RESPONSE to RC2

Simulating the effects of sea level rise and soil salinization on adaptation and migration decisions in Mozambique

Kushagra Pandey, Jens A. de Bruijn, Hans de Moel, Wouter Botzen, and Jeroen C. J. H. Aerts

---

The paper presents a comprehensive and well-constructed model addressing a significant issue, showcasing both the quality of writing and the relevance of the problem tackled. However, to ensure its suitability for publication, it's essential to address several major concerns crucial for enhancing the paper's credibility and impact within the scientific community.

We would like to thank the Reviewer#2 for the kind words and the helpful suggestions to improve the paper. We agree we can improve the credibility of our paper by improving the validation of our model. We have assessed each comment, and in our reply below, we explain how we would address the comments in our revised manuscript.

Major Comments:

The paper introduces a model focused on adaptation strategies in rural Mozambique but does not convincingly justify its suitability for this specific environment. The application of expected utility theory seems incongruent with the decision-making realities of rural Mozambican farmers, especially considering insights from urban coastal households (Noll et al., 2022). These insights suggest that adaptation behaviors are heavily influenced by non-economic factors, which are presumably more pronounced in rural settings where traditional knowledge and heuristics play a larger role.

This is a very relevant comment. The reviewer is right that our model does not capture all behavioral factors that influence adaptation and migration decisions. We have, therefore, extended the EUT model with a risk perception parameter and a risk aversion function (Ruig et al., 2022; Haer et al., 2020; Gandelman, Nestor, 2015). However, other behavioral factors (e.g., worry, fear, social networks etc.) are not included. We propose two ways to better explain the credibility of using the SEUT in our model:

- In the discussion section we will better explain that following the subjective expected utility theory, increase in risk would lead to an increase in adaptation and migration (Reimann et al., 2023; Hauer, M. E. et al., 2020; Chen and Mueller, 2018; Duc Tran et al., 2023). We then show that our model results show a similar increasing trend. However, to validate these results, we will use recent empirical survey results from a survey we conducted in Mozambique with more than 800 respondents. These data show similarly that increase in flood risk will lead to increasing outmigration. We include descriptive statistics from the survey in our revised paper to motivate our behavioural rules and underpin our results.
- Furthermore, we have will make a reference in the Discussion section that future research should further assess additional behavioral factors following overview studies such as by Noll et al. (2022). For example, such factors can include network effect, worry, climate change beliefs and self-efficacy.

Furthermore, the use of urban housing values to assess expected annual damages further questions the model's applicability, potentially leading to skewed results.

We agree with the reviewer's comments that urban housing values are generally higher than rural values; hence, we also performed a sensitivity analysis on property values in section 5.1c. A study by the World Bank in 2000 on flooding in Mozambique estimated that construction costs in rural Mozambique are six times lower than those of urban houses, while rural houses are half the size of urban houses. Therefore, for the revised versions, we will reduce the property value and adaptation cost in rural areas by a factor of 3, so that the difference between urban and rural areas is better captured.

Moreover, the model proposes structural adaptation strategies like elevation that may be impractical and unreflective of the actual measures farmers in rural Mozambique might undertake. This incongruity points to a critical need for the model to integrate a more nuanced understanding of the behavioral patterns and economic realities pertinent to the rural Mozambican context, raising the question of the reliability of the projections presented.

Before two project colleagues conducted a field survey in Mozambique, we had the same hypotheses as the reviewer. However, our fieldwork in two coastal locations (i.e., Beira and Nova Sofala) in both urban and rural environments revealed that in both areas, elevation is the most selected adaptation option. Hence, the adaptation option 'elevation' is based on the findings in our empirical survey. These data show that elevation does take place (88% of surveyed households have elevation as the first adaptation choice).

To address the reviewers' concern, we will include a new paragraph in the supplementary section of our revised paper on the survey results that substantiate the choices for the adaptation measures included in the model.

Another significant point that makes me doubt the results presented in this study is the lack of any type of validation. Validation is crucial for establishing the reliability of model outputs, and the absence of any such exercise undermines the strength of the conclusions drawn. Although the challenge of obtaining empirical data for rural Mozambique is acknowledged, the paper would benefit from an attempt to validate the model, perhaps through comparisons with historical trends or alignment with known stylized facts about the region. Without this, the model's predictions remain hypothetical and their relevance to actual scenarios in Mozambique is uncertain.

The reviewer is correct that validating an ABM in a data poor areas such as Mozambique is quite difficult. This is why most studies use models for exploring options without validation. However, in our study, we have conducted our own survey (n=828) to collect empirical data on the drivers of migration and adaptation under current and future flooding risk.

Based on the reviewers commend, we understand we have to more adequately describe our empirical data that underlies our modelling parameters and results. We will, therefore, revise the model using survey data to validate our increase projection of risk and adaptation with survey results. We have calibrated our model using a survey that assesses current adaptation levels in both households and farms. The survey also inquiries about future adaptation plans for the next five years. We will use this information to validate the model's results for the year 2027.

The sensitivity analysis presented in the study appears to be insufficient. A more robust analysis should consider a wider range of parameter values beyond a few discrete scenarios, which would allow for a better understanding of the model's behavior under different conditions (especially given the points raised before). For instance, the potential impact of soil salinization could be examined over a spectrum of possibilities, such as a 50% increase in salinity levels, to reflect possible variations in climate change outcomes.

The idea of running 3 values of parameter was to check the upper and lower bound of the possible output to test the uncertainty by running the model at extremes. Good suggestion, we agree with the reviewer to consider the uncertainty in prediction of hazard. We will run additional scenarios, for example, to test the extremes of salinity projections under RCP4.5 and RCP8.5

The paper needs to clearly articulate the relationship between income dynamics and environmental factors such as crop salinization. It is important to determine whether farmers' incomes are fixed regardless of the salinization process. The change in crop yield would have a significant impact on farmers' income, which would play a crucial role in their ability to undertake adaptation action or migrate. This is essential for realistically modeling farmers' capacity to adapt or migrate. Maintaining constant income despite climate changes risks underestimating the economic impact of salinization, potentially restricting farmers' options and leading to misleading results.

Thank you for highlighting this. Upon re-evaluating the paper, we agree indeed that our paper is not clear in describing these relations and will clarify this in a revised version of the manuscript, along the following lines: Our central DEU equations allow for dynamically simulating the relation between income and losses due to salinization and flooded buildings. Thus, our model dynamically simulates the interactions of crop yield loss on income over time and space.

$$DEU_1 = \int_{p_i}^{p_I} \beta_t * pi * U \left(\sum_{t=0}^{T} \frac{W_t + A_{x,t} + Inc_{x,t} - D_{x,t,i}}{(1+r)^t} \right) dp$$

In this equation, $Inc_{x,t}$ is income at a time t in region x which increases over time with the GDP growth rate and $D_{x,t,i}$ is damage experienced by a household every year which has two parts flood damage to buildings + damage to crops due to salt intrusion. The later factor captures the impact of change of crop yield on the ability of the farming household to undertake adaptation decision. In non-flooding years, household income is as expected plus the effect of the GDP growth rate. As an example, we here provide a graph that shows this effect. We propose to include this graph in the revised version of our paper.

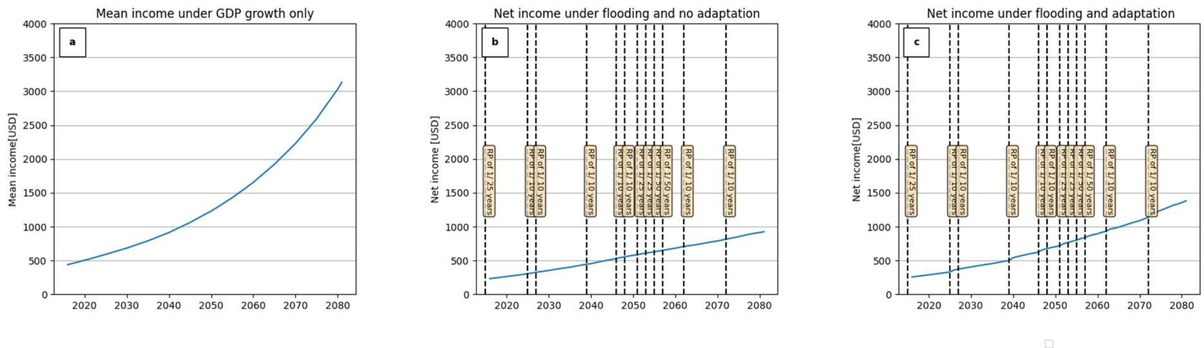

Figure 1 Average household income in Sofala province flood plain under a) GDP growth rate, b) flooding, salt intrusion and no adaptation, c) flooding, salt intrusion and adaptation

Minor Comments:

The justification for the choice of 50 repetitions within the model simulations is unclear. I am not saying it is wrong, but such methodological decisions should be supported by a metric that validates the number's adequacy to capture the variability in results.

Thank you for noting this. We based the 50 repetitions on the work of Tierolf et al. (2023), who also used a maximum of 50 model runs, each having randomly selected variables. Following their work, we will add a new section in the supplementary material with a new figure showing that 50 Monte Carlo runs are sufficient to capture the randomness and low-frequency flood events in the simulations, similar to figure 3 in Tierolf et al. (2024).

The manuscript has omissions in referencing (reference not found), such as missing citations in figure captions and on page 6, line 145.

Thank you, we will address these errors and perform an additional check for a revised version.

The consideration of demographic trends, such as the impact of young people's outmigration on fertility rates and population growth, is lacking. I'm not suggesting that the authors should include it explicitly, but they should reflect upon its implications (Hauer et al., 2024).

Good suggestion. We propose to address this in the discussion section. Outmigration indeed has an impact on population growth. In our model, population growth is determined by the growth rate and net coastal population. We have already incorporated the impact of out-migration on net coastal population and eventually on population growth. As for the fertility rate, it is important to note that our model considers households rather than individuals and currently does not distinguish between younger/older households. We are continuously developing the model, and we have plans to integrate the average age of households into our calculations. This will inevitably affect the fertility rate, mortality rate, and the social vulnerability index.

A reflective discussion on the broader implications of the study's results for the scientific literature and their practical significance would be beneficial. The paper should emphasize how its findings contribute new understanding in the field of climate adaptation.

We will include a discussion on the broader implications of the study and its practical significance, which includes the following points:

- Migration and managed retreat are emerging topics for policy and climate adaptation, especially in areas of the global south where communities have less coping capacity to deal with SLR.
- Our study shows the priority areas for flood and salinization risk and show when and where people intend to migration or adapt.
- The model addresses heterogeneity of households based on socio-economic characteristics such as income differentials, farm size, and types..
- These findings support policymakers in targeting their policies to support individual adaptation.
- We also show that apart from direct flood risk, salinization in rural areas can have similar impacts on communities.

References:

Chen, J., Mueller, V. Coastal climate change, soil salinity and human migration in Bangladesh. Nature Clim Change 8, 981–985 (2018). https://doi.org/10.1038/s41558-018-0313-8

Duc Tran, D., Nguyen Duc, T., Park, E., Nguyen Dan, T., Pham Thi Anh, N., Vo Tat, T., & Nguyen Hai, A. (2023). Rural out-migration and the livelihood vulnerability under the intensifying drought and salinity intrusion impacts in the Mekong Delta. International Journal of Disaster Risk Reduction.

Gandelman, Nestor and Hernandez-Murillo, Ruben, Risk Aversion at the Country Level (2015). Available at SSRN: https://ssrn.com/abstract=2646134

Haer, T., Husby, T., Botzen, W.J., Aerts, J.C.J.H. (2020). The safe development paradox: an agent-based assessment for flood risk in the European Union. Global Environmental Change, https://doi.org/10.1016/j.gloenvcha.2019.102009

Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., ... & Wrathall, D. (2020). Sea-level rise and human migration. Nature Reviews Earth & Environment, 1(1), 28-39

Hauer, M. E., Jacobs, S. A., & Kulp, S. A. (2024). Climate migration amplifies demographic change and population aging. Proceedings of the National Academy of Sciences of the United States of America, 121(3), e2206192119. https://doi.org/10.1073/PNAS.2206192119/SUPPL_FILE/PNAS.2206192119.SAPP.PDF

Noll, B., Filatova, T., Need, A., & Taberna, A. (2022). Contextualizing cross-national patterns in household climate change adaptation. Nature Climate Change, 12(1), 30–35. https://doi.org/10.1038/s41558-021-01222-3

Reimann, L., Jones, B., Bieker, N. et al. Exploring spatial feedbacks between adaptation policies and internal migration patterns due to sea-level rise. Nat Commun 14, 2630 (2023). https://doi.org/10.1038/s41467-023-38278-y

Ruig, L., Botzen W.J., Haer, T., Brody, S., Czajkowski, de Moel, H., Aerts, J.C.J,.H. (2022) How the U.S. can benefit from risk-based premiums combined with flood protection. Nature Climate Change https://doi.org/10.1038/s41558-022-01501-7 (2022).

Tierolf, L., Haer, T., Athanasiou, P., Luijendijk, A. P., Botzen, W. W., & Aerts, J. C. (2024). Coastal adaptation and migration dynamics under future shoreline changes. Science of the Total Environment, 917, 170239.

Worldbank, 2000. Republic of Mozambique: A Preliminary Assessment of Damage from the Flood and Cyclone Emergency of February-March 2000.