example, in a region with high topographic diversity, a species may be able to track its climatic niche through relatively small dispersal distances (e.g., 10s or 100s of meters) upslope or downslope. By contrast, keeping pace with preferred climate under the same magnitude of temperature rise in the plains may require much larger dispersal distances – 100s or 1000s of kilometers. Velocity of future temperature change used here follows the method of Loarie et al. (2009) and is essentially the ratio of the projected temporal rate of change (°C/year) to the spatial rate of change (°C/km). Projected temporal rate of change was based on the 20-year mean (2040-2060) projection for mean annual temperature from the HadGEM2-ES model (CMIP5) and the baseline (1960-1990) temperature available from Worldclim 1.4. Spatial rate of change was derived from 30 arcsec elevation data and calculated with the terrain function from the R ‘raster’ package. We also explored an alternative measure of climate risk: exposure to extreme events. Detailed methods and results for this alternative measure are in Supporting Information.

Multiobjective optimization of risk reduction

We created 15 planning scenarios, such that solutions accounted for all possible combinations of risk categories within each hierarchical level (Table 1). We then compared these risk-based solutions with those produced with a baseline scenario that adopted the traditional area-minimizing approach to optimization without considering risk.

We processed all data described previously to a 10 x 10 km resolution and clipped data to the extent of land based on the global administrative areas database to use as planning units in the optimization analyses. For biodiversity data, we calculated the proportion of habitat in each 10 x 10 km pixel. For governance risk and land-use risk, we used the nearest neighbor approach, and for climate risk we calculated the mean. We used this resolution as a trade-off between precision and computational feasibility. In our multiobjective approach, we used a hierarchical (lexicographic) framework that assigns a priority to each objective and sequentially optimizes for the objectives in order of decreasing priority. At each step, it finds the best solution for the current objective, but only from among those that would not degrade the solution quality for higher-priority objectives. We considered up to three objectives in our prioritization scenarios: governance risk, land-use risk, and climate risk. To compare different scenarios, we calculated solutions for each unique objective combination (*n*= 15), as well as one where we used a constant objective function as the baseline scenario because the order of the hierarchy can influence the results (details in Appendix S?).

In systematic conservation planning, conservation features describe the biodiversity units (e.g., species, communities, habitat types) used to inform protected area establishment. Planning units describe the candidate areas for protected area establishment (e.g., cadastral units). Each planning unit contains an amount of each feature (e.g., presence or absence, number of individuals). A prioritization describes a candidate set of planning units selected for protected establishment. Each feature has a representation target indicating the minimum amount of each feature that ideally should be held in the prioritization (e.g., 50 presences, 200 individuals). To minimize risk, we used data sets that described the relative risk associated with selecting each planning unit for protected area establishment. Thus, we sought to identify a prioritization that met the representation targets for all of the conservation features with minimal risk.

We set *I* to denote the set of conservation features (indexed by *i*), and *J* to denote the set of planning units (indexed by *j*). To describe existing conservation efforts, *pj* indicates (i.e., using 0s and 1s) whether each planning unit *j* ∈ *J* is already part of the global protected area system. To describe the spatial distribution of the features, we let *Aij* denote (i.e., using 0s and 1s) whether each feature is present or absent from each planning unit. To ensure the features are adequately represented by the solution, we let *ti* denote the conservation target for each feature *i* ∈ *I*. We let *D* denote the set of risk datasets (indexed by *d*). To describe the relative risk associated with each planning unit, we let *Rdj* denote the risk for planning units *j* ∈ *J* according to risk datasets *d* ∈ *D*.

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The problem contains the binary decision variables *xj* for planning units *j* ∈ *J*.

The reserve selection problem is formulated as follows:

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Text

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The objective function (eqn 2) hierarchically (lexicographically) minimizes multiple functions. Constraints in eqn 3 define each of these functions as the total risk encompassed by selected planning units given each risk dataset. Constraints in eqn 42c ensure the representation targets (*t,i*) are met for all features. Constraints in eqn 5 ensure the existing protected areas are selected in the solution. Finally, constraints in eqn 6 ensure that the decision variables *x*,*j* contain 0s or 1s.

For all scenarios, we locked in current protected areas. Following Hanson et al. (2020), we used flexible targets for habitat based on species’ ranges. Species with fewer than 1,000 km2 of habitat were assigned a 100% target (1,802 amphibians, 893 avian, 645 mammalian, and 1,707 reptile species), species with more than 250,000 km2 of habitat were assigned a 10% target (712 amphibians, 4,518 avian, 1,868 mammalian, and 595 reptile species), and species with an intermediate amount of habitat were assigned a target by log-linearly interpolating values between the previous two thresholds (2,683 amphibians, 5,190 avian, 2,557 mammalian, and 2,160reptile species). Migratory bird species were assigned targets for each seasonal distribution separately. To prevent species with very large habitats from requiring excessively large amounts of area to be protected, the targets for species’ distributions larger than 10,000,000 km2 were capped at 1,000,000 km2. This upper limit affected only 206 (1%) species, and sensitivity analyses in a similar study showed that it had a negligible effect on results (Extended Data Fig. 1 in Hanson et al. [2020]). These targets are arbitrary; however, they are more precise than previous targets based on species’ ranges (which can contain a large amount of area that is not habitat) and account for the increased vulnerability of species with small range sizes (Pimm & Raven 2000), as well as the difficulty in conserving all habitat for species that occur over large areas. We did not consider all sources of uncertainty, such as uncertainty in species distributions or climate predictions. Rather, we focused on the risk categories identified above.

**Results**

Scenarios that incorporated combinations of the three risk categories increased the priority area by only 1.6% on average (0.08 – 2.52%) compared with the baseline scenario based solely on ecological value to species. Among single-risk scenarios, accommodating risks due to climate change velocity required the greatest increase in global protected area compared with scenarios including only governance or land-use-intensification risks (Table 1).

Scenarios shared many overlapping spatial priorities, which can be considered reliably good investments in terms of both ecological value and risk management. Most notably, all 15 nonbaseline scenarios prioritized the same 8.5 million km2 (5.8% of global land area) (no regrets areas, Fig. 2), much of which was located in western South America and Southeast Asia (Appendix S?). There was also substantial overlap among the priority areas across scenarios within Conservation International’s global biodiversity hotspots (Myers et al. 2000), but many high overlap areas were either outside of (53.3%) or in small areas inside hotspots (Appendix S?).

Risk scenarios elicited several prominent shifts in spatial priorities among areas varying in risk exposure (Fig. 3; Appendix S?). In some cases, high risks to protected areas in weakly governed countries could be compensated by expanding protected areas in well-governed neighboring countries (Appendix S?). For example, challenges to the transborder conservation of the wide-ranging and IUCN-vulnerable caribou (*Rangifer tarandus*) due to weak governance in Russia (Appendix S?) were mitigated by increasing the land area protected by Finland from 16.2% to 36.4% (Fig. 4). High exposure to risks from land-use change could be offset in a similar fashion, such as by protecting more land in Liberia (32% versus 22.5% in the baseline scenario) than in the agriculturally intensifying nation of Sierra Leone (Fig. 4). Likewise, climate-associated risks in Hungary and Serbia (Appendix S?) might be tempered by protecting twice as much land (20.4% versus 10.2% in baseline) in nearby Kosovo, which has lower predicted climate velocity (Fig. 4). Addressing risks from extreme weather events (La Sorte et al. 2021) (Appendices S?-S?) also required shifting some priority areas to less climatically volatile locations. Combining climate velocity and extreme weather events into one metric illustrates a somewhat smoothed response (Appendices S?-S?).

**Discussion**

Although a growing body of literature shows that protected areas are seldom effective if subject to unmitigated risks from land-use change, weak governance, and climate change (Schulze et al. 2018; Tesfaw et al. 2018; Maxwell et al. 2019), most systematic conservation planning efforts prioritize land based on ecological value and some measure of cost. We showed how relatively small (1.6%) increases in land area, but importantly a change in the spatial configuration of where protected areas are placed, may reduce the vulnerability of protected areas to future threats if risk is explicitly considered during planning stages (Fig. 1). Across all planning scenarios, we identified 8.5 million km2 of priority lands that either uniquely contributed to conservation targets (e.g., high endemism) or were resilient to the risks we modeled. Countries with large proportions of land already in protection (e.g., Brazil with >30%) also had similar priorities for risk versus baseline scenarios. Although our results are meant to illustrate the importance of considering risk, rather than directly informing real-world decisions, such shared priority areas across planning scenarios appear to represent good return on conservation investments.

A novel contribution of our framework is that it explicitly incorporates multiple risk factors at the same time. Previous work has incorporated single risk factors analogous to those we used, including governance (Mascia & Pailler 2011; Eklund & Cabeza-Jaimejuan 2017), climate change (Hoffmann et al. 2019), and land-use change (Pouzols et al. 2014; Di Minin et al. 2016), demonstrating the importance of each type of risk in protected area planning. Our results similarly demonstrated that protected area expansion decisions can be profoundly influenced by all three risk factors combined, yet they also showed that relatively little additional protected area is required to account for these risks.

Despite relatively modest differences across scenarios in the amount of land required to conserve terrestrial vertebrates, shifts in the locations of priority areas sometimes resulted in substantial increases in a given nation. These asymmetries highlight the importance of cross-jurisdictional coordination to promote collaboration and improve the effectiveness of protected area systems (Dallimer & Strange 2015). In regions where nations vary widely in exposure to risks, coordination may provide opportunity to offset or otherwise mitigate risks by adjusting the geographic locations or boundaries of protected areas. Cooperative governance frameworks (Miller et al. 2019) are especially important for countries supporting wide-ranging species that are expected to be affected by climate, land-use, and governance risk across borders (Fig. 3). These governance frameworks would need to be developed in an environmentally just and equitable way to deliver benefits to biodiversity and local communities (Martin et al. 2013).

In countries, the implementation of enhanced protected area networks will be highly dependent on local legal frameworks regarding land-use protection. For example, in Canada, most land (approx. 86%) is controlled by provincial and territorial governments (Neimanis 2013), although there is increasing momentum for conservation partnerships with Indigenous peoples and their governments (IUCN 2018). In contrast, in the United States the federal government is the largest landowner (controlling approx. 27% of land); only 9% of land is owned by states (Rasker 2019 p. 20). Despite differences in governance structure among countries, cooperation among various jurisdictions within them will be essential for achieving broader protected area targets. Some level of rebalancing opportunity costs may also be necessary for those jurisdictions shouldering the largest burden of protected area expansion.

Our flexible framework and methods can also allow conservation agencies to set their own priorities from local to global scales and incorporate different metrics to assess the relevance of different forms and levels of risk. Nevertheless, we acknowledge two important caveats. We followed current practice in terms of spatial resolution for global scale analyses (Hanson et al. 2020; Jung et al. 2021) and used AOH because it is a better proxy for area of occupancy than unrefined IUCN features (Brooks et al. 2019) (original was an incomplete sentence; edits may have changed meaning). However, there a documented risk that processing IUCN range maps at fine spatial resolutions may overestimate biodiversity because a species is assumed to occupy all areas of a pixel (Hurlbert & Jetz 2007). Thus, our results should be assumed to be maximum biodiversity estimates. Second, our estimate of the additional protected area needed to account for risk reflects the measures used in this analysis and could differ in both amount and location with other measures of risk for governance, land use, or climate or if other types of risk are considered. Indeed, our risk metrics were chosen as reasonable examples, rather than definitive recommendations. Our alternative climate risk frameworks (Appendix S?) illustrate the importance of metric choice. The difference between our climate risk scenarios highlights the need for agencies to carefully consider their choices of risk metrics and suggests that smaller-scale planning exercises should choose metrics that are most relevant for each region.

The conservation community has traditionally neglected to estimate how future changes in climate (Kelly et al. 2020), land use (Di Minin et al. 2016), and governance risk might compromise the effectiveness of protected areas. Yet, as ambitious new plans are put into effect to curb biodiversity loss (CBD 2020) in a rapidly changing world, we showed that incorporating future risk has profound implications for the spatial distribution of protected areas. The risk of weak governance was particularly influential. Surprisingly, incorporating risk into decision-making added <2% to the total global area required to meet biodiversity targets. Thus, accounting for risk comes at limited extra cost, which is likely outweighed by increased likelihood of achieving global biodiversity targets. Our results also emphasize the importance of cross-jurisdictional conservation initiatives, especially in adjacent countries sharing wide-ranging species where risk varies considerably from country to country. Considering risk in conservation decision-making will result in more resilient and effective conservation plans into the future to help safeguard Earth’s biodiversity in the face of the current extinction crisis.

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All data, scripts, and full results are available from <https://osf.io/e2fuw/?view_only=46eb2e525daf42d29df318a92762d885>. (move this to Methods or Results)

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Tables and figures need to stand relatively on their own, so for some more context is needed

Table 1. XXX (what kind of scenarios, need context specific to your study) scenarios and global protection results in an examination of xxx (or something like this).

|  |  |  |
| --- | --- | --- |
| Scenario | Risk factors included\* | Global land area protected (%) |
| Null | - | 21.27 |
| 1 | G | 21.35 |
| 2 | L | 22.31 |
| 3 | C | 23.79 |
| 4 | G > L | 21.93 |
| 5 | L > G | 22.18 |
| 6 | G > C | 23.78 |
| 7 | C > G | 23.31 |
| 8 | L > C | 23.52 |
| 9 | C > L | 22.99 |
| 10 | G > L > C | 23.52 |
| 11 | G > C > L | 23 |
| 12 | L > G > C | 23.5 |
| 13 | L > C > G | 23.08 |
| 14 | C > G > L | 22.3 |
| 15 | C > L > G | 22.99 |

\* Order represents the order in which risk factors were included in the hierarchical prioritization. Abbreviations: G, governance; L, land use; C, climate).

**Figure 1:** Spatial representation of priority areas for protection that account for governance, land use, and climate risk to terrestrial vertebrates together and in that order. (move to Results if not already there; SSG, “Tables and Figures”

**Figure 2**: No regrets areas (i.e., xxx) comprising 8.5 million km2 of land that was identified as priority habitat for protection of xxx regardless of the type of risk (x, y, and z) included in our analyses of xxx (provide context; what did you analyze?).

**Figure 3:** Percent country-level variation between the baseline (traditional area-minimizing approach to conservation optimization without considering risk) selected-area scenario and the 15 scenarios that included x, y, and z risks to terrestrial vertebrates. Countries with consistent results across the 15 scenarios (e.g., Mexico) have low variation, whereas countries with less consistent results across the 15 scenarios (e.g., Finland) have high variation.

**Figure 4:** Contrast between the individual conservation risk objectives (governance, land use, climate) and the baseline scenario (null, traditional area-minimizing approach to conservation optimization without considering risk) of uniform objective structure for conservation area selection. The top panels show the individual risk data for the focal regions (left, northern Europe; center, West Africa; right, southern Europe). The bottom panels show xxx for the baseline scenario (brown) the specific risk-objective scenario (green, governance, land use, and climate), and where both scenarios agree (purple). The figures show how the spatial configuration of the protected-area solutions change when risk is considered. The top row of the maps represent data in their original resolution, the bottom row represents scenario results at a 10 x 10 km resolution.