Dear Mr. Schuster,

Thank you for submitting your manuscript "Protected area planning to conserve biodiversity in an uncertain world" (22-265) to Conservation Biology. I have received two thorough, constructive reviews. The full set of comments is pasted below.

The reviewers approve of the focus of this work. However, they also raise a number of important issues regarding the framing of the study and several of the assumptions underlying the analyses. On the basis of the reviews and recommendation, I invite you to respond to the comments and submit a substantially revised manuscript for potential publication in Conservation Biology.

…

Sincerely,

Mark Burgman,

Conservation Biology

REVIEWER COMMENTS

Reviewer: 1

Comments to the Author

I found this study comprehensive, sound, and relevant for biodiversity conservation globally. First, this study considered large numbers of vertebrate species which included mammals, birds, reptiles, and amphibians. Most of spatial prioritization studies focused on mammals, but the authors in this study considered large number of species comprising multiple taxonomic classes. Second, it focused on optimizing conservation area networks by considering not only the ecological values, but also the three risks, i.e. governance, climate change, and land use intensification, which will make the resulting priority areas are more likely to be successful in a long-term instead of just using biodiversity features as the prioritization goals. Therefore, I see the merit in this work. Moreover, the manuscript is well-written and concise, the method is reproducible, and the results are coherent.

***Thank you very much for this encouraging comment.***

I have two main comments:

1. There have been multiple studies about global spatial conservation prioritization with different scenarios, but I have not seen how this global target should be translated into country-level implementation strategies. While I understand this is not the main focus of the paper, it would be more relevant to conservation managers if the authors suggest clearer recommendations on how countries should increase the protected area size in their countries. A more challenging recommendation is how to get the leaders of the countries and their respective governmental institutions to be willing to increase protected areas in their countries and who should be doing that? NGOs, universities, the government, the CBD? The number of global scale analysis on conservation priorities keeps growing, but there is also a considerable gap between global-level target and implementable country-level conservation efforts. Another thing that may make the results of this study more relatable to conservation practitioners is how much increase in protected area size broken down for each country to meet the “no regret” scenario and the 15 risk scenarios.

***Thank you for this important comment. We have addressed it in two ways. First, we have provided more detailed recommendations in the Discussion section. In doing so, we emphasize the need for flexibility, given that land-use policy is implemented at various scales both within and among countries. Please see lines 257+. Second, we have provided a table of the increase in protected area size for each country to meet the 15 risk scenarios. Please see table S2. As the “No regrets” results don’t represent its own scenario, but are a subset of the scenarios we decided not to include these in Table S2 as presenting those results in that table would be misleading in our opinion. We did however provide a map of them (Figure 2) and if readers are interested to explore those results further, we do provide all data, scripts and full results on the Open Science Framework (OSF):*** [***https://osf.io/e2fuw/?view\_only=46eb2e525daf42d29df318a92762d885***](https://osf.io/e2fuw/?view_only=46eb2e525daf42d29df318a92762d885)

2. There are two climate risk metrics considered by the authors: the velocity of climate change and the exposure to extreme events. The authors have acknowledged that the spatial distribution of the two metrics were very different, and hence provide alternative priority area mapping in the Supplementary Materials. I think that both metrics are important to biodiversity and I am wondering if the authors have considered to combine both metric to represent climate change risk in one map by scaling each metric and adding the values. I think it is justifiable as the governance risk also consisted of several indicators. I suggest the authors to include both metrics for climate risk and re-run the analysis or provide more elaboration on why these two metrics cannot be combined and why one metric is chosen over another.

***Agreed. We have run the prioritizations with an alternative scenario combining the two climate metrics. This is now available in the Supplementary Information, in figures S10-S12, and described in lines 220+.***

Other minor comments and questions:

- Line 50: Put the opening bracket after Brooks et al.

***Done***

- Line 53-57: What does “habitat associations” here indicate: the suitable habitat only or suitable and marginal? And did it also consider the different types of “Major Importance”? Please elaborate in the text.

- Line 74: Why was 10x10 km resolution for protected areas used if the biodiversity raster resolution was 1x1 km?

***This was used because of computer time limitations. The processing time scales exponentially as the number of cells increases. Our 10x10km scenarios ran up to a max of 16h each. We have explored 5x5km as well, but they had a really hard time to finish as we often ran out of RAM (256GB). We have added text on this in the Methods section in lines 136+.***

- Line 123-124: Did the 16 scenarios also include a null model? If so, then “all possible combinations of risk categories” totalled 15, which were later compared to a null scenario. Please rephrase.

***Good point; thank you. We have corrected this number to “15”, given that the null scenario is described in the next sentence.***

- Line 127: Related to previous comment, if the 10 x 10 km resolution was used for processing all data, why the biodiversity features and ESA land cover to represent species’ habitat were processed at 1 km resolution? Were the habitat suitability rasters then aggregated from 1 x 1 km to 10 x 10 km? If so, how were they aggregated?

***Thank you for pointing this out. We have now added more details on this in the Methods section in lines 132+.***

- Lines 165-172: Why did these numbers of species not include reptiles?

***Thank you very much for pointing this out. We accidentally omitted these numbers. Reptiles are now included in this section, see lines 51 and 177+.***

- Line 176: Would the sensitivity analyses be included in the Supplementary Information?

***Thank you for this comment. We have now updated the methods section to point interested readers to the sensitivity analysis results. See lines 185-186.***

- Like 183-185: Another interesting point to present and discuss is how much additional areas from existing protected area network are needed to meet the risk scenarios? Because although a little additional area of 1.6% is needed to take into account of conservation risks compared to only targeting ecological values, the more challenging effort to do is to add more protected areas to the existing ones by creating new ones or expanding existing ones, as shown on Figure 1 and 2. Please also add this on the abstract.

***Thank you for this comment. We have to admit that we are not clear on what the reviewer is asking here. As a consequence, we have decided to not change anything in the manuscript. If the reviewer could clarify their comment, we would be happy to make changes to the manuscript.***

- Line 189-191: I am not sure if the same 8.5 million km2 refer to comparisons among the 15 risk scenarios OR between null scenario and 15 risk scenarios because the “no regret” area is mentioned in this sentence. Please rephrase to clarify and define the meaning of “no regret” area. And how were these countries (Canada, Kenya, Peru) were selected? A glimpse at Figure S4 seems to show that not much priority areas in Canada, but much more in Central American countries, South and mainland South East Asian countries, and Madagascar. As an addition, the regional areas could also be mentioned other than the individual countries.

***Thanks. We agree that this needed clarification. We like the idea of referring to regions rather than individual countries. We have changed lines 202-205 accordingly.***

- Figure 1: The color for priority areas in the legend appears brown, but purple on the map.

***Thank you. We have adjusted the figure legend of Figure 1 now.***

- Figure 4: Annotate country names on the map.

***Thank you for this comment. We removed any mention of countries in the figure legend as we felt this was easier to do than to add all country names of the map, which would have made it even busier than it is.***

- Supplementary materials Table S2: the example of 5 countries used different notations (N = null, G = governance, L = land use, C=climate) than the one in Google Drive folder (A, S, L, C?) for the 15 prioritization scenarios.

***Thank you for catching this! Change made.***

Reviewer: 2

Comments to the Author

Thank you for the opportunity to provide feedback on this interesting article. I have detailed below my impressions and shared some comments and suggestions for improvement. I think there is value in the article, but I also think that some limitations of the data must be acknowledged to avoid the risk of readers using this analysis inappropriately. These limitations are an inevitable trade-off when dealing with ~ 30.000 species, but on-the-ground recommendations should be provided with much caution given well-known biases in range maps (even when adjusted as done here).

***Thank you for this important comment. We hope the changes outlined below help to address the concern re potential inappropriate use of the analysis.***

General comments

Wording: I found the title a bit misleading, in the sense that referring so broadly to uncertainty made me think right away to uncertainty in the predicted distribution of species, another concept that has been poorly investigated in conservation planning. Perhaps something similar to “Protected area planning to conserve biodiversity in world of uncertain climate, land use, and governance” might be easier to connect the reader with the topic discussed in the paper. Also regarding wording – the “null scenario” is really not a null model in the traditional sense of a model generated with randomization, but rather a “no cost” scenario. I was a bit confused by this terminology, particularly in figure 4.

***Thanks for these comments. We have considered a title change but were not comfortable with the suggestion. We did however made a slight modification in the title changing ‘world’ to ‘future’. We have changed the term “null” to “baseline” throughout.***

Introduction: I found the introduction clear and well written, perhaps a bit short. I don’t think it is necessary expanding this section, but if the authors think it might be a relevant addition, they could provide details on how incorporating uncertainty has improved conservation planning outcomes (line 28), or cases where not accounting for uncertainty has resulted in negative consequences.

***Thank you for this suggestion. We have expanded on the issue of degazettement and degradation, by noting that patterns in them regionally vary. This supports our argument that there is varying uncertainty in protected area viability, and that this needs to be accounted for. Please see lines 25-29.***

Methods: My main concern on this article is on how conservation features, the distribution of species, have been represented in analysis. Starting by rasterizing species ranges at a 1-km grain ignores a very well known problem in the literature on range maps, since stacking range maps overestimates local biodiversity at grains larger than tens (if not hundreds) of kilometers (e.g., Hurlbert and Jetz 2007 in PNAS;<https://www.pnas.org/doi/10.1073/pnas.0704469104>). I realize that there is an additional step of including land cover categories and elevation as additional filters in the analysis, but I personally still feel like the reliability of these surfaces at a 1-km resolution might be limited. Even aggregation to the majority rule of 0.3 km ESA land cover is complicated, in the sense that many metapopulations can persist in landscapes with broken habitat remnants (e.g., tens of cells with 40% forest in an agricultural matrix would be considered agriculture, but could indeed support many species). I do recognize the effort of performing this analysis on thousands of vertebrate species, and I do not think that this aspect invalidates the general point the authors make, but it is worth clarifying and discussing more in the manuscript. For instance, the authors could describe how these limitations of the method might bias the spatial patterns in their results. On a side note, one easy test of the map reliability could be testing for the correlation between your range-based maps and other products, like e-Bird maps based on models calibrated with empirical data.

***Thank you very much for these important comments. We have expanded the Methods section to clarify that we used the 1-km AOH data as a building block for the analyses, and that we aggregated those data to a 10-km resolution which is the resolution we used in all our optimization analyses (see lines 64-65). We have further added a caveat to the Discussion section pointing out potential problems with the resolution we have used here (see lines 269-274).***

I don’t think you reported explicitly the planning unit side, which (if I understood properly) is 100 km2. I wonder why in figure 4 there are much coarser cells?

***Thank you for pointing this out. We have clarified this in the Methods section now. Please see lines 133-137.***

Discussion: I think you need to caution the readers from taking the results of your analysis as a guideline for on-the-ground conservation. I do believe you make a good point that risk including international dynamics must be incorporated into conservation efforts, and that the cost of accounting for uncertainties is relatively low. However, I also think that your analysis only scratches the surfaces in terms of really accounting for uncertainty. Other important sources of uncertainty are the predicted distributions of species (which might have a much larger effect on your increases in areas) and especially the choice of your measures of risk. You do acknowledge that changing climate velocity affects the inference, but those effects are compound and I think it is an overstatement that your analysis resolves this can of worms and that only minor gains are sufficient to resolve the problem. That said, I do think it makes valuable points on the need to start accounting for these sources of uncertainty.

***In the Discussion, we now explicitly state that our results are meant to illustrate the importance of considering risk, rather than informing real-world decisions (which will likely take place at smaller scales, using more local information). Please see lines 234-237. We also have added lines 190-192 to the Methods, which explicitly note that we do not consider all forms of uncertainty.***

***(In part this is a contrasting suggestion from main comment 1 of reviewer 1 which wanted specific recommendations. These two comments represent a bit of a contradiction and***

***we tried to deal with them both as best we could.)***

Also, I do think that an increase of 1.6% on average over 21% of the planet is not that a negligible of an increase, so I personally don’t agree with one of the messages of the paper that we “just need” an additional 1.6%. This is about 7% more than what would be needed without accounting for the cost of uncertainty, and an area larger than many European countries. But this is a matter of opinions, I understand why you stated that 1.6% of the planet surface isn’t that much overall. I raise this point knowing that ultimately it will be up to the authors and the editors to decide whether this view is justifiable.

***This is a good point; thank you. We have toned down the wording regarding the magnitude of the addition in several places (see lines 244+, 274+).***

Detailed comments

Line 23-24: great point.

***Thank you!***

Line 58-59: please report where the species’ elevational level was extracted from.

Line 70: please report the size of the buffers adopted.

***The buffer sizes are detailed in the World Database on Protected Areas (UNEP-WCMC and IUCN [insert year of version]). To improve clarity, we have amended the sentence to ensure that readers know where the buffer sizes were obtained (line 74-75).***

Line 74: was every 10-km cell containing a protected area considered as “protected”? This will have a substantial effect and different effects across space, e.g., PAs in Europe are often smaller than 100 km2, whereas in Africa they are often much larger. In this case, Europe will seem to be more protected than it actually is, for instance. I would suggest discussing somewhere in the paper this pitfall.

***Thank you for this comment. We have adjusted the Methods section (lines 64 – 65) to better reflect what we did and that we followed examples in the literature (lines 269 – 274).***

Line 103: perhaps the first comma is a typo?

***Fixed, thank you!***

Line 134: please refer to table S1, so that it is easier to figure out right away which scenarios you compared.

***Done.***

Line 122-180: I found the description of the conservation planning analysis clear. I am not familiar with lexicography, so I am not qualified to review the specific details of the methods employed, but I am familiar with the specifics of the conservation planning exercise and I thought the authors did a good job in explaining those.

***Thank you! This section took a long time to get right, and we appreciate the supportive comment on it.***

Line 182: In my opinion, 1.6% more land protected on average is not a small area overall. It is also 7.5% more than the null scenario estimates.

***Please see response to comment above. We have toned down the wording regarding the overall area added.***

Line 191: are you sure that Canada includes much of the “no regrets” areas? Figure 2 seems to have not many cells based on visual inspection. Mexico, for instance, seems to have more cells.

***Agreed. Please see response to Reviewer 1 comment above. It’s a good point that other areas have more “no regrets” areas. We have changed the areas being referred to here.***

Line 197-207: these examples are great, but are based on the assumption that your adjusted range maps capture well the distribution of species. I would suggest adding a disclaimer that, for these specific cases, more detailed studies should be used to confirm your findings (e.g., based on species distribution models). The risk I foresee is directing international policy based on data that is, in my opinion, not compelling to make these sorts of decisions.

***Thank you for this comment. In our disclaimer regarding real-world decisions in response to the general comment above, we explicitly noted that real decisions would likely use more local biological information.***

Line 213: Again, 1.6% might seem small but is 7.5% more than your “species-only model” and an area larger than most European countries. I am not debating that it would be worth adding this area to mitigate risks, but I think it is a substantial investment.

***Please see response to the general comment above regarding the 1.6% addition.***

Line 224-226: great point.

You acknowledge the sensitivity of your analysis to the choice of metrics of risk in governance, climate, and land use. I think, given that the metrics were selected quite arbitrarily, you should stress that 1.6% more land protected to account for risk is a measure limited to your “cost space”, and likely an underestimation. Truly accounting for uncertainty, e.g., having multiple cost surface for each risk factor AND a metric of uncertainty on the distribution of species would be a much more difficult task, will likely result in larger requirements of additional protected land.

***We agree that this is important to acknowledge and have now included it in a paragraph in the Discussion on caveats (lines 274 - 279). For this point, we now acknowledge that estimating how risk affects protected area amounts and location is dependent on the choice of a risk measure and the types of risk categories considered. In response to another concern we had conducted a sensitivity analysis to examine how different measures of climate risk affect outputs. This example works well to highlight how the measure of risk can affect outcomes and therefore the importance of carefully considering a relevant measure depending on the region where protected area planning occurs.***

***The concern here also referred to uncertainty and we appreciate the caution, however we are not sure we agree on that aspect. Adding additional parameter uncertainty could provide some confidence bounds on the results (though such a process would be extremely time-consuming given the size of the problem). However, we do not see how this would affect the mean values, which is what our results essentially represent. If managers were risk averse (which sometimes the case), then they may favour an increased land base. This would of course come with higher cost.***

Fig. 1: I don’t understand this figure. Which scenario(s) does it illustrate? All risks together? If yes, in which order? Or is it a combination of multiple scenarios?

***Thank you for this comment. We have adjusted the figure legend to clarify.***

Fig. 4: why is the resolution (grain) in the bottom row coarser than the grain of your conservation planning analysis?

***Thank you for this comment. We have now adjusted Figure 4 legend to clarify that 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.***

As there is no attached R script, I cannot provide feedback in the software development associated with the manuscript.

***We have clarified that the R script is indeed available and was part of the original submission. Please see line 403-405.***