**GEC GEC-D-21-01576R1**

**Response to Reviewers (second revision)**

Reviewer comments | Author responses

**Reviewer comments:**

Reviewer #1: The authors have done a commendable amount of work revising the manuscript. The clarifications make it much easier to understand what the authors sought to do but I will admit that now that the manuscript is easier to follow, I have perhaps more questions with the approach the authors take. I'm simply not convinced that the scale of behavioral assertions and most notably, the economic conclusions around profit, are supported by the data / analyses that the authors present.

One of my first concerns may be due to my lack of familiarity with the west coast fisheries and perhaps the authors can simply clarify this. The entire story is about fishers that focus more on crab or pursue more diverse fishing. However, only those crab fishers that also participate in other fisheries (e.g., groundfish) that require VMS are included in this study (with some exceptions, I'm sure). So it seems there is perhaps a critical sampling bias in that we only have information for vessels with a certain domain of behaviors. And among those vessels it seems that the amount of revenue matched with VMS is worryingly low (e.g., as low as 4%). Furthermore, Figure A10 suggests that there may be an inter-annual pattern in the number of vessels/revenue, with the least amount of data available during these heatwave years. It seems that there may in fact be an interesting story here, but perhaps it is more about participation than spatial behaviors or revenues (e.g., it seemed that Fig A13 may have the most interesting story and be best supported by the data at-hand).

In our data, we are capturing all vessels with VMS that fish in the Dungeness crab fishery. These vessels are required to use VMS throughout each fishing season—-without turning it off—-if they hold a permit or participate in any way in groundfish fishing (50 CFR 660.14) (Lines 121-123 in the revised manuscript). Although this is certainly a subsample of the entire west coast Dungeness crab fishery, lines of evidence suggest that it is an appropriate sample of the west coast Dungeness crab fishery participants, with a potential undersampling of Local Specialists (see new Appendix Figure A.11). First, the vessel size data we have suggests that VMS and non-VMS vessels have a similar size distribution (Figure A.11b). We capture a large size range of vessels (21-103 feet), with a peak in the smoothed histogram at around 40 feet for VMS-equipped vessels and slightly smaller for non-VMS vessels. This 40 feet cutoff coincidentally is precisely the cutoff used by previous studies in this system to distinguish between small (<40 ft) and large vessels (e.g., Kasperski and Holland 2013, Jardine et al. 2020, Fisher et al. 2021, all cited in the main text). This means that we are capturing significant variation in the most-commonly used single variable to partition groups of Dungeness crab fishers. While this is not a comprehensive sample of every Dungeness crab fishing vessel on the west coast, we believe a sample of hundreds of vessels each season represents a viable sample at the coastwide scale. The cumulative revenue accrued by VMS and non-VMS vessels—i.e., the derby pattern in the fishery—-is similar as well (Figure A.11a). The only discernible difference is for small vessels without VMS, which seem to proceed with their season at a slightly slower rate (i.e. have longer crab seasons) than small vessels with VMS (line 394). Finally, we can compare VMS and non-VMS vessels’ revenue diversity estimated by the inverse Simpson index (as described in the Methods Lines 220-227), shown in Figure A.11c. VMS-equipped vessels have, on average, higher mean revenue diversity than non-VMS vessels, although the distributions overlap substantially. These three lines of evidence (vessel size, cumulative revenue time series, revenue diversity) imply that our sample likely captures the range of behaviors across the entire Dungeness crab fleet, but also that non-VMS vessels are likely most similar to the Local Specialist group (smaller vessels, longer seasons, lower revenue diversity).

We added language in the Results section acknowledging this caveat (line 356 and 390), and discussed the implications of our sample again in the Discussion (lines 508-514). Overall, while we believe our results describe important behavioral groupings of Dungeness crab fishing vessels at the coastwide scale, they will not necessarily represent all the subtle behavioral differences at state or local levels. Finally, and excitingly, all 3 west coast states are working on the implementation of non-VMS based electronic monitoring systems for their Dungeness crab fisheries, partially in response to growing concerns about whale entanglement (line 673). In the future, this will enable the extension and improvement of the work we present in this study. While currently our spatial analyses necessarily rely on VMS-tracked vessels, and our study remains the most comprehensive analysis on spatial changes in the Dungeness crab fleet in relation to the marine heatwave available.

To the reviewer’s comment about participation, others (e.g., Fisher et al., 2021, Jardine et al. 2020, Holland and Leonard 2020) have tackled drivers of fishery participation during the marine heatwave, using a variety of methods, and that was not our intention with this study. Rather, we used the available spatial and landings data to observe distinct behavioral segments within the coastwide Dungeness crab fishing fleet, and tracked the performance of those groups over time. While we can show some of the movement of vessels between these behavioral groups between seasons (e.g., Figs. A.13, A.14), our analysis is not aimed at, and indeed not appropriate for assessing the behavioral drivers of fishery entry/exit decisions. We make this point in the Discussion section when discussing how we only observe “survivors” (around line 581 in the revised draft), but we have also added more of a discussion of the relationship between our work and other studies of this fishery system.

My second major concern is one that I expressed during my first review, related to the lack of cost information for non-Dungeness trips. Without having an estimate of non-Dungeness trip costs, I guess I'm just not sure what the value of the economic analysis is. You used an old methodology from pre-VMS days to estimate costs for crab fisheries but no methodology to try to estimate non-Dungeness revenues? Referring to the profit of crab and the revenue of non-Dungeness trips seems like an apples-to-oranges comparison. In your clustering analysis, the proportion of revenue from non-Dungeness fisheries was the most important clustering variable. But you have no idea how revenue v. costs compare in non-Dungeness fisheries. However, you go on in the discussion to assert which vessels were more profitable…but you have not assessed the profitability of non-Dungeness fishing so how you can you know anything about the profitability of a particular fishing strategy (especially one

that relies on a higher degree of non-Dungeness revenue)? It seems reasonable to say that crab trips for certain vessels may have been more profitable under certain circumstances but you have explicitly ignored costs for non-Dungeness trips and thus, you are explicitly unable to speak to profitability of any behaviors beyond crab trips. In the abstract you assert that "the combination of these strategies appeared to be the most adaptive, as it produced the greatest increase in profits" and I just don't think your analyses support such conclusions about profit.

We appreciate the reviewer’s feedback on this issue. Here we provide our reasoning for the inclusion of the cost and profit model for the Dungeness crab fishery only, a description of the infeasibility of compiling profits for all other fisheries, and finally a summary of the changes we have made in the manuscript to be as clear as possible in outlining what we believe we can and cannot infer from our analyses.

Throughout the manuscript, we have made edits to ensure that we are as transparent as possible with what can be concluded from our analyses. We agree with the reviewer that we “are explicitly unable to speak to profitability of any behaviors beyond crab trips” and made sure that all references to profitability or profits were properly designated as “Dungeness crab fishery profitability” or, “profits from Dungeness crab”, to indicate that we are only estimating Dungeness profits. In contrast, when referring to income streams from non-crab fisheries we refer to these as “revenues”, to be clear that we have not (and cannot, see below) calculate profits comprehensively in all other fisheries. We have added language to the Methods (Line 322) and Results (Line 441) sections clarifying this distinction and the reasoning behind calculating profits for the Dungeness crab fishery only.

Ideally, we agree with the reviewer that it would be informative to have cost and profit estimates for all alternative fisheries. Unfortunately, the estimation of profits across all U.S. west coast fisheries is a monumental task likely requiring multiple years of data collection and analysis. Studies like Dewees et al. (2004), which we adapted to simulate Dungeness crab fishing costs, simply do not exist for most fisheries on the west coast (one exception is the groundfish catch share fleet, Errend et al. 2018 cited below), and therefore cost estimation would have to be done through primary data collection. This is a task that is simply not feasible within the scope of our analysis. We have added a statement to this effect in the revised Methods lines 322-327.

However, multiple pieces of evidence suggest that this lack of profit calculations for other fisheries should not invalidate the importance of Dungeness crab profits for describing fisher behavior. First, Dungeness crab fishing is an extremely profitable venture, for all behavioral groups, early in the season. Our calculations suggest that in the first few weeks of the season, permit owners are accruing thousands of dollars per day in profit (Fig. A.4), and on the order of $100,000 or more per vessel for some groups over the course of the crab season (main text Fig. 5). We contend that when the Dungeness crab fishery opens, it is by far the most profitable venture for fishers. We have added a new Appendix figure (the new Figure A.15) showing that for the first 120 days of a typical season, Dungeness crab dominates the total revenues of all behavioral groups, with more than 80 percent of all revenue per vessel derived from Dungeness crab. Both Holland and Leonard (2020) and Fisher et al. (2021) describe how there are very few alternative fisheries in the winter months when the Dungeness crab season mainly operates, creating a lack of other opportunities during that time frame. In studying the delayed 2015-16 crab season, Holland and Leonard (2020) found that many fishers did not fish at all during the delay, suggesting that either those vessels did not have permits for other fisheries, or that fishing was not worth it at all if the crab fishery was closed. Moreover, even when the fishery did open in California that season, most fishers chose to participate in the crab fishery at the expense of other fishing opportunities, providing evidence that crab fishing is the preferred choice when available. In our study, then, we believe that Dungeness crab profit calculations describe key differences between behavioral groups during the intense, early-season crab fishing derby, while dynamics in non-Dungeness revenue among behavioral groups reveal distinctions between groups that occur after the majority of the season’s crab has been caught. Although this fact does not invalidate the potential utility of profit calculations for other fisheries if the data were available, it emphasizes that the use of both Dungeness crab profit and non-Dungeness revenue is not an apples-to-oranges comparison, but rather an informative juxtaposition. We added this context to the revised manuscript in section 3.3 of the Results.

Finally, we agree with the reviewer that estimation of profits from all fisheries that Dungeness crab vessels participate in is an interesting and important area of future inquiry, and have added text to the Discussion (paragraph starting at Line 641) of the revised manuscript outlining how these calculations could further managers’ understanding and ability to manage the crab fishery more effectively.

Errend, M.N., Pfeiffer, L., Steiner, E., Guldin, M. and Warlick, A., 2018. Economic outcomes for harvesters under the West Coast groundfish trawl catch share program: Have goals and objectives been met?. Coastal Management, 46(6), pp.564-586.

Some minor points that need clarification:

I assume that you are defining profit for the boat owner and not assuming that the captain is the owner / permit holder? In other words, just wondering how you are determining crew share - do you know if the captain was the permit holder? Maybe this isn't a concern in these fisheries but often the captain can just be another crew member but with higher crew share. Depending on the vessel's business structure, the captain could be one of the crew member that gets paid out or the captain may be the owner that ostensibly receives all of the revenue remaining after the crew and other costs have been paid out.

Thank you for this comment, since this is indeed an important clarification to make. The Dewees et al. survey (which forms the basis for our fishing cost simulation) was given to permit owners, which we assume are either owner-operators or permit holders that hire a captain as well as crew. It is not possible to identify which boat is in which ownership situation, but the cost estimation likely includes both possibilities. We have made it more clear in the revised text (line 295) that the profits we report are accruing to the permit owner, not necessarily the captain.

I am a tad confused but perhaps it's just the way the data are reported. Are your revenue and cost data reported at a daily-level or at a trip-level. Clearly from what you're showing, you have a need to break the data down to the daily level and then aggregate. Are your fish tickets providing daily revenue or trip revenue? Also, I think readers might benefit from understanding why you use days to calculate fuel costs instead of trip distance? With VMS data and the purpose of this study around space utilization, wouldn't distance traveled more accurately enable you to estimate fuel costs? You mentioned in the reviewer response that trip duration and distance were "highly correlated" with a rho of 0.61. This doesn't actually seem very high if you are trying to calculate costs using one versus the other variable to me. Also, I believe that in the text, you mentioned that you omitted values with a rho value > 0.7. So perhaps just double check whether there was a typo?

The revenue data in their most basic form (the fish tickets) are reported at the trip level, as described in the Data sources portion of the Methods. Trip length (both distance and time in days) was calculated after joining the VMS data to the fish tickets. Hence, after joining the VMS and fish ticket data, we are able to organize the data in different ways, including calculating daily or weekly revenues per vessel. We added a sentence in the Methods (line 156) to clarify this point.

Additionally, while either trip duration or distance could theoretically be used to estimate costs, we chose trip duration for three reasons. First and most importantly, trip duration was the variable for which we had estimates of its relationship to cost (from the Dewees et al. study). Second, trip duration is used in many estimations of fishing costs (e.g., Das 2014), since total distance traveled is often not recorded. Moreover, vessels vary substantially in their fuel intake based on fuel efficiency, vessel speed, and unobserved vessel characteristics (e.g., engine type, age, horsepower, weight, etc.). Hence, we reasoned that the self-reported daily estimates of fuel cost from the Dewees et al. study (and their associated standard deviations) were likely at least as reliable as a distance-based calculation with unknown parameters. Third, the cost model is most sensitive to vessel size because both crew size (labor cost) and fuel cost increase with larger vessels, such that the choice of trip duration or distance is much less consequential for the estimation of profits than the assignment of vessel size (Figures A.19-A.20).

Finally, we did indeed thin the clustering variables such that no two variables had a rho>0.7. Although trip distance and duration had a rho of 0.61, trip distance was removed because of its high correlation with other variables, particularly cumulative choice entropy (our measure of exploratory behavior).

Das, C. 2014. “Northeast Trip Cost Data: Overview, Estimation, and Predictions.” NOAA Technical Memorandum, NMFS-NE-227, National Marine Fisheries Services, Woods Hole, MA.

Should make sure to speak to the increasing trend of the roving generalists over a larger part of the time series. I know you make a case for your selection of the particular MHW period but it seems like readers will be interested in the gradient of increase for the roving generalists. Lines 429-433, you assert that this was generalist behavior was a response to the MHWs but your figures suggest that non-Dungeness revenue was already rising prior to the MHW for several years.

We agree with this assessment, and the other reviewer had a similar comment. We have added language in both the Results and Discussion sections (lines 413-416, 519-528) describing the phenomenon. It seems the Generalists benefited from increases in landing from the pink shrimp and groundfish fisheries, while the Local groups did not.

Figure 5b. Is the Roving Specialists really a significant difference? The bars appear to overlap substantially.

Yes, the Tukey’s HSD analysis indicated a significant difference (p < 1.1E-06).

Figure A.17 - interesting how, despite the large apparent differences in fuel prices by state, the daily trip cost seems scarcely different in most years. Is this because trip distances are just that much shorter in California?

The differences in fuel price are more apparent after about 2014 or 2015 (Fig. A.18). Before 2015, estimated mean daily fishing costs from our cost simulation are very similar across states. During and after 2015 the states are more divergent, and on average California fishing is about $40 more per day than the other states in our simulation, across all vessel lengths. Moreover, fuel is just one element of our cost calculation (albeit a major one along with bait), so some of the differences in fuel price by state are diluted by the other costs associated with fishing. As mentioned above, costs are most sensitive to vessel size, since labor, fuel, and bait costs all scale with increasing vessel length (Figures A.19,A.20).

Reviewer #2: The authors have done admirable job addressing the technical concerns raised by myself and the other reviewer during the initial review. I find the result to be a scientifically rigorous analysis that is of broad theoretical significance which will be of great interest to the journal's readership. With that said, below I have identified several opportunities for additional improvement which I believe would increase the relevance and utility of the work for regional fisheries managers and practitioners. Importantly, I don't believe that addressing any of the minor comments below will require re-running any of the analyses or reproducing any of the figures. Ultimately, I would congratulate the authors on this effort and leave it to their and the handling editor's discretion concerning if and how to address these points with additional text insertions.

Thank you for your feedback and supportive comments! We have addressed all of your comments and points below, and we appreciate how your comments have helped make the manuscript more clear to the reader and more grounded in relation to other recent literature in the Dungeness crab fishery.

Point 1: With the authors having spent considerable time and effort re-clustering their vessel-seasons to incorporate a vessel size metric, more space could be spent in the main text unpacking related results, their implications for different segments of regional fishing fleets, and their connections with other relevant literature. Indeed, the authors findings seem to support the assertion that, on account of large vessel's broad fishing areas and diverse harvest portfolios they were more adaptive in this specific circumstance as compared to range-restricted small-scale fishing specialists. I believe Lines 351-365 represent one opportunity to make such an insertion without major restructuring.

- Young, T., Fuller, E.C., Provost, M.M., Coleman, K.E., St. Martin, K., McCay, B.J. and Pinsky, M.L., 2019. Adaptation strategies of coastal fishing communities as species shift poleward. ICES Journal of Marine Science, 76(1), pp.93-103.

- Papaioannou, E.A., Selden, R.L., Olson, J., McCay, B.J., Pinsky, M.L. and St Martin, K., 2021. Not All Those Who Wander Are Lost-Responses of Fishers' Communities to Shifts in the Distribution and Abundance of Fish. Frontiers in Marine Science.

Thank you for this suggestion. We agreed that there could be more discussion of the implications of these findings. We have added and edited text in the suggested place in the Results section (new Line 372-399), as well as the Discussion section (lines 537-546 and 551-556) to bring in these references and discuss how vessel characteristics can enable adaptive behaviors under an uncertain climate.

Point 2: I think it would be productive for the authors to devote some space in the discussion to reconciling their findings with those produced and described by others examining the same system. In particular, I am curious to know more about why their results (which show that all fishers generated more revenue from Dungeness and non-Dungeness fisheries during the MHW period) differ from those described by Holland et al. 2020 & Seary et al. in review (the pre-print is available online) who used hurdle models to estimate revenue losses (from both Dungeness and non-Dungeness fisheries) during parts of the same time period. While I don't doubt the scientific rigor of either approach and believe that such differences can likely be attributed to different vessels sampled, time periods used for aggregation, or modeling approaches, it would be valuable to hear an explanation from those intimately familiar with the data. From a policy and narrative perspective, these other papers

seem to suggest that the fishery disaster and/or insurance programs are needed to help mitigate revenue losses associated with environmental change, while the current manuscript suggests that many fishers may be able to overcome such challenges on their own (maintaining and/or increasing revenue) by employing some combination of adaptive strategies.

-Holland, D.S. and Leonard, J., 2020. Is a delay a disaster? economic impacts of the delay of the California dungeness crab fishery due to a harmful algal bloom. Harmful Algae, 98, p.101904.

-Seary, R., Santora, J.A., Tommasi, D., Thompson, A., Bograd, S.J., Richerson, K., Brodie, S. and Holland, D., 2022. Revenue loss due to whale entanglement mitigation and fishery closures.

We appreciate this comment because it illuminates a key difference between our analysis and others that have studied the same time period from different angles and with different methods. We chose in our analysis to aggregate our fishing behavioral metrics on the scale of individual crab seasons. However, because of various management issues (harmful algal blooms, whale entanglement, price conditions, etc.), seasons do not start on the same date in each year, and are also variable across the coast. We used a variable start date for each season and port group based on observed crab landings, as described in the Methods, and therefore our metrics are based on the “realized” Dungeness crab season rather than a pre-determined time period (e.g., November 15 to September 1). This means that our season by season metrics are not directly comparable to Holland and Leonard (2020), since they performed a counterfactual estimation of revenue losses due to the delayed 2015-16 crab season in California, assuming a November start date each year. Other differences include Holland and Leonard’s observation of non-participating vessels (an impossibility in our study because of the use of VMS data), their focus on California only (where the delay was most severe; in fact they state that revenues actually increased in OR and WA during this season), and their selection of only the 2015-16 season (we used 2015-16 to 2017-18 as our focal MHW period because of the persistence of MHW effects on the ecosystem, *sensu* Suryan et al. 2021, Samhouri et al. 2021). Similarly, Seary et al. also focus on both participants and non-participants in California only to estimate the impacts of whale entanglement mitigation measures in the 2019-2020 seasons.

All this to say, it is useful to compare our results to those of others, but care must be taken in the direct comparison. We believe that our results actually align with those of Holland and Leonard, showing that for vessels that stayed in the crab fishery in 2015-16, those that were still able to take advantage of their mobility and efficiency to harvest both crab and other species—despite the delay—were able to maintain similar revenues and estimated Dungeness crab profits as they had in previous years. Additionally, the studies align on the positive effects of vessel size and fishery diversification on expected revenues.

We have added some text explaining the differences described here to the Discussion section of the manuscript (Lines 506-528, 583-614). We have also added text to include the idea that fishery disaster and/or insurance programs may help to mitigate revenue losses associated with environmental change in the crab fishery and perhaps others (paragraph starting at line 641). We thank the reviewer again for raising this important point.

Point 3: With respect to whether or not landings and revenue dynamics associated with other fisheries may have had an impact on the decision-making behavior and trends in revenue that the authors report; I would urge the authors to dig into the vessel-level data that they have access to explore this phenomenon rather than referring to the trend lines reported in the CCIEA ecosystem status report. I have attached two time series plots regarding landings and revenue associated with pink shrimp and groundfish (excluding pacific whiting and sablefish but including all rockfish, flatfish, round fish, skates & dogfish) in Oregon and Washington. While it is possible that I've made a mistake in aggregating the data, and I can't say for sure what information the CCIEA trends are based upon, my cursory analysis does indeed show a Pink Shrimp boom, peaking in 2015, and a progressive recovery of the groundfish stocks. Likewise, I am not a groundfish expert and can't immediately point

to a peer-reviewed publication documenting recent trends, but I believe the recovery of that sector, as driven in large part by increased landings across the Midwater Rockfish Trawl fishery, is widely acknowledged and accepted (see references copied below). As both rockfish and pink shrimp are important seasonal targets of many of the larger and more profitable vessels engaged in the Pacific Northwest Dungeness crab fishery (see Oken et al. 2021, Frawley et al. 2021, Fisher et al. 2021), I urge the authors to consider such dynamics carefully in the interpretation of their results.

<https://wdfw.wa.gov/sites/default/files/2019-04/pink_shrimp_newsletter_2019.pdf>

<https://www.seafoodsource.com/news/environment-sustainability/us-west-coast-rockfish-recovery-hailed-as-success-story-by-edf>

<https://www.fisheries.noaa.gov/species/west-coast-groundfish>

<https://www.pcouncil.org/documents/2021/06/g-4-a-nmfs-report-7-fishing-effort-in-the-2002-2019-u-s-pacific-coast-groundfish-fisheries.pdf/>

-Oken, K.L., Holland, D.S. and Punt, A.E., 2021. The effects of population synchrony, life history, and access constraints on benefits from fishing portfolios. Ecological Applications, 31(4), p.e2307.

-Frawley, T.H., Muhling, B.A., Brodie, S., Fisher, M.C., Tommasi, D., Le Fol, G., Hazen, E.L., Stohs, S.S., Finkbeiner, E.M. and Jacox, M.G., 2021. Changes to the structure and function of an albacore fishery reveal shifting social‐ecological realities for Pacific Northwest fishermen. Fish and Fisheries, 22(2), pp.280-297.

-Fisher, M.C., Moore, S.K., Jardine, S.L., Watson, J.R. and Samhouri, J.F., 2021. Climate shock effects and mediation in fisheries. Proceedings of the National Academy of Sciences, 118(2).

This comment is well taken, and is similar to a comment from the other reviewer. We have added language in both the Results and Discussion sections describing the phenomenon (lines 413-416, 519-528). It seems the Generalists benefited from an increase in the pink shrimp and groundfish fisheries, while the Local groups did not. We added a supplementary Figure (A.16) showing similar trends to those provided here, indicating that increases in groundfish and pink shrimp landings coincided with our time period. This is important to our results because obviously, the “diversify” adaptive strategy will not work if there are no productive fisheries outside of Dungeness crab to diversify to. In this edit, we made sure to acknowledge this point in the relevant portions of the Results and Discussion sections (lines 531-537).