Dear Editor,

Thank you for giving us the opportunity to re-submit a revised draft of our manuscript newly titled, "*Social-ecological models with social hierarchy and spatial structure applied to small scale fisheries*". We thank the reviewer for their constructive comments on the manuscript. We have now altered our framing and clarified other points in the text.

Below we detail the changes we made to our manuscript in response to each reviewer comment. We leave the *original reviewer comments in red, italicized font*. Our responses are in black, Roman font. We have also included line numbers of the revised manuscript for each response

Reviewer Comments:

This paper reports on the development of a simple, socio-ecological fisheries model that tests the impact of fish movement and social influence on outcomes in a two patch, co-managed fishery. Its contribution to the field would be improved by a clearer explanation of the rationale behind the model and a fuller explanation of the assumptions behind some of the model parameters.

We appreciate the feedback and provide more detailed responses below.

I recommend including a description of co-management in the introduction and an alignment of the model's parameters with the tenants of co-management. For example, are there limits on the movement of fishers between and beyond the two patches? The introduction references the difficulty of constraining fishing to one group but that is a basic principle of co-management because it changes fishers' incentives from maximizing harvests to developing conservation strategies. Are there mechanisms for dispute resolution and enforcement? That would affect how conflict between overharvesters and sustainers might be resolved.

We agree with a point made later by the reviewer that this model doesn't really reflect co-management practices, but instead disjointed management between two groups. The model reflects two patches connected by fish movement that are fished by separate groups of people who are fishing based on individualized perception of benefits vs costs as opposed to organized consensus about fishing practices. The following lines have been changed to remove all references to co-management in the paper:

- Lines 14-15 "Next, we developed a case-study of a two independently managed fisheries that were connected by fish movement"
- Lines 127-130 "This model reflects two fisheries are connected by the stray rate of two subpopulations of fish, where each subpopulation is independently managed. The two management regimes influence one another based on how many people are fishing in the other group."
- Lines 133-135 " 3) use a two patch small-scale fishery as a case study to understand how fishery dynamics are driven when one group fishes sustainably while the other over-harvests."
- Lines 273-275 " We used this overfishing parameterization for the rest of the analysis of a two patch small-scale fishery"
- Lines 306-308 " This finding is especially relevant to fisheries where different areas where a particular species is fished may be subject to different regulation, environmental conditions, or opinions about conservation. "

We have also added to our discussion a conversation about the benefits of co-management and dispute resolution and enforcement and how these are limitations of the model that can be explored in future research. This is seen in lines 369-382 where we state:

- "Here, we model individual decisions to fish based on the perceived benefits and costs of fishing activity. It does not account for organized decision making on fishing practices or co-management, and there is no mechanism for dispute resolution and regulation enforcement. Co-management is the organized collaboration between stakeholders to regulate ecological extraction while resolving societal conflicts, and is one such way manage ment can incorporate complex social ecological structures (Armitage et al., 2009). Fisheries are increasingly applying principles of co-management as it creates cooperation and conflict resolution between different stakeholders while focusing on ecological sustainability (Butler et al., 2015; Trimble & Berkes, 2015; Murunga et al., 2021). Co-management can also be a mechanism for addressing social inequalities in fisheries (Goetze, 2005; Freitas et al., 2020; Haque et al., 2022). However, they can also fail if social structures are ignored when making conservation decisions (Cumming et al., 2017; Baker-Médard, Concannon, et al., 2021). A limitation of this model is that it does not account for this organized decision-making, and only represents fisheries that have not yet instituted these governing mechanisms."

Finally, the model doesn't account for movement of fishers between patches, and assumes that fishers are only fishing in their respective patch. The patches are only connected by fish movement as well as the social influence that one human population has on the other. This has been clarified on the following lines:

- Lines 152-156 "Humans in this population can either be harvesters (therefore participating in harvesting activity) or conservationists (who do not partake in resource extraction) in their respective patch, but can change from their current opinion to the other based on the perceived values and costs of each stance."
- 184-186 "Fishers are only fishing in their respective patches and do not move to the other. Instead, they influence fishing in the opposite patch through the outside social influence of ρi."
- 383-385 "This model does not account for the movement of fishers between patches, which could be a possible extension of this model to represent a fishery where there is overlap between the fishing grounds of the two human groups."

In this model, there are not mechanisms for resolution and enforcement, further showing how this is not a co-managed fishery. We have added this point on lines 369-372 with "Here, we model individual decisions to fish based on the perceived benefits and costs of fishing activity. It

does not account for organized decision making on fishing practices or co-management, and there is no mechanism for dispute resolution and regulation enforcement."

The tendency of fishers to move from patch to patch is noted in the introduction and referred to as "high migration". However, the model includes only movement of fish, not people. In the introduction and elsewhere, references to populations and movement between patches are not always clear regarding whether the reference is to fish or people.

Migration in this model only refers to fish movement between patches. All references to movement or migration have been changed to fish movement or fish migration on the following lines:

- 75, 121-122, 132, 149-150, 203, 209, 225, 248-256, Figure 2, 292-293, 303, 305-308, 346-347, 352

Further, we have clarified this point that humans do not move between patches on the following lines:

- 154, 184-186, 383, 385

Failure of conservation due to a lack of stakeholder participation is mentioned in the introduction but is not addressed in the model. Similarly, the reference "cross-group communicators" as a solution to overharvesting is overly simplistic and unsupported.

We agree, this point is not addressed in the model so mentions of stakeholder participation and cross-group communicators have been moved.

I found it curious that the model tested the social influence of fishers from the overharvested patch and not vice versa. My experience is that groups of fishermen who fish sustainably exhibit a high degree of social cohesion (required to generate adherence to conservation strategies). As a result, they are more likely to "influence" non-conforming fishermen whose unsustainable practices threaten their patch. Therefore, I find the conclusion that fishers in population 2 will reduce their numbers in response to declines in fish population 2 unlikely. Perhaps the model needs more information on the access of either population of fishers to alternative behaviors (such as reducing fishing effort, protecting juveniles, etc.).

If the reviewer is talking about figure 4, this analysis increased both ρ parameters simultaneously in order to show how this parameter affects the fishery overall. However, we reran a similar analysis on the two-patch scenario comparing the effects of changing ρ_1 vs ρ_2 so that we could

explore this point made by the reviewer more clearly. Figure 4 has been replaced with the following figure:

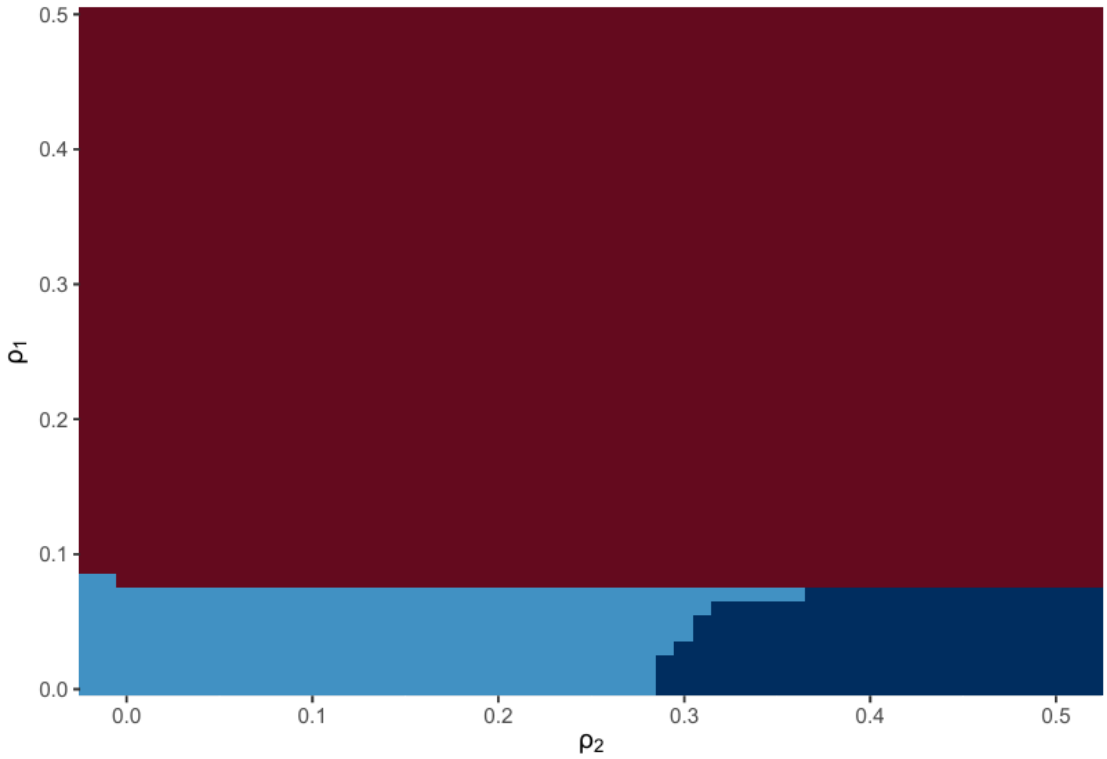

Figure 4: ρ_1 and ρ_2 were incrementally increased and the model was run 200 years. This graph shows the final dynamics of the system after those 200 years where the red area indicates a fishery collapse, where both patches fish at full capacity until stocks go to 0. The light blue area shows where some fish populations stay at a constant level, and only X_2 continues to fish where as X_1 ceases fishing all together. The darker blue patch shows where both patches stop fishing all together and fish stocks in both patches remain at full capacity.

In short, because there is no access to alternative behaviors, each group is simply incorporating the benefits vs cost opinions of the opposite population. Because of that, this demonstrates somewhat of an opposite effect described above, where if the overfished population is more influenced by the success of the sustainably fished population, they will actually increase fishing numbers, resulting in the collapse of the whole system. Alternatively, if we increase the influence of the unsustainable patch on the sustainable one, individuals in the sustainable patch will actually reduce fishing. This has been clarified on the following lines which now read:

- 17-19 “We also found that because in this model, the influence of one human patch on another only communicates the amount of each catch and not fishing strategies employed, increased social influence decreased the sustainability of the fishery. ”

- 22-24 “Further, we demonstrate how incorporating fishing methods from outside sources can result in higher stability of the harvested population, demonstrating the need for effective communication across management regimes.”
- 182-184 “Also, the only information that is being communicated to human patch i is how many people from human patch j are fishing (1 − Xj). Human patch i is not receiving any information on fishing practices or changes in the opposite patches fish population.”
- 200-202 “Therefore, if human population j is continuing to fish, humans in population i will be more influenced to do so as well.”
- 334-338 “The importance of information can be reflected in real-world fisheries such as in Lake Kariba between Zambia and Zimbabwe. Here, small scale fishers are reluctant to participate in co-management of this shared resource and have been found to resort to illegal fishing practices in order to maximize fish catch (Nyikahadzoi et al., 2017).”

This model serves to show fishing behavior when there are no mechanisms for management or alternative behavior. We have replaced figure 4 with this analysis, as well as changed the following lines to better interpret these findings:

- Lines 276-282 “ext, we ran our model with the parameterization outlined in table 2 with incrementally higher external social influence values (ρ) in each population and observed how this affected the final population of each fish patch (Figure 4). We found that higher values of ρ1 actually resulted in fish stocks collapsing in both patches whereas increases of ρ2 maintained fish populations. At low values of ρ2, X2 continued fishing but X1 stopped fishing all together, resulting in stable fish populations. As ρ2 increased, fishing eventually stopped in both patches and fish populations remained at 1.”
- The paragraph of 232-243

“Fish movement” should be clarified. Is the reference to the stray rate between demographically subpopulations? Or to the overlap of subpopulations that can occur among resident and migratory subpopulations? The implications are very different. Asymmetrical movement seems to be a reasonable if not typical assumption (but should be acknowledged as such).

On lines 127-130 and 147-148 we have clarified this point. Fish movement is a “stray rate” as these are two demographically distinct subpopulations. We examine scenarios of both symmetrical and asymmetrical movement.

Some factors were discussed in the discussion that I believe should have been addressed as assumptions in the description of the model. For example, a reference to “the only information being passed on to the other human population is the number of fishers as opposed to what sustainable practices were used” is a limitation that may explain model outcomes under high levels of social influence but should be declared – and explained earlier. The rationale for this assumption is stated in the next paragraph: the race for fish doesn’t allow for explanation of

conservation practices. This has certainly been documented in boom and bust fisheries. But this usually precedes rather than follows the development of co-management. Perhaps the two patch model doesn't model a truly co-managed fishery. Co-management presumes that governance has been established that is unlikely to result in a boom and bust fishery.

As explained above, we agree with the reviewer in that our model doesn't really reflect co-managed fisheries but two independent management regimes that are connected by fish movement and social influence. See the points above for how we address this in the text.

The reference to homophily is relevant but should be addressed up front.
We agree and have restructured the paragraph on lines 84-111 to better emphasize this point as well as on lines 179-181 in the methods:

- " In other words, higher values of ρ indicate higher homophily between the groups and lower values of ρ indicate these groups only adopting fishing practices from within their patch. "

Normative social learning processes are often proposed for structured natural resource decision making processes. But fishers making decisions based on the benefit-cost ratio of conservation strategies are more likely to exercise whatever power or influence they have to get what they think is best for their fishery in real time than to participate in structured decision making that may take weeks or months.

We have added the following to lines 314-322 to show how this is reflected in our model.

- 314-322 "Increases in d1 and ρ2 model how dynamics will change if human patch 1 is more influenced by themselves (d1) or if they have more influence on the other patch (ρ2) (Figure 3). This analysis showed that increasing either parameter maintained the oscillatory behavior of the model, however as either d1 or ρ2 increased, the frequency of these oscillations decreased. In other words, as a human population began to incorporate influence more, this resulted in similar dynamics, but over longer timescales. This is an example of how as humans begin to coordinate with the actions of their peers, changes to fishing pressures can also actually be delayed. The dynamics of the model change from individual decisions, which happen almost instantly, to coordinated efforts, which can take longer to implement."

The development of socio-ecological models with social hierarchy and spatial structure is important in increasing our understanding of the dynamics in small-scale fisheries. With some modifications I believe that this paper can make an important contribution to the literature.

We appreciate the constructive comments and hope we have addressed each one adequately above. Thanks.