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Title: Protected areas for biodiversity conservation in an uncertain world

Protected area planning to conserve biodiversity in an uncertain world

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**Abstract:** Despite being key instruments for conservation, protected areas are vulnerable to risks associated with weak governance, land-use intensification, and climate change. Using a spatial optimization routine to maximize protection of all known terrestrial vertebrate species, we found that plans for expanding the global protected area system that explicitly account for such risks require remarkably small (0.8%) increases in the amount of land protected relative to ignoring risk. Among the three risk categories, governance drove the greatest variation in the location of land prioritized for protection. 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 global planning efforts.

**One-Sentence Summary:**

For more resilient protected areas to safeguard biodiversity, planning will require a consideration of future risk

To safeguard biodiversity, protected area planning will require a consideration of future risk due to weak governance

**Main Text:** Protecting habitat is one of the best strategies for stemming the alarming decline of biodiversity5. As such, international agreements to protect increasing amounts of land area have become cornerstones of efforts to protect biodiversity4. Most current approaches for identifying important areas to protect rely upon estimations of the conservation value of the land for biodiversity and the threats it faces4,6,7. Seldom articulated in such plans is the tacit assumption that protection will be enforced, effective, and permanent, yet it is well known many protected areas are subject to risks from weak governance, land use intensification, and climate change. For example: the quality of governance relates to investment in conservation8,9; political instability and corruption can reduce protected area effectiveness10,11; protected areas with high deforestation rates are at greater risk of degazettement and failure to meet protection goals12; and shifting temperature regimes and increased extreme weather events cause declines and extirpations in native populations13. Thus, to make effective use of limited conservation resources, planning for investment in protected areas must account for these risks14,15. Here we demonstrate how accounting for governance, land-use, and climate risks can influence decisions for establishing protected areas at a global scale and may ultimately improve the resilience of protected areas and the species they support. The risks we consider here represent unstoppable risks that are best avoided, which stand in contrast to stoppable risks that can be abated through effective protected areas management alone16,17.

We defined the following three broad categories of risk, which we considered to be factors likely to diminish the long-term effectiveness of protected areas: (i) governance, (ii) land-use, and (iii) climate. For governance risk, we used a national-scale metric that combines six governance indicators from the World Bank18: accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption (Figure S1). For land-use risk, we estimated the average change in biodiversity per land-use category using methods19 that model the risk of biodiversity loss for land systems due to agricultural expansion and intensification (Figure S2). For climate risk, we used predicted climate velocity, which is the horizontal velocity along the Earth’s surface needed to maintain a constant temperature as climate changes materialize. In addition, to illustrate the effect of using alternative risk measures, we use the duration of extreme heat events, calculated using a probabilistic framework that estimates the novelty of temperatures relative to historical year-to-year variation from 1979 to 2019, identifying areas where heat events are likely to have the most significant effects on biodiversity20 (see Supplementary Material for details). We used these three risk categories for illustrative purposes; the approach we propose is flexible and can easily incorporate additional risk metrics21.

We considered the influence of risk categories on allocating protection decisions at a global scale for suitable habitat for all 30,930 vertebrate species from the IUCN Red List of Threatened Species22 using a multi-objective optimization approach. To incorporate risk categories, we built on a classical problem formulation from the systematic conservation planning literature – the minimum set problem - where the objective is to reach species distribution protection targets, while accounting for one constraint such as land cost or area23–25. We expand this approach to include multiple objectives accounting for varying risk in the problem formulation, by treating each risk layer as a separate objective in the problem formulation26. We use a hierarchical approach that assigns a priority to each objective, and optimizes for the objectives in decreasing priority order. At each step, the approach finds the best solution for the current objective, but only from among those that would not degrade the solution quality for higher-priority objectives.

In total 16 planning scenarios were created, such that solutions accounted for all possible combinations of risk categories within each hierarchical level (Table S1). We then compared these risk-based solutions to those produced with a null scenario that adopted the traditional area-minimizing approach to optimization without considering risk27. Because our scenarios aimed to build upon the current protected area portfolio globally, we incorporated current protected areas into our solutions. For each scenario we set species-based targets based on percentages of suitable habitat[Hanson et al.]. Specifically, we obtained suitable habitat maps [original citation], and set target percentages for each species, from 100% for species with less than 1,000 km2 of suitable habitat to 10% for those with greater than 250,000 km2 of suitable habitat, and linearly interpolated on a log-linear scale between these thresholds.

Surprisingly, scenarios that incorporated combinations of the three risk categories required only 1.6% more global area on average (0.08 – 2.52%) than the null scenario for protecting species’ suitable habitat. Thus, accounting for risks cost relatively little compared to the potential gains from selecting a more resilient conservation network (Figure 1). When only looking at scenarios that included one risk factor, climate change risk forces the greatest increase in global protected area, compared to scenarios only including governance and/or climate extreme risks (Table S1).

We found that protected areas identified across scenarios overlapped spatially, with the same 11.5 million km2 (7.8% of global land area) being prioritized for expansion of the current protected area system in at least eleven scenarios and 8.5 million km2 (5.8% of global land area) in all fifteen risk scenarios (Figure 2). These “no regrets” areas provide examples of places that should be immediate priorities for international agencies aiming to maximize the resilience of protected area networks, as they are robust to assumptions of the relative importance of risk factors. Example countries that have contiguous areas of high overlap among different scenarios are Canada, Kenya and Peru (Figure S4). There is considerable overlap among the priorities across scenarios within Conservation International’s global biodiversity hotspots28, but many high overlap areas lie either outside these hotspots (53.3%) or occur within small portions of the biodiversity hotspots, likely because these areas are important to protect regardless of future risk (Figure S5).

We also found variation in the locations of priorities for protection when risks were introduced (Figure 3; Table S2). These differences were driven largely by governance (Figure S6). Countries with relatively high governance scores had greater area requiring protection under risk scenarios relative to the null scenario, especially when species were wider ranging and when neighboring countries had low governance scores. Thus, risk is connected across jurisdictions, where planning scenarios favor protection of species in nearby countries with low governance risk (i.e., high governance scores). For example, many vertebrate species ranges span northeastern Russia and Finland, with one of the most iconic being caribou (*Rangifer tarandus*), which has an IUCN conservation status of vulnerable. Because Russia suffers from low scores for ‘voice and accountability, rule of law, and control of corruption’ (Table S3), whereas Finland has relatively high governance scores, the scenarios including governance pressures led to a selection of 36.4%of Finland’s land area compared to the null scenario with 16.2% (Figure 4).

Land-use and climate change also influenced variation in the locations of priorities for protection compared to the null scenario. For example, large areas of Sierra Leone are experiencing high risk of biodiversity loss due to expanding intensive land-use practices (Fig. S2), whereas this same risk is lower in neighboring Liberia. Scenarios including land-use risk selected 32.1% of the land area in Liberia compared to 22.5% in the null scenario (Figure 4). Large areas of Hungary and Serbia are have high predicted climate velocity (Fig. S3), whereas most of nearby Kosovo has lower predicted climate velocity. Scenarios including climate impact risk selected of 20.4% of Kosovo’s land area compared to the null scenario with 10.2%, and (Figure 4). The alternative climate risk metric predicting frequency of extreme events[cite LaSorte] (Fig. S\*) indicated different priority areas in some cases. For example, large areas of Libya, which is experiencing fewer extreme heat events than neighboring countries, were prioritized in this scenario and not in the null scenario. This difference between 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 regionally appropriate.

Our overall results emphasize the importance of coordinated cross-jurisdictional conservation planning initiatives29 and identify countries where opportunities for collaboration would yield more resilient protected area systems. To illustrate this point, we consider the Great Green Macaw (*Ara ambiguus*), with <2500 individuals remaining30 and a range that stretches from southern Honduras to western Colombia. Because Great Green Macaw habitat spans several countries differing in governance, land use, and climate risk, coordinated efforts among countries will be necessary for the species to persist in the future. For countries with a predominance of wide-ranging species whose ranges will be impacted by varying climate, land-use, and governance risk across borders, conservation projects can focus on cooperative governance frameworks31 (Figure 3). These governance frameworks, both within and between countries, would need to be developed in an environmentally just and equitable way to deliver benefits to biodiversity and local communities32.

In contrast, there is little difference in protection priorities in some countries at high risk from climate change, land-use, and low governance scores, but with high endemism. Given high endemic biodiversity, and homogeneity of risk, these countries all require high rates of protection within their borders. Moreover, some countries with a large proportion of their land already protected, such as Brazil, which has protected 30.3% of its land area, had lower differences between scenarios that incorporate risk and the null scenario, despite having high climate, land-use, and governance risk. This outlines the importance of further considering the effectiveness of existing protected areas in planning analyses, where pressure from cropland conversion in tropical protected areas has increased to similar rates outside protected areas33.

Previous work has incorporated individual risk factors analogous to those we used, including governance1,34, climate change3 and land-use change2,35. Yet, our results show that protected area expansion decisions can be profoundly influenced by all three risk factors combined. If data on risk alters the effectiveness of biodiversity protection, our results show that they should be used together to support decisions for resilient protected area networks. As an example, climate metrics such as disappearing climates36 might be relevant if the consideration is on small-ranged and threatened species. Our flexible framework and methods can allow conservation agencies looking to set their own priorities from the global to local scale and incorporate different metrics to explore the influence of individual metrics on decisions.

The conservation community has traditionally neglected to estimate how future changes in climate37, land-use35, and socio-economic conditions might compromise the effectiveness of protected areas. Our results show that the spatial distribution of protected areas, rather than the land area *per se*, can be profoundly influenced by risk, particularly from governance. Surprisingly, incorporating risk into decision-making adds <1% to the total global area required to meet biodiversity targets. Accounting for risk comes at limited extra cost, but potentially large benefits to 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 our planet’s biodiversity in the face of the current extinction crisis.

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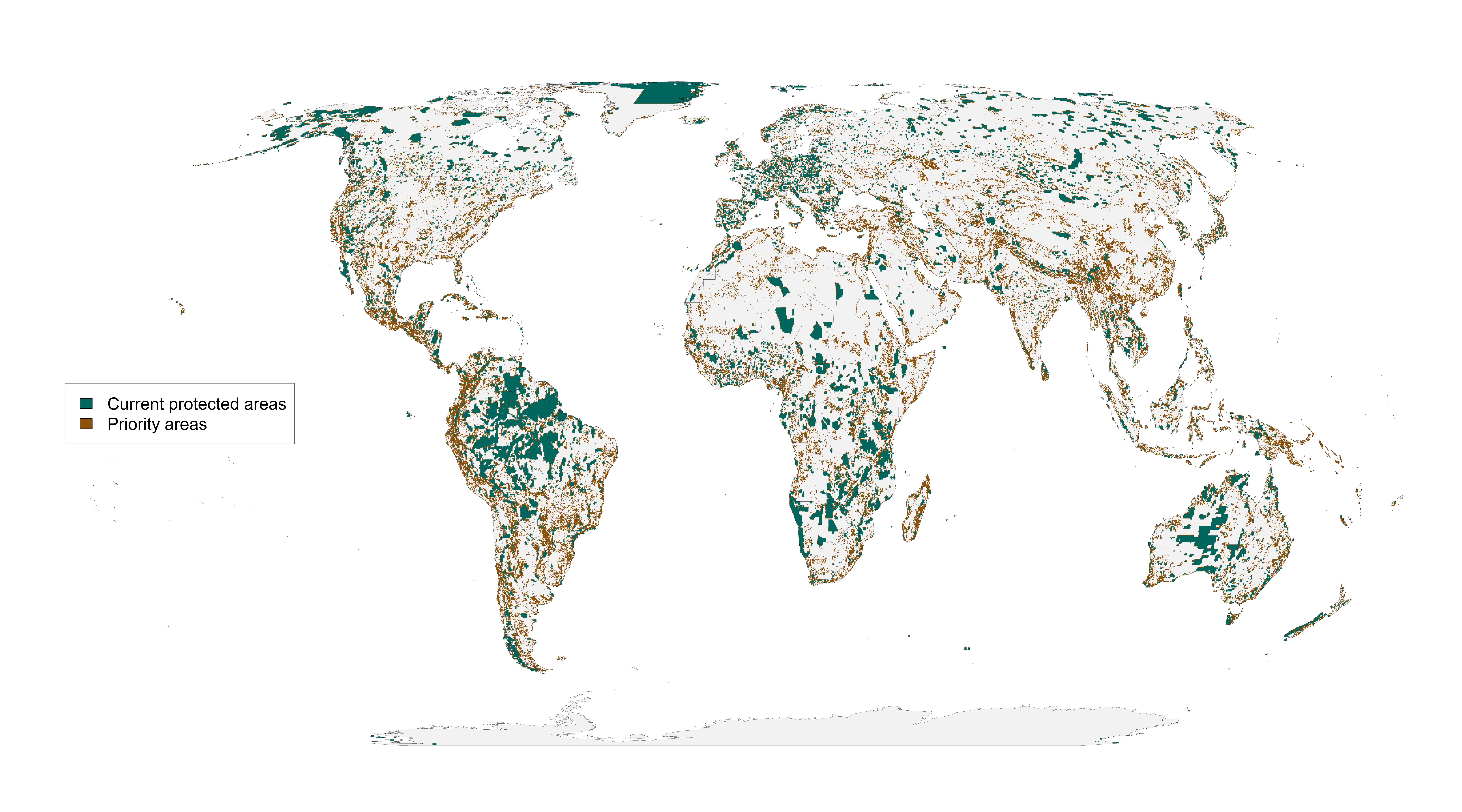
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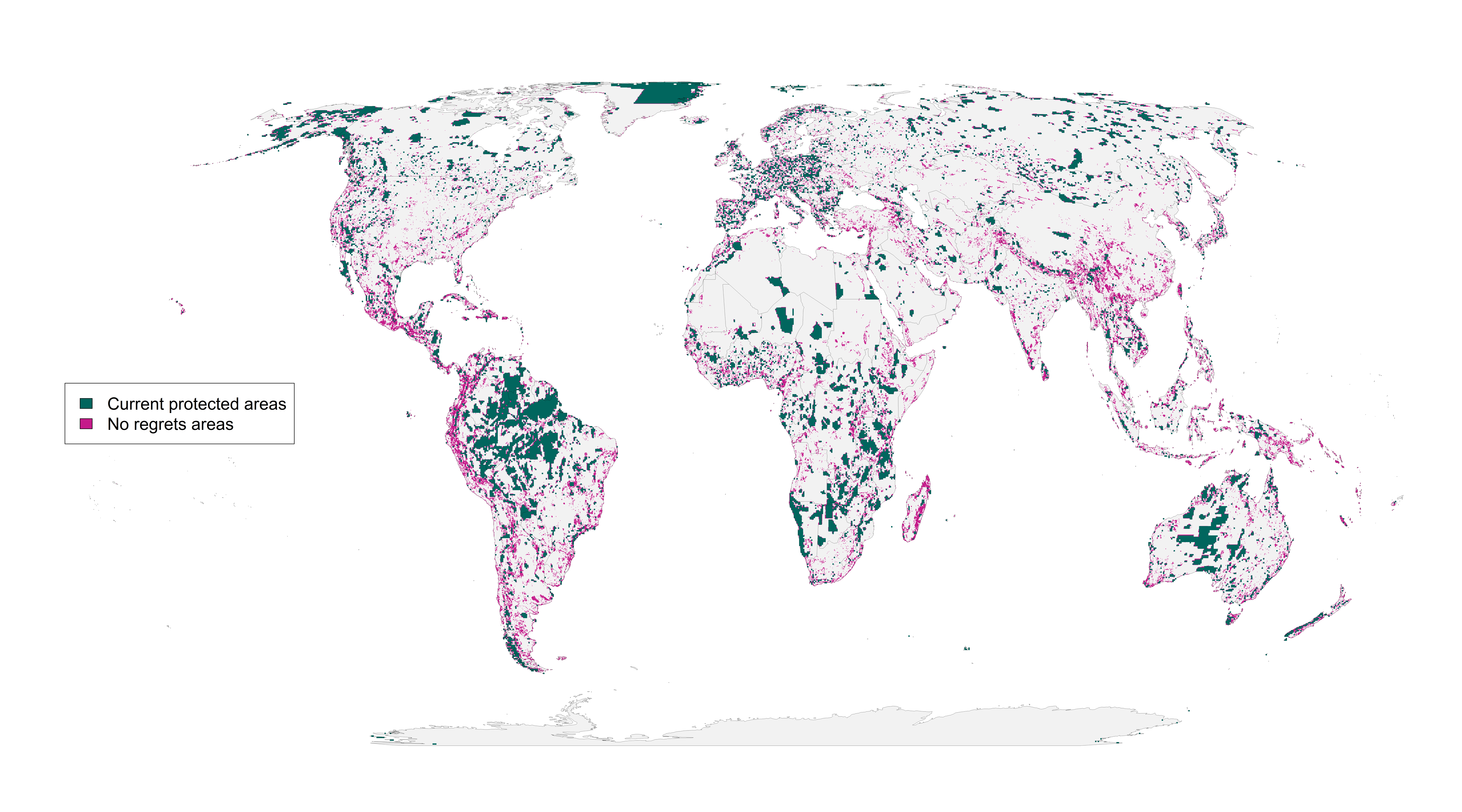
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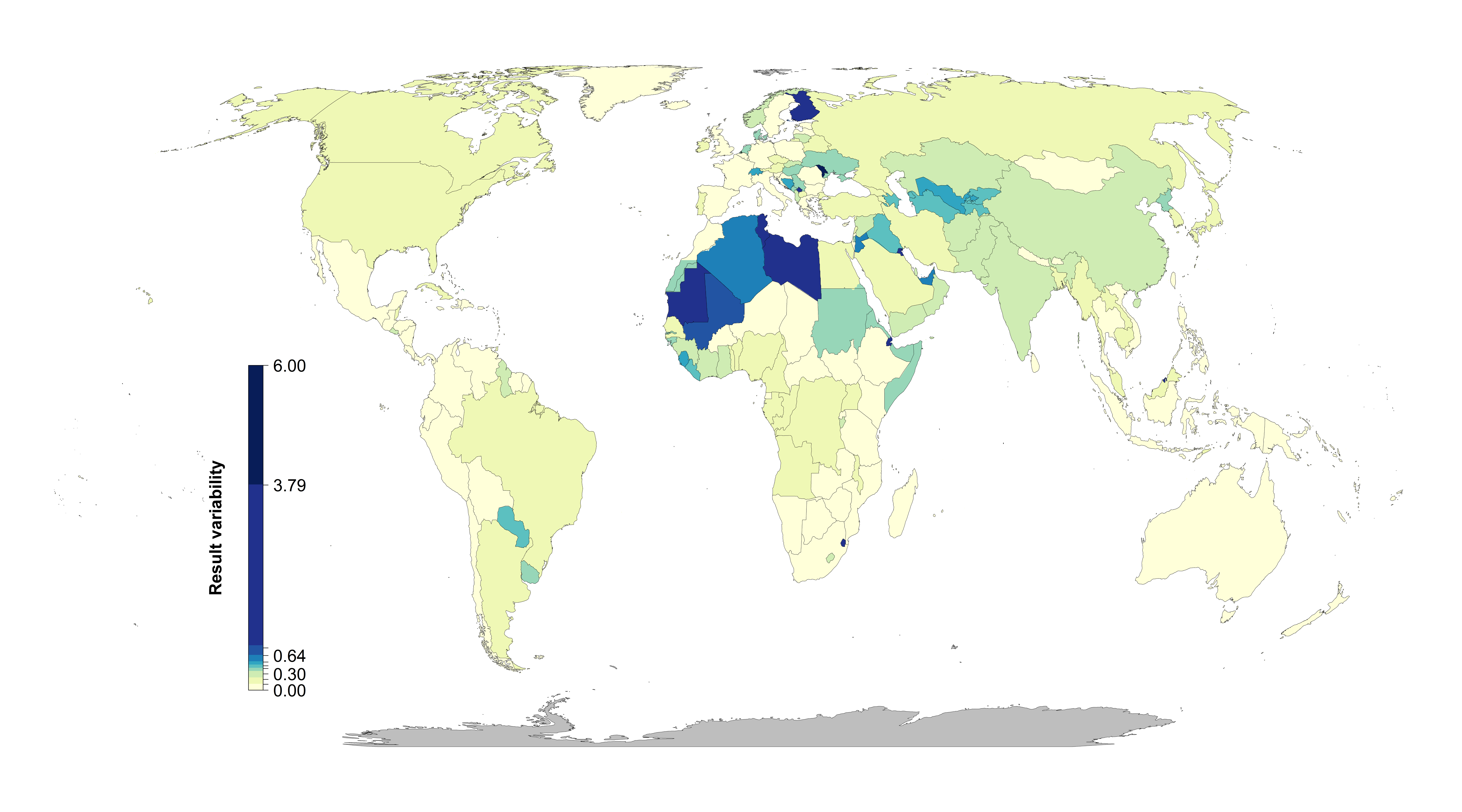
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**Fig. 1.** Spatial representation of priority areas for protection to account for governance, land use and climate risk. Accounting for these risks to protected area effectiveness to produce more resilient conservation networks would require 23.5% of land surface to reach suitable habitat protection goals[cite Hanson] for vertebrate species from the IUCN Red List of Threatened Species22.



**Fig. 2.** Figure 2: “No regrets” areas comprising 3.74 million km2 of land that was identified as priority habitat for protection regardless of the risks included in our analysis.



**Fig. 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. The kmeans method38 was used to generate class intervals for visualization.

Map

Description automatically generated

**Fig. 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.

(Please delete before submission) Supplementary materials should be included in a separate supplementary materials file. A template for this file can be found at: <http://www.sciencemag.org/sites/default/files/Science_Supplementary_Materials_Word_template.docx>.