Impacts of marine heatwaves on small-scale fisheries

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Abstract

Marine heatwaves pervasive in space and time, and are becoming more frequent and intense [1–3]. These events negatively impact commercial and recreational fisheries [4, 5], but their impacts on indigenous and small-scale fisheries remain notoriously understudied. We investigate the impacts of marine heatwaves on small-scale fisheries operating in an important biogeographic transition zone along the Baja California Peninsula, Mexico. We estimate the effects of the longest and most extreme marine heatwave on fisheries production from 43 economic units operating in a system of 55 Territorial Use-Rights for Fisheries (TURFs). TURFs were exposed to an unprecedented annual cumulative marine heatwave intensity of 513.95 ± 234.46°C days (M ± SD) in 2014-16. This led to large and negative impacts on aggregate fisheries production; landings of lobster, sea urchin, and sea cucumber species decreased between 15-58%, depending on the fishery. A total of 56% (N = 31) operations presented large reductions in landings (25.4% significant), whose losses outweigh the moderate increase detected for the other 44% (N = 24; 25.4% significant). The impacts were larger for operations near the southern distribution limit of the targeted species (around 25°N), and for those operating in areas of high historical environmental variation and low historical variation in fisheries production. Climate models predict that all TURFs will be exposed to more frequent and intense marine heatwaves between now and 2050, but the change will be greater for TURFs in the north, thus leading to an homogenization of the existing latitudinal gradient. In the face of extreme environmental shocks such as marine

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heatwaves, small-scale fisheries operating near transition zones are amongst the most vulnerable groups.

1 Introduction

Marine heatwaves occur in all ocean basins, and their frequency and severity are increasing under climate change [1–3]. Extreme events of this nature are known to negatively impact commercial and recreational fisheries [4, 5], but their impacts on indigenous and small-scale fisheries remain notoriously understudied. This is a critical knowledge gap and a priority for informing policy action in support of a sector that provides essential nutrition and livelihoods to an estimated 492 million people [6, 7]. Here, we show that marine heatwaves have large negative impacts on small-scale fisheries production, even in the presence of "winners" and "losers". By analyzing fisheries production data of small-scale fisheries operating along an ~1,000 km latitudinal gradient, we also show impacts of extreme events are stronger for fishers operating near the equatorward distribution limit of their target species, though future climate projections suggest that climate change will homogenize this latitudinal gradient. Collectively, these results advance our understanding of the impacts of extreme climate events on small-scale fisheries, particularly those operating near biogeographic breaks and transition zones.

Marine social-ecological systems are intrinsically linked to environmental dynamics, and their intricate balance is threatened by the accelerating impacts of climate change [8, 9]. In recent years, a growing body of literature has highlighted the substantial influence of climate change on the distribution and productivity of marine populations, particularly those that provide livelihoods and sustenance to millions of fishers worldwide [10–12]. Extreme climatic events affect fisheries and other food-provisioning sectors around the world, but small-scale fisheries are amongst the most vulnerable due to their dispersed and opaque nature, which limits our ability to study and support them [5, 13].

Most marine ecosystems have been exposed to prolonged periods of anomalously warm water known as marine heatwaves [2, 12, 14]. Exposure to these events can lead to losses of important habitat-forming species, modify the structure of marine communities, and alter the productivity of ecosystems [5, 15–20]. Marine heatwaves can affect the provision of ecosystem services, among which fisheries production is one of the most important [4]. These warm-water events have garnered substantial attention from the climate, fisheries, and marine science community who seek to understand how these have impacted fish and fisheries, how climate change may exacerbate their impacts, and that seek to inform the design and implementation of policy interventions [4, 21].

While the impacts of marine heatwaves on fisheries vary across geographies and target species, the growing consensus is that –through changes in stock productivity, recruitment, survival, spatial distribution and catchability of the targeted species– marine heatwaves frequently result in large negative impacts that jeopardize the long-term persistence of these operations [4, 22, 23]. However, most of these valuable insights have been derived from data that were coarsely aggregated at large spatial scales, typically at the level of biogeographic provinces [22], stocks [24], or basins [5, 23]. This approach may suffice when studying aggregate impacts on mostly homogeneous fleets, like those in industrial fisheries, but it lacks the resolution needed to understand how fine-scale biophysical and socioeconomic processes –including the individual characteristics of resource users [25]– mediate the impacts. The types of data needed for this are rarely available for small-scale fisheries, which hinders our ability to understand how marine heatwaves affect one of the largest, and most vulnerable marine sectors.

Local biophysical and socio-economic characteristics of a system can influence, or at least predict, its vulnerability to climate change. From an ecological point of view, biological populations near transition zones are more vulnerable because these are more likely to experience earlier and more pronounced effects of a changing climate [19, 26, 27]. From this "biogeographic" hypothesis, it follows that small-scale fisheries operating near transition zones may also be amongst the most vulnerable in the face of extreme environmental shocks. This hypothesis, however, has not been tested and the question of how vulnerability of small-scale fisheries may vary across latitudinal gradients remains a key knowledge gap. Moreover, climate refugia –places with relatively stable climatic conditions [28, 29]-– can confer resilience against the impacts of climate change. Thus, this alternative "climate refugia" hypothesis predicts that impacts of climatic shocks will be smaller for places with more stable local environmental conditions, potentially distributed throughout species ranges. In parallel, historical stability in the performance of a socio-ecological system may predict a system's adaptive capacity and its ability to withstand future climatic shocks [30]. In the context of fisheries, this "social adaptation" hypothesis predicts that operations that have historically maintained a stable production (*i.e.* landings) when faced by shocks will be able to withstand future shocks better than those with high variability in production. Whether these last two predictions hold true for shocks of unprecedented magnitude remains unclear.

Each of these potential drivers of the vulnerability, or, conversely, resilience of small-scale fisheries to climatic shocks has important implications for designing and implementing management and adaptation strategies in highly heterogeneous but poorly understood socio-ecological systems. Our main objective is thus to understand how marine heatwaves affect small-scale fisheries and how climate change might exacerbate their impacts. We concentrate on small-scale fisheries operating in a ∼1,000 km latitudinal gradient along the Pacific coastline of the Baja California Peninsula in Mexico (Figure 1A). Between 2014 and 2016, the region was exposed to an unprecedented regime of intense and prolonged marine heatwaves (henceforth "marine heatwave regime") that impacted local marine ecosystems [17, 31], and has been labeled as the most intense marine heatwave on record [3]. The region is also home to a diverse array of economically important marine species that inhabit a transition zone between temperate and subtropical waters [32]. Benthic invertebrate fisheries are managed under a system of Territorial User Rights for Fisheries (TURFs; Figure 1a) that grant spatially-exclusive access rights to well-defined groups of resource users, here termed economic units [33–35]. We focus on three of the most economically valuable target species in the region: spiny lobster (*Panulirus interruptus*), sea cucumber (*Apostichopus parvimensis*), and sea urchin (*Mesocentrotus franciscanus* and *Strongylocentrotus purpuratus*; Figure 1b-c).

To understand how marine heatwaves affect small-scale fisheries and how climate change might exacerbate any impacts we pursue two lines of inquiry. We first conducted a retrospective analysis of observational data on marine heatwaves and fisheries production from 55 TURFs belonging to 43 economic units, where we 1) quantify their historical (*i.e.* 1982-2022) exposure to marine heatwaves, 2) estimate the impacts of marine heatwaves on fisheries production (*i.e.* 2001-2022), and 3) explore how characteristics of each system predict these impacts. On this last point, we ask whether TURFs closer to a species distribution limit are subject to greater impacts (the biogeographic hypothesis), whether historical environmental stability is associated with lower impacts of marine heatwaves (the climate refugia hypothesis), and whether the historical performance of a fishing operation predicts its resilience to marine heatwaves (the social adaptation hypothesis). Then, the second part of our work presents a prospective analysis of climate model output from 11 CMIP6 models across three shared socioeconomic pathways (SSPs) to 4) estimate TURFs' future exposure to marine heatwaves and 5) identify the most vulnerable TURFs. Our results are presented in direct relation to the five points listed above, and our methods section provides detailed information on the data sources, processing, and statistical analyses performed.

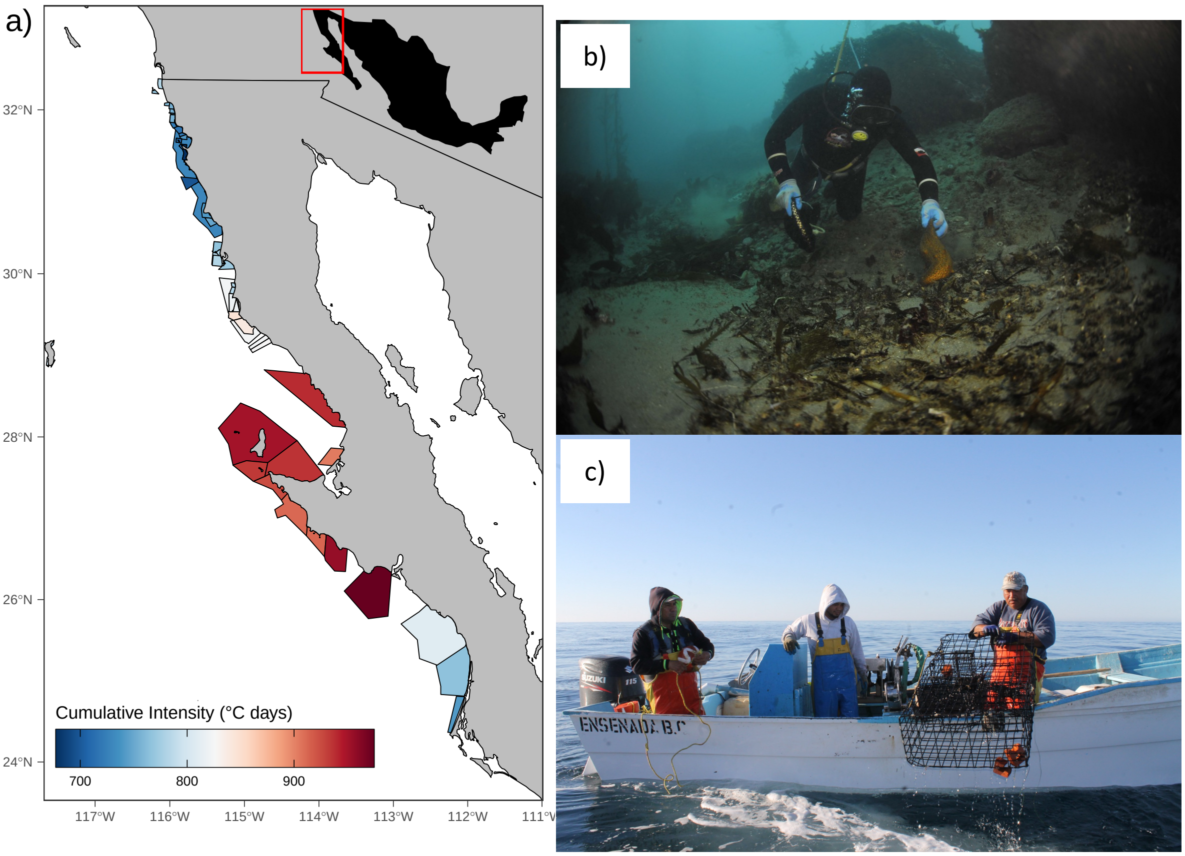

Figure 1: TURF-based benthic fisheries along the Baja California peninsula. **a)** Map of the Baja California Peninsula showing the ocation of the 55 TURFs (*i.e.* polygons) belonging to 43 economic units (*i.e.* organized groups of fishers) considered in our analysis. Note that it is possible for some economic units to "own" more than one TURF. The color of each polygon shows the maximum annual cumulative marine heatwave intensity registered for each TURF during the 2014-2016 marine heatwave regime. The figures on the right show the main fishing gears and methods. **b)** Shows sea cucumbers and sea urchins are hand-collected by hookah divers. **c)** Lobsters are caught using set traps, soaked for 24-48 hrs at depths 10 - 50 m (bottom). Pictures used with permission by the author (Arturo Hernández-Velazco).

2 Results

2.1 Exposure to and impacts from historical marine heatwaves

2.1.1 Historical frequency and intensity of Marine Heatwaves

Historical data (1982-2022) show that TURFs in Baja California have been frequently exposed to marine heatwaves (MHW; Figure 2a). The average annual probability of a TURF experiencing at least one marine heatwave was 0.76 ± 0.02% (M ± SD), but most events have been short-lived (18.58 ± 29.48 days) and only moderately intense (2.02 ± 0.52 °C above the threshold). These patterns do not differ significantly across fisheries (One-ANOVA results: $F(2, 52) = 0.55; p = 0.57$), but TURFs near the south have been exposed to more marine heatwave events and marine heatwaves of higher intensities (Figure 2a). The data also show the occurrence of four distinct periods characterized by prolonged and intense marine heatwave regimes that coincide with El Niño events (1982-'83, '91-'92, '97-'98, and 2015-'16; Figure 2a). Our analysis focuses on the latest, longest and most intense one, occurring between 2014 and 2016. On average, this period was twice as intense as any of the previous El Niño events (Figure 2b). In fact, cumulative intensities registered between 2014-2016 were higher than the intensity of all other three El Niño events combined (Figure S1).

During the 2014-2016 regime, TURFs were exposed to an average of 6.53 ± 1.77 events per year, with a mean duration of 204.38 ± 68.18 days, a mean intensity of 2.42 ± 0.43°C, and average cumulative intensity of 513.95 ± 234.46°C days (Figure 2c-f). This level of exposure is significantly higher than the historical mean cumulative intensity of 84.22 ± 107.68°C days (One-sided Student's T-test results: $t(441.08) = -47.72, p < 0.001$, data were log-transformed). Going forward, we will refer to three distinct periods in relation to this intense marine heatwave regime: before (2001-2013), during (2014-2016), and after (2017-2022). Unless otherwise specified, the use of "cumulative marine heatwave intensity" refers to the annual cumulative intensities. Additionally, since these metrics of exposure to marine heatwaves are all correlated (See Figure S2), we will focus on the annual cumulative marine heatwave intensity measured in °C days [14].

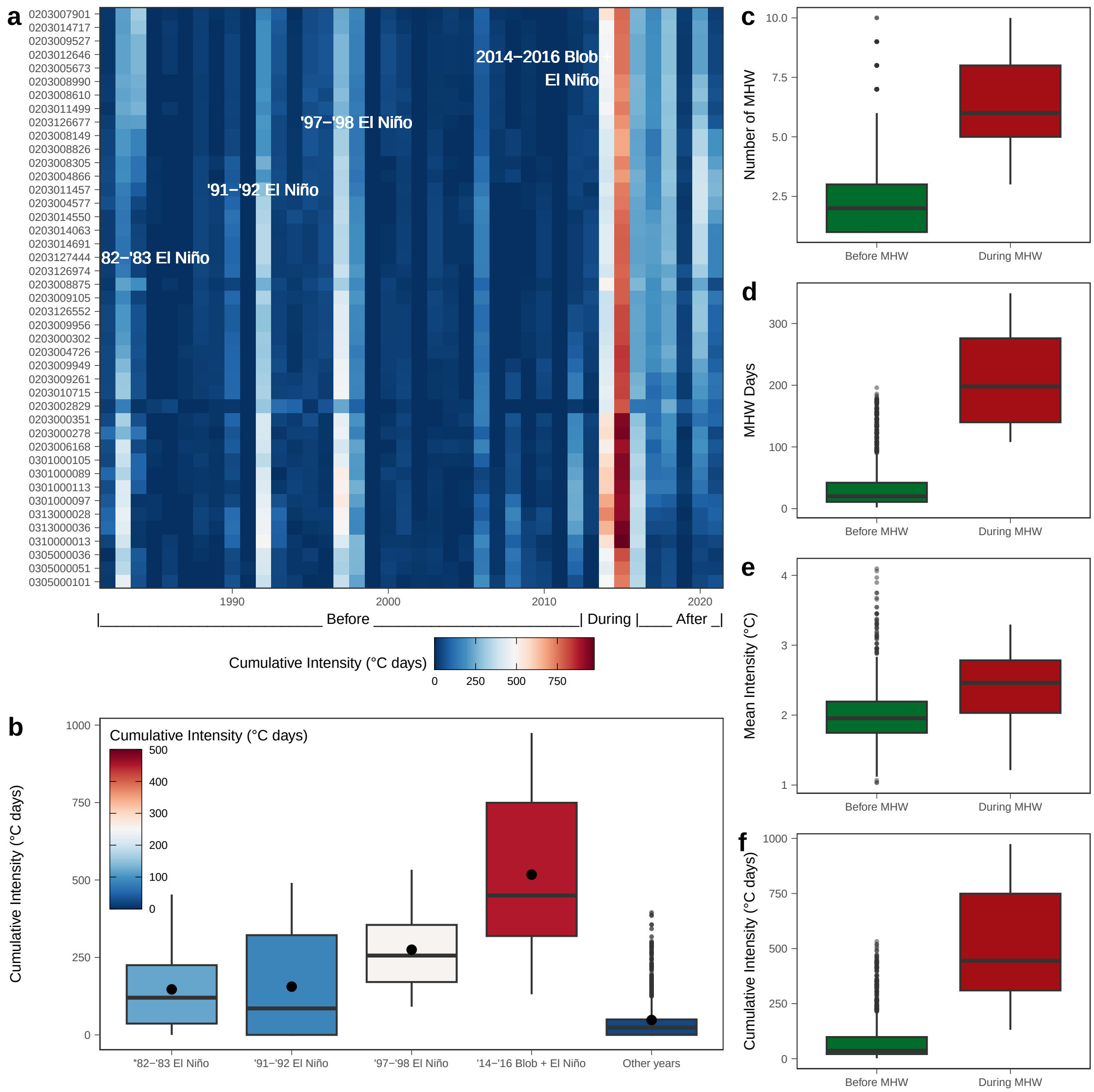

Figure 2: Exposure of 43 economic units to historical marine heatwaves between 1982 and 2022. Panel **a** shows a discrete Hovmöler diagram with time along the x-axis (years) and unique economic unit identifiers along the y-axis [latitudinally organized, north (top) to south (bottom)]. The color scale indicates the annual cumulative marine heatwave intensity (°C days) experienced by each economic unit; a value of cumulative marine heatwave intensity of 0 indicates no marine heatwave for that year and TURF. For economic units with more than one TURF we show the area-weighted mean. Panel **b** shows boxplots for annual cumulative marine heatwave intensity during each El Niño event (points inside boxplots show the mean cumulative intensity), and non-ENSO years. Panels **c-f** show boxplots for the number of marine heatwaves, days under marine heatwave, mean marine heatwave intensity and cumulative intensity (°C days) before and during the marine heatwave regime.

2.1.2 Impacts of historical marine heatwaves on fisheries production

Historical fisheries production data (2000-2022) of lobster, sea cucumber, and sea urchin fisheries show that mean normalized landings differed between the three periods, with sharp reductions (15.8 - 57.9%) coinciding with the timing of the marine heatwave regime (2014-2016; Figure 3a). These differences were not statistically significant for the lobster fishery ($F(2) = 1.47; p = 0.25$) and oscillated between 57,981 and 71,632 tons per economic unit. The differences were statistically significant for the sea cucumber (One-way Type II ANOVA, $F(2) = 24.17; p < 0.01$) and the sea urchin fisheries ($F(2) = 7.38; p < 0.01$). In the sea cucumber fishery, landings before the marine heatwave regime (19,414.3 ± 6,107.8 tons per economic unit) were higher than during (8,177.5 ± 2775.2 tons per economic unit) and after it (6,969.1 ± 1156.6 tons per economic unit), but note that the decline in landings began nearly five years before the onset of the marine heatwaves. Sea urchin landings after the regime (68,787.7 ± 34,758.5 tons per economic unit) are different from the pre-regime period (81,688.2 ± 25,190.7 tons; all post-hoc testing was done via Tukey's HSD). However, the patterns observed in averaged landings data obscure the idiosyncratic and heterogeneous responses of each economic unit (Figure 3b). For example, landings of some economic units actually *increased* during the marine heatwave regime, calling for a detailed analysis that can capture the diversity of responses and accounts for pre-existing trends in the fishery.

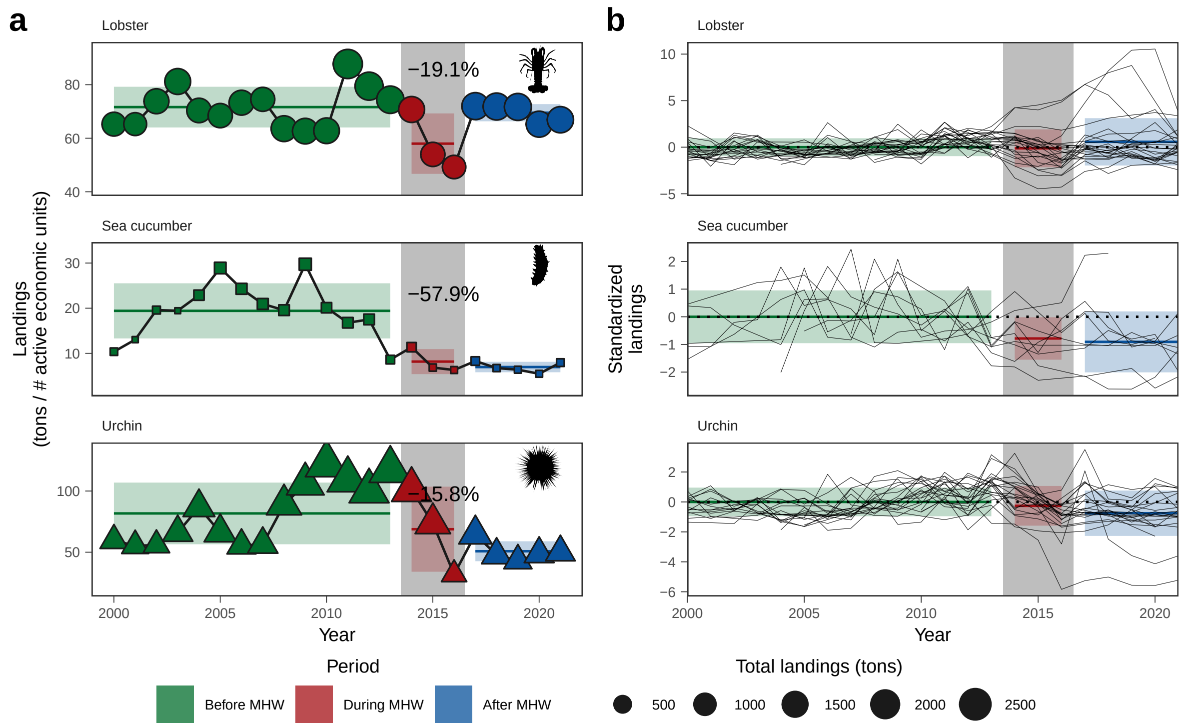

Figure 3: Time series of landings by species. Panel **a** shows the total normalized landings (*i.e.* total tons landed divided by the number of economic units participating in the fishery each year, in the y-axis) and the total landings (point size) through time. Overlaid numbers indicate the percent change in landings relative to levels before the marine heatwave regime. Panel **b** shows a time series of anomalies in total annual landings by species and TURF (*i.e.* data have been standard-normalized relative to the mean and standard deviations observed for each economic unit before the marine heatwave regime). In all panels, the colored horizontal segments in the background show the mean and standard deviation across all data in each period, and the gray vertical shading shows the 2014-2016 period.

We estimated the effect of cumulative marine heatwave intensity on fisheries production of each fishery with fixed-effects models that account for pre-existing temporal trends in landings and allow for variable effects of marine heatwaves by TURF (See methods section for details). We find that 56.4% of TURFs (N = 31) exhibit negative effects of cumulative marine heatwave intensity on landings; these effects are statistically significant in 25.5% of them (N = 14, $p < 0.05$). The lobster fishery shows the largest diversity of impacts, with coefficients between -0.86 and 0.78 (these coefficients can be interpreted in terms of standard deviations away from the mean). This fishery was also the most impacted by marine heatwaves, with 14 of the 24 economic units (58.3%) showing negative impacts (9 significant, $p < 0.05$). In the sea cucumber fishery, seven of the nine economic units were negatively impacted (only two significant, $p < 0.05$). And nine of the 22 economic units participating in the sea urchin fishery show negative effects (only 3 are significant, $p < 0.05$). For economic units targeting more than one species, the effects are also concordant across these (Figure S3). The estimated effects (coefficients) are shown in Figure 4a, and are robust to modifications in a number of other assumptions regarding potential regime shifts (Figure S4), lagged effects (Figure S5), and modeling frameworks (Figure S6).

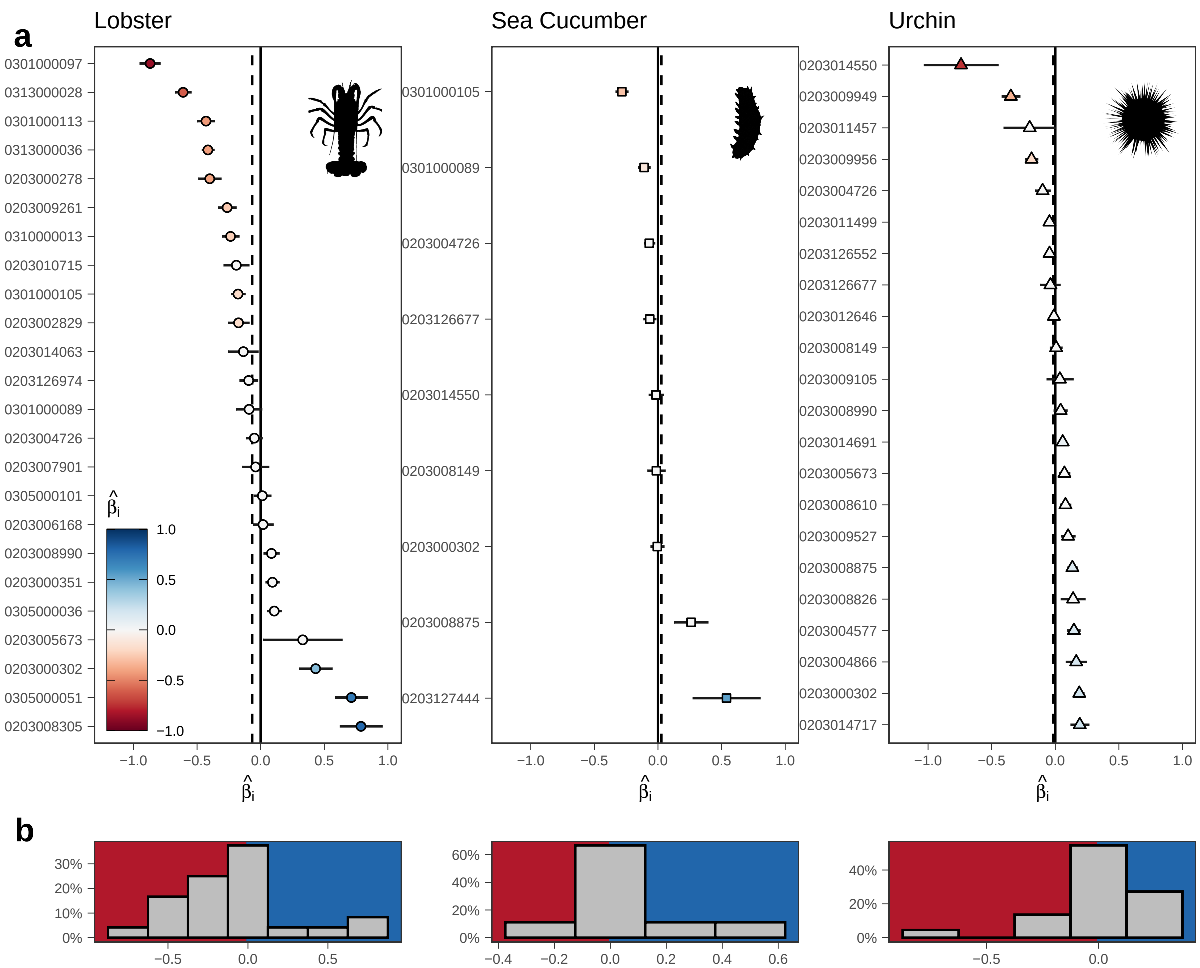

Figure 4: Influence of cumulative marine heatwave intensity on landings. Panel **a** shows the estimated effects. Points are coefficient estimates (change in mean landings, measured in standard deviations away from the mean for every 1 std.deviation change in cumulative marine heatwave intensity) and error bars show heteroskedasticity and spatiotemporal consistent standard errors (following Conley [36]; temporal lag = 5 years, spatial cutoff = 100 km). Coefficients that are significant ($p < 0.05$) are colored. The color of the coefficient also maps onto its magnitude, given by the colorbar. Insignificant coefficients are shown in white. The solid vertical lines indicate 0 (no effect), and the dashed lines show the mean average effect across all economic units in each fishery. Panel **b** shows the frequency distribution of the effects using a binwidth of 0.25.

2.1.3 Correlates of impacts

We are interested in understanding how the impacts of marine heatwaves are driven by a TURF's proximity to a species' distribution limit (the biogeographic hypothesys), the historical variation in its environmental conditions (the climate refugia hypothesis), or the historical stability of their fisheries production (the adaptation hypothesis). We test the biogeographic hypothesis by investigating the relationship between the distance from a TURF's latitudinal centroid to the species distribution limit (here ∼25°N) and the effect of marine heatwaves on fisheries production (Figure 5a). We find support for the biogeographic hypothesis: TURFs closer to the distribution limit presented the largest negative shocks ($p < 0.05$). We tested the climate refugia hypothesis –low historical environmental variation in an otherwise changing climate confers resilience to climate shocks [29]– by analyzing the relationship between the historical coefficient of variation of SST and the effect of marine heatwaves on fisheries production (Figure 5b). We found that the magnitude of *negative* coefficients increases as SST becomes more variable ($p < 0.01$), thus lending support to the climate refugia hypothesis. Finally we test for the social adaptation hypothesis by inspecting the relationship between historical variation in fisheries production and the estimated impacts of marine heatwaves (Figure 5c). The largest negative shocks are observed for TURFS with lower historical variation in fisheries production ($p < 0.01$), in contrast with the hypotheses prediction that historical stability equals future stability. Coefficient estimates are shown in Table 1.

Table 1: Regression coefficients testing for the biogeographic, climate refugia, and adaptation hypothesis.

	Biogeographic	Climate refugia	Adaptation
Slope	0.269*	−0.489***	0.640***
	(0.146)	(0.135)	(0.124)
Num.Obs.	55	55	55
Std.Errors	Conley (100km)	Conley (100km)	Conley (100km)
FE: fishery	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01 All models include fixed-effects by fishery and use spatial standard errors with a 100 km buffer. Regressors were resacled to 0-1 range to help comparision of coefficients between drivers.

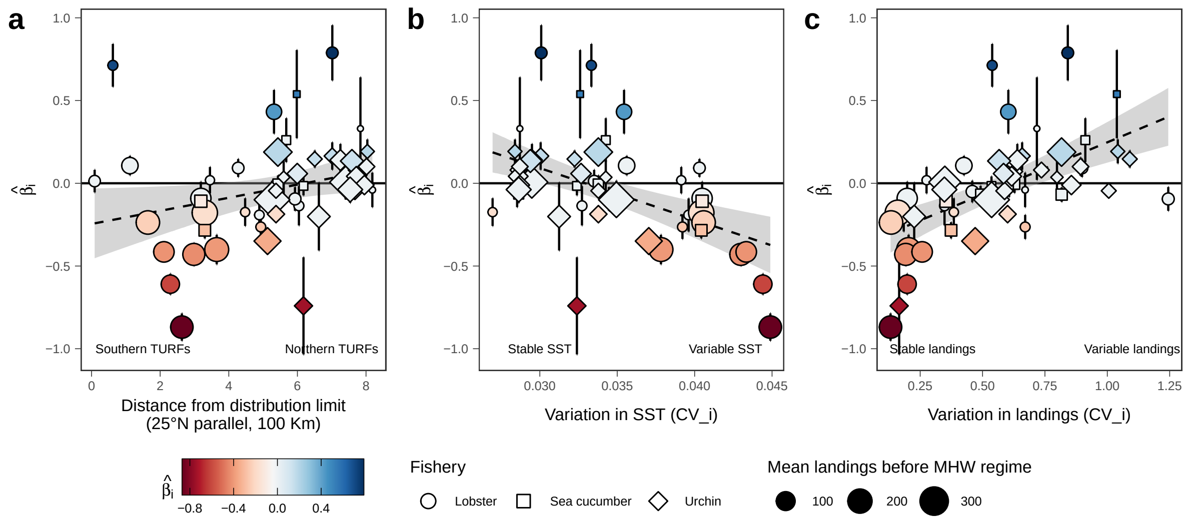

Figure 5: Relationships between biophysical and socioeconomic characteristics of each system and the impacts of marine heatwaves on its fisheries production. Points show coefficient estimates ($\hat{\beta}_i$) and error bars show heteroskedasticity and spatiotemporal consistent standard errors (following Conley [36]; temporal lag = 5 years, spatial cutoff = 100 km). The color of the marker maps onto the coefficient's magnitude, the size of the marker is given by the historical mean landings, and the shape of the marker indicates the fishery. The dashed lines show a line of best fit via simple linear regression for all points in each panel.

2.2 Marine heatwaves in the face of climate change

2.2.1 Future probability of exposure to marine heatwaves and extreme vents

We used projected SST from 11 CMIP6 models and three Shared Socioeconomic Pathways (SSP) to quantify the projected frequency and intensity of future marine heatwaves (present - 2050). We find that, regardless of SSP, the annual probability of experiencing at least one marine heatwave will be higher (between 0.969 $\pm$ 0.021 and 0.976 $\pm$ 0.01) than the historical probabilities (p = 0.76 $\pm$ 0.025, on average) observed for all TURFs and fisheries (Figure 6a; Type II, Two-way ANOVA in Table S3; Tukey's HSD in Table S4). However, we find that the *change* in probability of exposure will be up to two times larger for TURFs in the north (Figure 6b). Extreme exposure events (*i.e.* a year with as much intensity as what we observed for the most intense year on record: 2015) are also more likely to occur in the future, with significant differences between SSPs and fisheries (Fig 6c; two-way Type II ANOVA, $F(2) = 13.89; p < 0.01$ and $F(3) = 933.92; p < 0.01$). These differences arise due to the greater probabilities expected for sea urchins relative to lobster TURFs, and for the greater probabilities expected under SSP5-8.5 relative to both SSP1-2.6 and SSP2-4.5 (Post-hoc

Tukey's HSD tests; Table S6).

2.2.2 Identifying TURFs that are the most vulnerable to future marine heatwaves

We define vulnerable TURFs as those negatively impacted during the 2014-2016 marine heatwave regime and whose exposure to marine heatwaves is expected to increase (See Figure 7a). We find that between 12.5% and 33% of TURFs are vulnerable to future marine heatwaves under SSP1-2.6 (Figure 7b). These numbers drastically increase for SSP5-8.5, where between 41% and 55% of economic units are vulnerable to future extreme marine heatwave events. Importantly, we find that TURFs in the north were frequently identified as vulnerable to future marine heatwaves, regardless of SSP (Figure 7c).

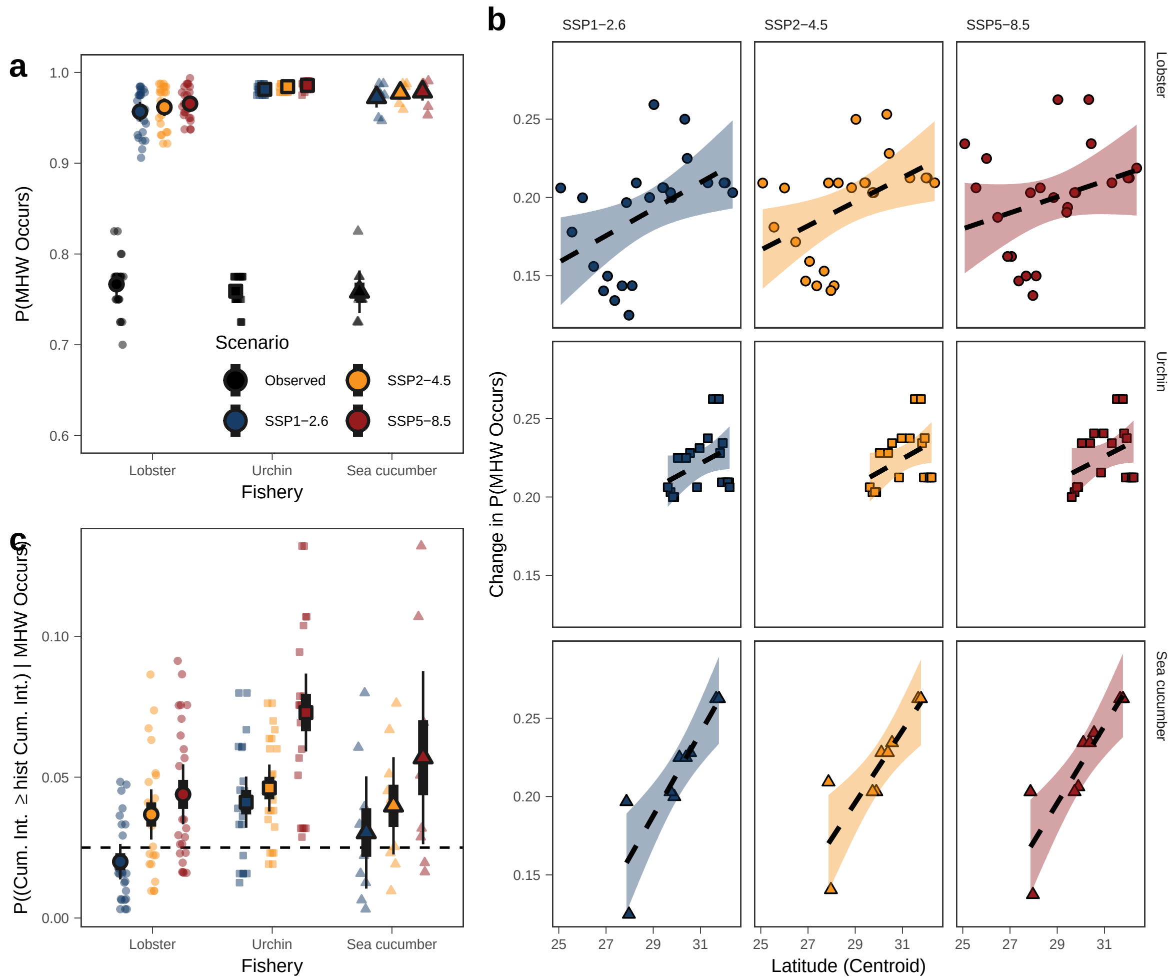

Figure 6: Future probability of exposure to marine heatwaves by 55 TURFs. Panel **a** shows the average probability that at least one marine heatwave will occur for each fishery. Panel **b** shows the relationship between the latitudinal centroid of each TURF and the change in probability of a future marine heatwave, with colors and markers representing SSP scenarios and species, respectively. Panel **c** shows the average probability that TURFs will experience another year of extreme events, conditional on there being a marine heatwave (*i.e.* a year with the same or more cumulative marine heatwave intensity as the maximum recorded, see Table S5). The dashed horizontal line represents the maximum historical probability of occurrence (p = 0.025: 1 event in 40 yrs on record). Small opaque points in **a** and **c** represent TURF-specific ensemble means from the 11 CMIP-6 models, and colors indicate the shared socioeconomic pathway (SSP). The large markers show the average across all TURFs within a given SSP, with a thick portion of the bars showing the standard errors, and error bars showing 95% Confidence Intervals. Note that the y-axis is truncated in both plots, and that they show different scales.

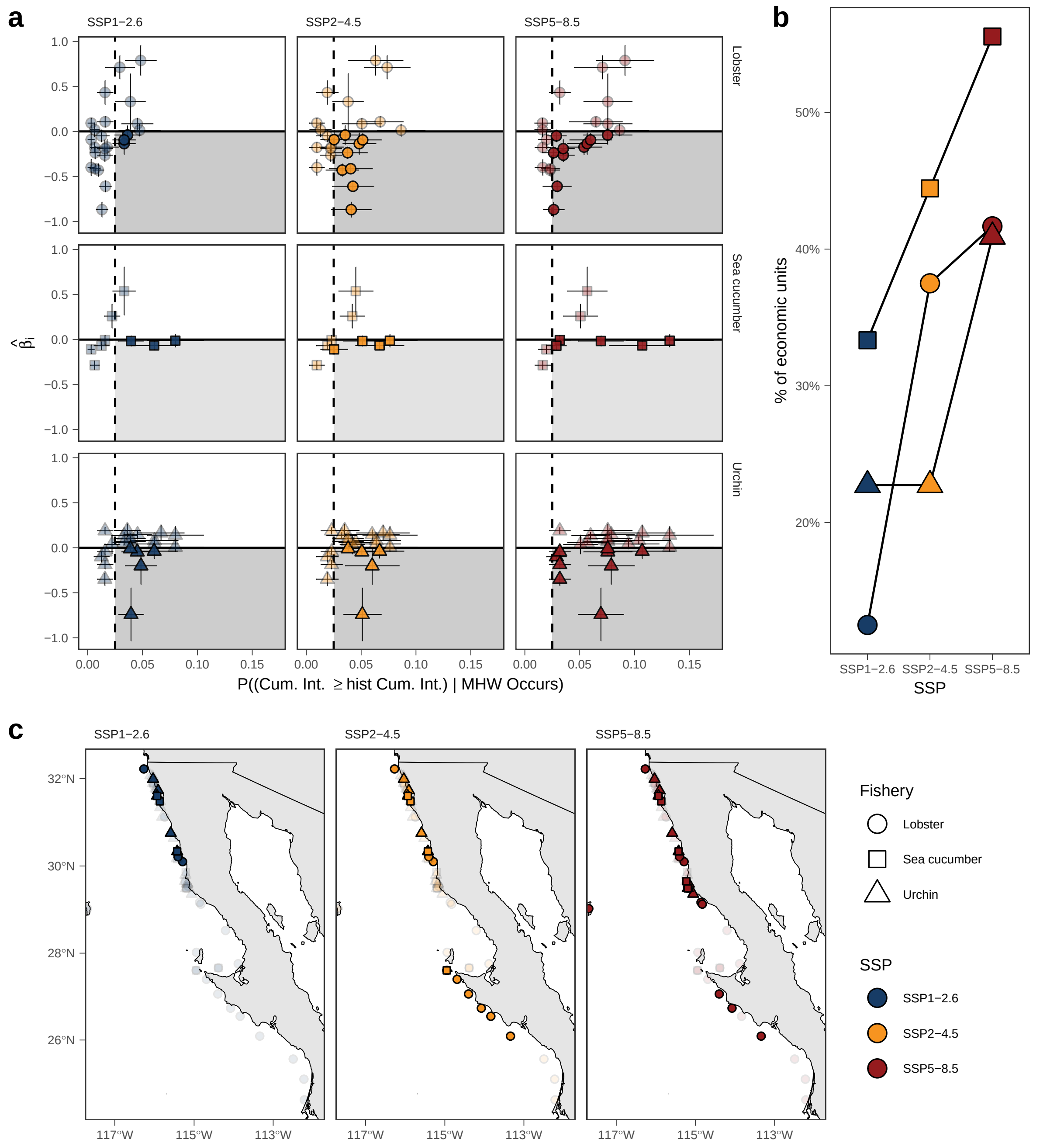

Figure 7: Future vulnerability of TURFs and benthic fisheries to extreme marine heatwaves under climate change. Panel **a** shows the relationship between coefficient estimates ($\hat{\beta}_i$) and the conditional probability of experiencing another extreme year between now and 2050. The error bars show spatiotemporal and heteroskedasticity consistent standard errors on the coefficient estimates, and standard errors around the mean probability derived from model output from 11 models. Panbel **b** shows the proportion of economic units that fall in the bottom-right quadrant of panel **a**: economic units for which we identify a negative influence of marine heatwave on landings and for which the probability of an extreme event is higher than 0.025 (*i.e.* 1/40). Panel **c** shows the centroid for each polygon, with those identified as vulnerable under each SSP fully colored. Across all panels, colors indicate the different climate change scenarios as indicated by the Shared Socioeconomic Pathways (SSP).

3 Discussions and Conclusion

Our analyses of fine-scale, long-term historical data and modeling projections reveal significant and escalating negative impacts of marine heatwaves on small-scale fisheries. Specifically, we found that marine heatwaves negatively impact small-scale fisheries production; that impacts are magnified near biogeographic limits, in areas with high environmental variation, and in TURFs with low variation in production; and that climate change is expected to increase exposure and vulnerability to marine heatwaves. The following paragraphs provide further interpretation of our results and draw connections between the different portions of our analysis. We also discuss the drawbacks and limitations of our approach and highlight potential directions for future. We finalize with concluding remarks.

3.1 Historical exposure to marine heatwave and impacts on fisheries production

We characterized historical exposure to marine heatwaves at the spatial scale of each TURF, an empirical exercise never done before. In line with previous findings from regional [17] and global analysis[3], we found that short-lived and less intense marine heatwaves are common in the region and that TURFs had never been exposed to events as extreme and prolonged as those recorded between 2014 and 2016. However, an advantage of estimating exposure metrics at the scale of individual TURFs –as opposed to arbitrary pixels or regions– is the direct applicability of our findings because fishers and managers alike may find it easier to incorporate findings at scales matching those of management units into their decision-making processes [37]. This scale also allowed us to match a TURF's marine heatwave exposure metrics to their fisheries production data, enabling the first ever fine-scale analysis of the impacts of marine heatwaves on small-scale fisheries production.

Consistent with findings from work on more industrialized fisheries, we found that marine heatwaves result in net reductions in fisheries production from small-scale fisheries, even in the presence of "winners" and "losers" [5, 19]. Yet, an important difference between small-scale and industrialized fisheries is the magnitude of the impacts. For example, we find that fisheries production during the marine heatwave regime was up to 58% lower than levels observed in the pre-MHW period. This figure is of course shadowed by the implied 100% reduction in landings of closed fisheries [38–40], but is still larger than what was observed for lobster, urchin, and cucumber fisheries that remained operational in adjacent waters in California. For example, data from Free *et al.* [5] show that aggregate commercial landings of these species were 28.2% lower during the same marine heatwave event, relative to the pre-mhw years (Table S7). And even if the impacts had been proportionally similar, the socioeconomic consequences of these types of shocks to small-scale fisheries are likely more pronounced because fisheries are an opaque and diverse sector, which hinders government's ability to provide direct economic support (*e.g.* through Federal Disaster Relief *sensu* Nielsen *et al.* [40]) and, at the same time critically important to economies and livelihoods of millions people worldwide [6].

3.2 Correlates of impacts of marine heatwaves on fisheries production

Previous work has shown that there are differences in the pace of redistribution between the poleward and equatorward edges of a species' range [41, 42], and that habitats and biological populations closer to temperate-tropical transition zones are more vulnerable to warm-water anomalies [15, 18, 43]. Our findings show that this vulnerability extends to the human component of the social-ecological system, and that its effects can be amplified or buffered by local characteristics. For example, for the same level of exposure, TURFs in the southern region –close the the species' equatorward range edge– have experienced a proportionally larger reduction in landings than those in the central areas. However, TURFs exposed to high historical environmental variation also experienced proportionally larger reduction in landings, supporting calls for harnessing marine climate refugia to promote adaptation in resource management [44]. We note that our broad definition of climate refugia and the macro-scale of our analysis implicitly prevent us from identifying micro-climate refugia within TURFs. Our findings also showed a lack of support for the adaptation hypothesis, at least at the scale of this unprescendented event. It is possible that the 2014-16 marine heatwave regime was so anomalous that even well-adapted communities were unable to cope with the magnitude and durations of the shock.

These valuable insights rely on fisheries-dependent data, which hinder our ability to identify the mechanisms driving the reductions in landings. Other research in the region confirms local reductions in density of benthic invertebrates during the marine heatwave regime [17]. A combination of increased natural mortality and redistribution of organisms in search for colder waters (either north or deeper; [23, 45] could explain the reductions in densities (and by extension, landings). Measuring the direct contribution of each process would require data that are not available, but patterns in the landings data can still help us identify their relative importance for each fishery and overcome the ever-pressing need for more and better data.

For example, lobster landings were at their historical low during the marine heatwave regime and promptly recovered to pre-MHW levels as soon as temperature anomalies subsided, a pattern consistent with momentary stock redistribution rather than mass mortality events. Indeed, the same dip-and-recovery pattern has been reported for the small-scale lobster fishery in the Galapagos during el Niño events [46], where reproductive migration of spiny lobsters to deeper waters is thought to explain it [47]. Spiny lobster in Baja California engage in earlier-than-usual breeding during warm-water events [48] and, although lobsters typically move $\sim$150 m/day [49], movements associated with deep-water reproductive migrations may be in the order of 1 km/day [50]. Temporary redistribution due to warm water is likely the main contributing factor influencing the localized changes in lobster densities, and therefore landings.

On the other hand, data show that sea cucumber and sea urchin landings are yet to return to pre-MHW levels, a pattern consistent with mass mortality events and the slow recovery that follows it [51, 52]. Sea cucumbers are sessile invertebrates with limited mobility, and are thus not able to redistribute in response to rapid warming events. Additionally, sea cucumber populations along Baja California have been historically subject to intense fishing pressure [53, 54]. Since sustained overfishing can increase a stock's vulnerability to environmental shocks [55], and heat stress has been shown to induce stress spawning and mortality in sea cucumbers [56], mass mortality is likely the main driver of changes in sea cucumber landings.

Finally, in the sea urchin fishery –which is relatively well-managed, but with room for improvement [57, 58]– the answer likely lies in the well documented changes in distribution and availability of kelp in the region [59]. Fishery impacts from starvation and reduced gonad size following loss of kelp are well-documented along the north eastern Pacific [52, 60]. In Baja California, local loss of kelp is a leading factor explaining the reduced quality and size of urchin gonads. In response, fishers are known to occasionally relocate sea urchins from barrens to areas with greater algal cover as a way to artificially support gonadic development, growth and survival [61].

3.3 Future impacts of marine heatwaves on small-scale fisheries

Climate model output suggests there will be an increase in the frequency and severity of marine heatwave across all TURFs and fisheries, but that the change in exposure will be greater for TURFs in the north. Although the exact mechanisms remain unclear, this latitudinal gradient is broadly consistent with large-scale analysis of marine heatwave projections, particularly under intense emission scenarios [62]. This means that there will be a regional convergence towards higher levels and frequencies of exposure to marine heatwaves, but it does not necessarily imply that the impacts will be uniform. Previous studies have found that the strength of adaptive responses implemented by small-scale fishers is typically proportional to the historical frequency and intensity of the climatic shocks to which they have been exposed [30]. This is important because TURFs in the south have been subject to more frequent and more intense marine heatwaves, and their impacts are larger due to their proximity to the temperate-subtropical transition zone. But this high historical exposure may have incentivized proactive adaptive responses that may confer some resilience to future marine heatwaves (*e.g.* temporal fishing bans over certain species, implementation of community-based marine reserves, and even manipulation of their environment [61, 63–66]). TURFs in the north, on the other hand, may be the most impacted by future climate change, particularly if the rate of change in heatwave exposure outpaces the rate at which fishers can produce and implement adaptive responses.

This tension between potential marine heatwave exposure for southern TURFs in the short-term and projected increase in exposure for northern TURFs in the long-term may pose a management challenge. Managers will need to consider a TURF's local characteristics when promoting the adoption or transferability of adaptive responses observed elsewhere [67]. Finally, there will always be a need for more and better data to further our understanding of the natural world and of social-ecological systems and to inform resource management. But we note that even simple interventions, such as modest reforms to improve fisheries management, can go a long way in mitigating the adverse impacts of a changing climate [55, 68]; any additional, tailor-made approaches will only yield marginal gains.

3.4 Shortcomings

As is par for the course with analysis using observational data, it is difficult to make causal statements about patterns and correlations in the data alone [69]. This general limitation is shared by other work studying the interaction between heatwaves and fisheries [5], but we note that our main results are robust to a series of different specifications (Figure S4), lag structures (Figure S5), and modeling assumptions(Figure S6). To the best of our knowledge, there aren't any other social, economic, political, or environmental factors that may have co-occurred with the marine heatwave regime, and we are unaware of any other plausible mechanisms that could explain the reductions in landings and consequent recovery pathways, or lack thereof. We emphasize that our estimates should be interpreted as the net effect of exogenous exposure to marine heatwaves, inclusive of any *ex post* adaptation by fishers. Similarly, our analysis of vulnerability to future marine heatwaves should be interpreted as a *ceteris paribus* case that can not, by definition, account for unforeseen adaptation or policy interventions.

There are at least three immediate opportunities for further research. First, we focused on analyzing the effect of marine heatwaves on landings. Although the effect is expected to be similar, future work should attempt to collect and analyze high-resolution data on the economic performance of the fishery (that is, revenue, costs, and profits) in order to estimate the economic impact of marine heatwaves. Secondly, our sample of economic units was constrained by current data availability on the spatial outline of TURFs. Although notable work is being done to make these types of data available (See [35]), we cannot, and do not, claim that we have analyzed all TURFs in the region; we simply analyzed those for which data was available, and encourage our analysis to be re-visited should more data become available. Finally, our analysis of vulnerability to climate change does not account for longer term shifts in species distribution (sensu Cheung & Frölicher [22]), and highlights an area where process-based dynamic range models may prove fruitful [70].

3.5 Conclusions

Our work provides the first-ever analysis on the influence of marine heatwaves on individual fishing operations, and is also the first to do so for small-scale fisheries, and for fisheries that operate along a biogeographic transition zone. We showed that marine heatwaves have had large negative impacts on small-scale fisheries production, and that these impacts were larger for fishing operations near species distribution limit and for areas with highly variable environmental conditions. We also show that reductions in landings are likely driven by the interaction between marine heawaves and species life histories, historical (over)exploitation, and changes in ecosystem productivity. Finally, we confirm an all-too-common observation that climate change is expected to exacerbate these impacts, but note that future vulnerability of TURFs to marine heatwaves is highly dynamic. Our work also provides the first empirical proof that, in the face of extreme environmental shocks such as marine heatwaves, small-scale fisheries operating near transition zones where target species find their distribution limit are amongst the most vulnerable groups.

4 Methods

4.1 Data sources

We use historical sea surface temperature data, projected sea surface temperature data, spatial information on the location of fishing activities (*i.e.* TURFs), official landings data, and underwater ecological surveys. The following sections provide more information on each data source.

4.1.1 Historical sea surface temperature (SST)

We use NOAA's AVHRR Optimum Interpolation v2.1 - SST product. This version provides daily measurements of sea surface temperature at a 0.25°X0.25° grid [71]. We retain data within a spatial bounding box between -119 and -110 of longitude and 23 to 32.75 of latitude. We use data from Jan 1, 1982 to Dec 31, 2022. Data were retrieved with repeated requests to the ERDDAP data server (See coastwatch.pfeg.noaa.gov) using a general purpose client for ERDDAP servers[72].

4.1.2 Fisheries production data

We use historical fisheries production data for spiny lobster, sea urchin, and sea cucumber reported in landing receipts to Mexico's fisheries management agency, CONAPESCA (2000 to 2022). This dataset includes information on fisheries production of all "economic units" in Mexico and is provided by Mexico's fisheries management agency (CONAPESCA). The term "economic unit" is used by CONAPESCA to identify financial entities, which may range from multi-actor fishing cooperatives to individual fishers. The data includes information on economic unit name, month, year, species, and volume of catch (Kg). We retain economic units that reported annual landings at least twice in each period before, during, and after the marine heatwave regime. We then obtained information on the spatial distribution of the economic units for our study area from a recently published dataset that compiles the spatial polygons corresponding to the territorial user rights for fisheries (TURF) assigned to each economic unit and marine resource in Mexico [35]. We note that the spiny lobster fishery operates annually from September to February [73], the cucumber fishery operates from March to September [74], and the sea urchin fishery operates from July to February [75] . Therefore, lobster and urchin landings reported in January and February of a given year were assigned to the opening season of the previous year. Thus our final landings data cover the seasons starting in 2001-2021 and report annual landings by species and economic unit.

4.1.3 Projected Sea Surface Temperature (SST)

We use projected SST data from the Coupled Model Intercomparison Project Phase 6 (CMIP6 project). We use data from eleven models across three experiments that assume different shared socioeconomic pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5) considered appropriate for studies in fisheries and marine conservation [76]. These scenarios assume different CO_2 emissions and mitigation pathways, with SSP1-2.6 being an optimistic scenario, SSP-2.45 mitigation, and SSP-5.85 business as usual with continue CO_2 emission increase. See Table S2 for a complete list of institutions, data sources, and their nominal resolutions. We retained data between 1982 and 2050, and performed the same spatial filtering process as for historical SST data. Data were retrieved using the rcmip6 package [77].

4.2 Analysis

4.2.1 Historical marine heatwave exposure, frequency and intensity

Marine heatwaves are defined as discrete periods where temperatures exceed the 90th percentile threshold established based on a 30-year climatology for at least five consecutive days and without being interrupted for more than two days[14]. Their identification requires a long-term daily time series of sea surface temperatures, which we produce by combining the long-term historical SST gridded data with the spatial location of our 55 TURFs. We first produce a daily time series of mean SST for each TURF by calculating the mean SST of all pixels occurring within a TURF. We then identify historical marine heatwaves for each TURF based on a climatology of the first 30 years of the time series (January 1, 1982 to Dec 31, 2012) to establish a climatology. Finally, we identify marine heatwave events and calculate their durations (days above threshold) and cumulative intensity (°C / day). This part of the analysis was performed using the heatwaveR package [78].

To aggregate these data into annual and TURF-level time series that we can match with our annual fisheries production data we must employ a summary statistic that captures the severity of the annual historical exposures. Some measures discussed in the literature include the total number of marine heatwaves in the year, the total number of days of all heatwaves, or the cumulative marine heatwave intensity experienced during a year [5, 14, 79]. The latter is our preferred measure as it jointly represents the duration and intensity of all marine heatwave events to which marine resources are exposed over the course of a year, but we note that these measures are strongly correlated (Figure S2). For the remainder of the text, we will refer to three distinct periods in our date: Before the marine heatwave regime (1982-2013), during the marine heatwave regime (2014-2016), and after the marine heatwave regime (2017-2022).

For each polygon in our data set, we first calculate the probability with which at least one marine heatwave occurs in a year (*i.e.* P(MHW occurs)) by dividing the number of years in which at least one heatwave occurred by the number of years in the data. This allows us to characterize the baseline expectation of experiencing at least one marine heatwave, and the potential impacts of climate change on future marine heatwaves. We test for differences in exposure probabilities between species using a Type II One-way ANOVA with heteroscedasticity-corrected coefficient covariance matrix.

We then calculate the mean annual number of events, their duration, intensity, and cumulative intensity for the pre- during, and post- regime periods. We use one-sided Student's t-tests to test whether the cumulative intensity during the marine heatwave regime was greater than what has been historically observed. While this has been broadly corroborated in the literature (see Arafeh-Dalmau *et al.* [17], it is the first time that this analysis is performed at a scale relevant to fishers and fisheries managers in the region (*i.e.* at the TURF-level, rather than at a pixel- or region-level)

4.2.2 Impacts of historical marine heatwaves on fisheries production

The preferred measure of the heat stress to which marine organisms are exposed is given by the annual cumulative marine heatwave intensity, measured in °C days (sensu Hobday *et al.* [14], as the sum of daily °C exceeding the threshold). We thus estimate the influence of annual cumulative marine heatwave intensity on historical landings of lobster, cucumber, and sea urchin fisheries along the Baja California peninsula using a flexible framework that allows for heterogeneous effects of cumulative intensity across economic units. This is a common approach in the literature, and similar approaches have been used to estimate the influence of sea surface temperature on fisheries productivity (*e.g.* Free *et al.* [10]). We standard-normalize the cumulative marine heatwave intensity and landings of each species and economic unit relative to their pre-marine heatwave regime mean and standard deviations. For each fishery we then model the standard-normalized landings of economic unit at time as:

$$y_{it} = \alpha + \beta_i \mathrm{EU}_i \times \Omega_{it} + \tau \mathrm{year}_t + \epsilon_{it} \tag{1}$$

Where the vector β_i captures the coefficients of interest: the TURF-specific slope between landings and standard-normalized cumulative-marine heatwave intensity (*i.e.* Ω_{it}). Here α is a common intercept, captures a general time trend given the year (year_t) and ϵit is the error term for unit i at time t. Since our main dependent and independent variables are standard-normalized, the estimated coefficients ($\hat{\beta}_i$) can be interpreted in terms of standard deviations: a 1 standard deviation increase in annual cumulative marine heatwave intensity corresponds to a $\hat{\beta}_i$ standard deviation change in landings. Thus, a positive (negative) $\hat{\beta}_i$ implies that an increase in annual cumulative marine heatwave intensity is associated with an increase (decrease) in landings. We compute standard errors that are robust to heteroskedasticity and spatio-temporal autocorrelation following Conley [36]. We use a 100km cutoff and 5-year lag. All models in the main text were estimated via Ordinary Least Squares regression via the fixest package (v0.11.1)[80] in R (v4.3.1) and RStudio 2023.06.1 Build 524 [81]. Our supplementary information contains alternative specifications where we test for a regime change (**Fig S4**), the influence of lagged versions of Ω_{it} (**Fig S5**), or where we estimate a series of mixed effects models with a random effect of temperature by economic unit (**Fig S6**) and find general agreement in the direction and magnitude of our results. All these show general agreement in the direction and magnitude of the coefficients estimated by our main specification.

4.2.3 Correlates of impacts

We test three non-competing hypotheses that seek to explain the magnitude and direction of the influence of marine heatwave on landings (*i.e.* $\hat{\beta}_i$). The biogeographic hypothesis predicts that the impacts of marine heatwaves should be greater for fishing operations near a species' equatorward range edge so we analyze the relationship between impacts of marine heatwaves on landings and a TURF's distance to a species distribution limit, here the 25°N parallel for simplicity. The second hypothesis predicts that locations subject to large environmental variation (*e.g.* SST) are more resilient to environmental shocks, so we analyze the relationship between the historical coefficient of variation of mean annual sea surface temperature of each polygon (1982-2013) and the impacts recorded during the marine heatwaves. The third and final hypothesis predicts that economic units with historically stable operations (*i.e.* here proxied by landings) will withstand future shocks better than those with high historical variability. In this case we test this hypothesis by regressing the estimated coefficients on the coefficient of variation of landings (2001-2013) by each economic unit and fishery. We test each process using fixed-effects regressions estimated via ordinary least squares. We pool information across fisheries and economic units and use heteroskedastic and spatial autocorrelation consistent standard errors with a 100 km cutoff [36]. All regressors were standardized to be between 0-1 to aid in interpretation and comparison across tests.

4.3 Exposure and vulnerability of fisheries to future marine heatwaves

4.3.1 Marine heatwaves under climate change

Because the projected SST of each model has different nominal resolutions, we downscaled SST projections using bilinear interpolation to match the same standard 0.25°X0.25° grid used in the historical data. We use hindcasts (1982-2014) and projections (2015-2022) to perform bias correction through quantile delta mapping. This process is performed for each combination of TURF, fishery, SSP, and model. We then use projections (2015-2050) to calculate marine heatwave metrics for each model and scenario. We limit projections to 2050 because this implies a 30-year window that matches the tenureship cycles in TURFs [35].

We then calculate the probability with which at least one heatwave occurs in a year in the respective time period for each of the 11 models and three SSP scenarios between 2023 and 2050 (*i.e.* 29 years). We follow methods from Laufkötter *et al.* [3] and divide the number of years in which at least one marine heatwave occurs by the number of all years. We then average across all models to obtain the mean annual probability of experiencing a marine heatwave for each TURF and SSP.

We are also interested in the future probability of experiencing another extreme event, conditional on there being a marine heatwave: P((marine heatwave $\geq$ maximum observed cumulative intensity) — marine heatwave occurs). That is, for each TURF, SSP, and model, we calculate the conditional probabilities that a year's cumulative intensity equals or exceeds the maximum cumulative intensity recorded during the marine heatwave regime, conditional on there being at least one heatwave event. We follow methods by Laufkötter *et al.* [3] and compute this probability by dividing the number of heatwaves exceeding the maximum cumulative intensity observed in each TURF by the number of years that have at least one heatwave (See Table S5 for a timing and magnitude of the maximum cumulative intensity experienced by each TURF during the marine heatwave regime). We then average across all models to obtain a TURF's probability of experiencing an extreme event under each SSP scenario.

4.3.2 Future vulnerability

We define vulnerable economic units based on their potential future exposure (greater than historical) and that have been identified to be negatively impacted by marine heatwave. For each fishery, we explore how the number of vulnerable economic units changes across our three SSPs, and how this relates to their geographic location.

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5 Supplementary materials

5.1 Supplementary figures

5.1.1 Comparing the 2014-2016 marine heatwave regime with previous ENSO events

Our main text shows that the cumulative marine heatwave intensities of the marine heatwave regime were significantly higher than the historical baseline and higher than previous el Niño events (1982-‘83, ‘91-‘92, ‘97-‘98, and 2015-‘16; Figure 2a). The magnitude and intensity of this event can be put into perspective with the following: For each TURF, take the annual cumulative marine heatwave intensities of all pre-MHW regime years labeled as positive ENSO phases (*i.e.* 1982-‘83, ‘91-‘92, ‘97-‘98) and sum them into a single metric. Then, repeat the process but only for data in the MHW regime (204-2016). If we plot one against each other, we obtain Figure S1. This figure clearly shows that the cumulative marine heatwave intensity during the marine heatwave regime (with only three years of data) is much higher than the total cumulative marine heatwave intensity of all El Niño events on record (with six years of data). Normalizing these metrics by years would only exacerbate this difference.

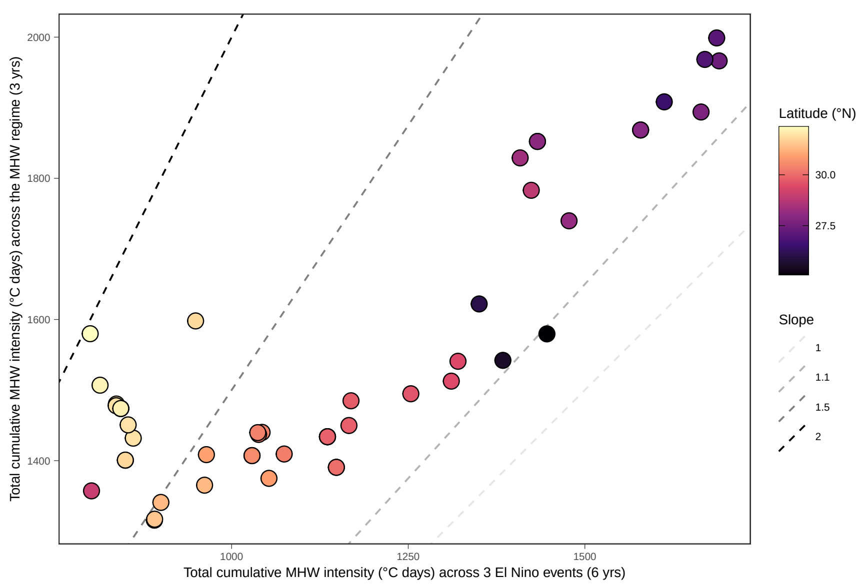

Figure S1: Comparison between the total cumulative marine heatwave intensity during three ENSO events (x-axis) and total cumulative marine heatwave intensity during the marine heatwave regime (2014-2016; y-axis) that were experienced by each fishing community. All dashed lines have a y-intercept at 0 and their slopes indicate the multiplicative factor between the axes. For example, a point falling along the slope line of 1.5 implies that the marine heatwave regime was as 50% more intense than three ENSO events combined.

5.1.2 Other metrics of exposure to marine heatwaves

Hobday *et al.* [14] provide different measures of exposure to marine heatwaves. Our main text mentions some of them in Figure 2. Here, we compute the pairwise correlation between these different metrics to show these are all heavily correlated and, to an extent, interchangeable. Specifically, we compare the annual maximum sea surface temperature, the annual maximum intensity, the annual number of events, annual days under marine heatwave state, and the annual cumulative marine heatwave intensity (measure used throughout our analysis) for each TURF through a simple correlation analysis.

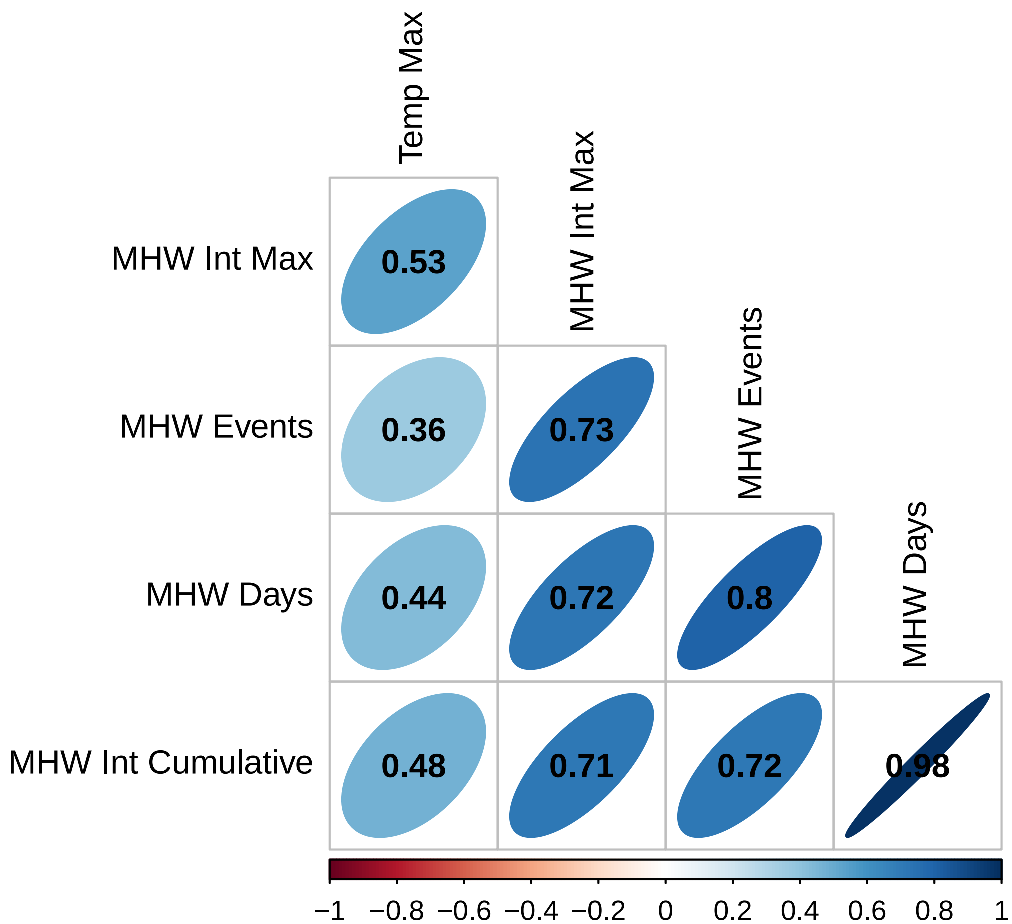

Figure S2: Correlogram of different measures of Marine Heatwaves. The colors and numbers indicate Pearson's correlation coefficient for the pairwise variables being compared.

5.1.3 Comparing magnitude and direction of shocks for economic units targeting more than one species

There are a 10 economic units that participate in more than one fishery. We are interested in exploring whether the effects across species but within economic units are concordant or not. The figure below shows the coefficient estimates (*i.e.* $\hat{\beta}_i$) for economic units that participate in more than one fishery (Figure S3). Each group along the x-axis shows one of the 10 economic units, and the magnitude of $\hat{\beta}_i$ is shown in the y-axis. Note that coefficients within an economic unit have similar magnitudes and directions, highlighting the role of local characteristics in mediating impacts. Simply put, the effect of marine heatwave on fisheries production is characterized by local biophysical and socio-economic characteristics of en economic unit (along with its TURF).

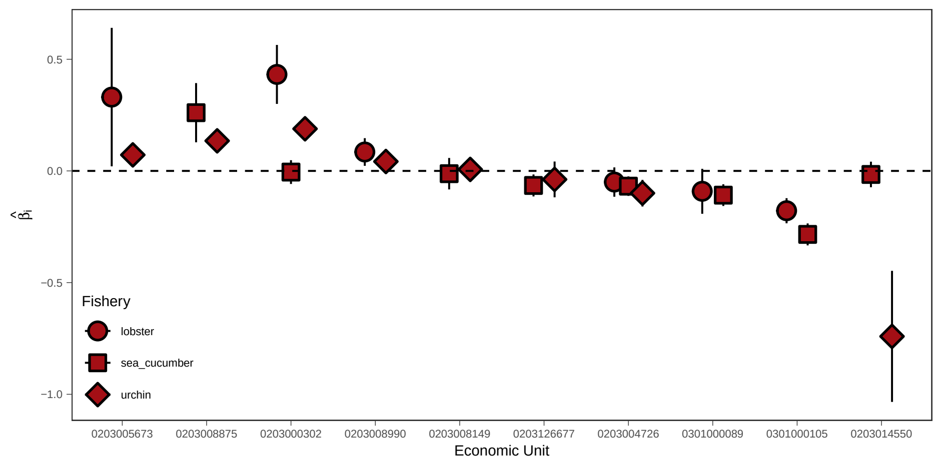

Figure S3: Coefficients for Economic Units participating in more than one fishery. Note that, for a given economic unit, the direction of the coefficient is generally correlated (i.e. negative shock to lobster fishery equals a negative shock to cucumber fishery).

5.1.4 Alternative Model Specifications

This section presents alternative model specifications for estimating the effect of annual cumulative marine heatwave intensity on fisheries production. We first define a model that allows for a regime shift following the marine heatwave regime. Since coastal ecosystems underwent significant changes in their structure, it is possible that the effect of marine heatwaves on fisheries production has changed since the marine heatwave regime. We are not interested in testing for a regime shift *per se*, but we are interested in testing for a *change* in the main estimates if we were to allow for the possibility of a regime shift. This is achieved by interacting the cumulative marine heatwave intensity with a dummy variable for the periods before and during *versus* after the marine heatwave regime. The estimation then takes the form:

$$y_{it} = \alpha + \beta_{i1}\mathbb{1}\{P_t \ = 0\} \times \mathrm{EU}_i \times \Omega_{it} + \beta_{i2}\mathbb{1}\{P_t \ = 1\} \times \mathrm{EU}_i \times \Omega_{it} + \tau \mathrm{year}_t + \epsilon_{it} \tag{2}$$

The interpretation of all coefficients and variables remains the same as in the main text, with the exception of the indicator variable P_t that takes the value $\mathrm{P}_t = 0$ for years before and during the marine heatwave regime, and P_t for years after the marine heatwave regime. Essentially, this estimates two slopes between marine heatwave intensity and landings. The first slope (β_{i1}) is the same β_i from the main text. The second slope (β_{i2}) is only relevant to all post-MHW regime years. We estimate the equation above and compare $\hat{\beta}_i$ from the main text with $\hat{\beta}_{i1}$ estimated here. The comparison of coefficients is shown in Figure S4. We find that our estimates of the influence of cumulative marine heatwaves on landings remain largely the same. Note that allowing for a regime shift only changes the coefficient estimates for economic units previously identified as benefiting from the regime, and that only one coefficient changes sign (in the lobster fishery). Our conclusions thus remain unchanged when we allow for a regime shift, but we decide to keep the more parsimonious model in the main text.

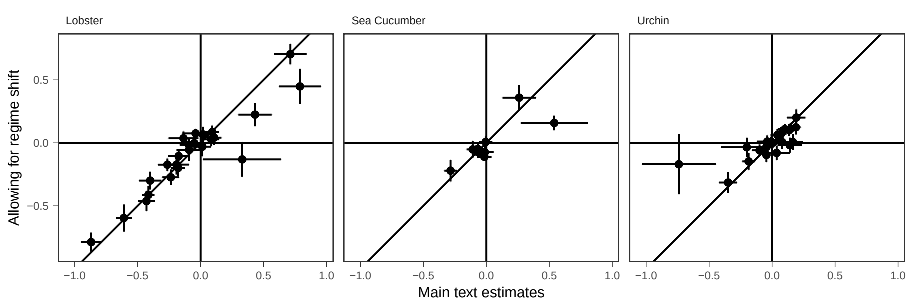

Figure S4: Coefficients estimates when we allow for a regime shift. The x-axis shows $\hat{\beta}_i$, the y-axis shows $\hat{\beta}_{i1}$. The horizontal and vertical lines show 0-values, and the diagonal line shows a 1:1 line between both measures.

We then move on to test for the lagged effects of marine cumulative marine heatwave intensities on fisheries production. Specifically, we re-fit the main specification, but modify our main explanatory variable to be 1-yr and 3-yr lags of annual cumulative marine heatwave intensities. We find a general attenuation of the coefficients, but the effects remain qualitatively the same (Figure S5).

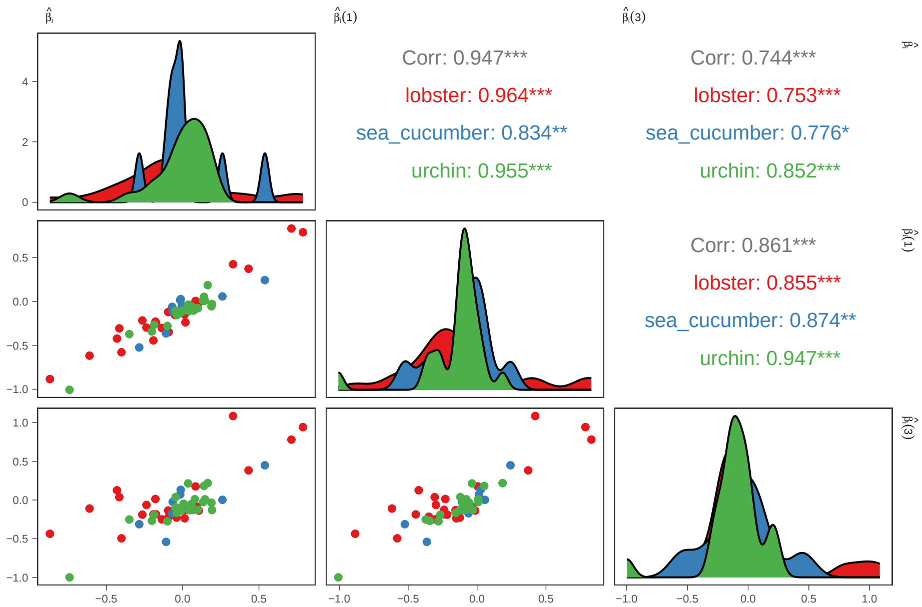

Figure S5: Comparison of coefficients presented in the main text and two alternative specifications using the 1-year and 3-year lag of marine heatwave cumulative intensity to test for legacy or recruitment effects. The "bottom triangle" shows scatter plots of coefficients estimated from two pairs of models, the "diagonal" shows a distribution of the values by species, and the "top triangle" Pearson correlation statistics. Note that most coefficients on the 3-year lag are zero, implying that marine heatwave intensity from three years ago is not correlated with fishery performance today.

Finally, we estimate a random effect model equivalent to our main specification. Here, we also allow for a varying slope of cumulative marine heatwave intensity by economic unit, but retain the shared intercept. We do this for the main set of explanatory variables, but also for the lagged versions. The results are shown in Figure S6. We find that the estimates of effect of cumulative marine heatwave intensity on fisheries production is similar across modelling frameworks, although we note that the fixed-effect estimates have generally wider confidence intervals. Our general conclusions thus remain unchanged.

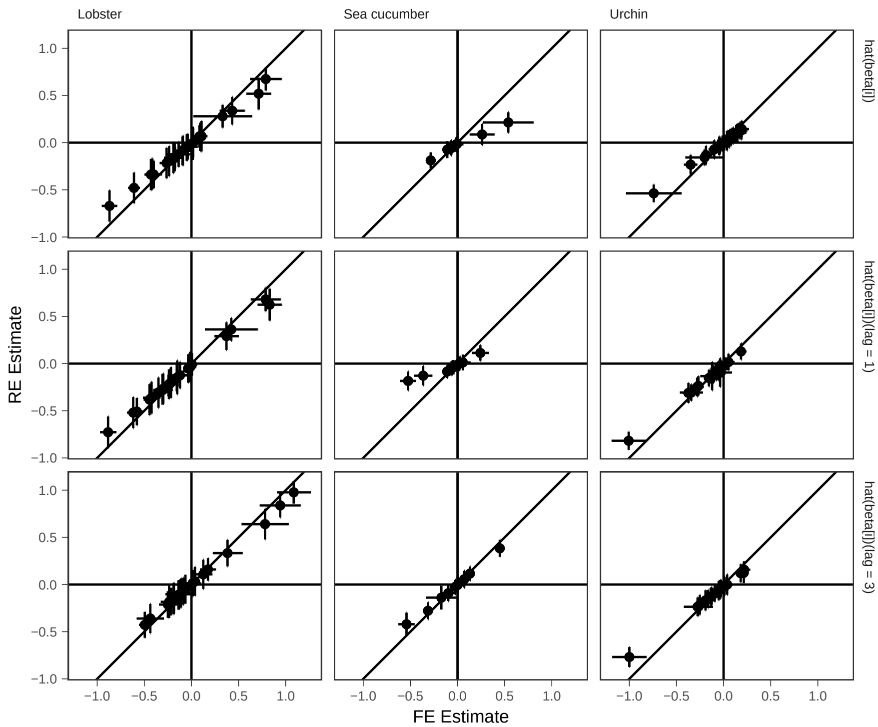

Figure S6: Comparison of coefficient estimates using random effect (RE) or fixed effect (FE) models. Each column shows the coefficient estimates for a fishery and each row the coefficient estimates for a set of lags in the main explanatory variable.

763 ## 5.2 Supplementary tables

Table S1: Summary statistics for all marine heatwave events experienced across all TURFs between 1982 and 2021

	Mean	SD	Min	Max	Median
Duration	18.58	29.48	5.00	305.00	10.00
Mean intensity	2.02	0.52	1.02	4.37	1.94
Maximun intensity	2.54	0.82	1.09	6.33	2.39
Cumulative intensity	42.41	80.55	5.18	827.75	19.45

Table S2: Information on the climate model output data used in our analysis.

Institution id	Source id	Nominal resolution
CSIRO-ARCCSS	ACCESS-CM2	250 km
CSIRO	ACCESS-ESM1-5	250 km
BCC	BCC-CSM2-MR	100 km
CMCC	CMCC-ESM2	100 km
CCCma	CanESM5	100 km
EC-Earth-Consortium	EC-Earth3	100 km
NOAA-GFDL	GFDL-ESM4	50 km
MIROC	MIROC6	100 km
MRI	MRI-ESM2-0	100 km
NCC	NorESM2-LM	100 km
NCC	NorESM2-MM	100 km

Table S3: ANOVA results testing for differences in future probability of exposure relative to historical probabilities

Statistic	N	Mean	St. Dev.	Min	Max
Df	3	73.000	122.111	2	214
F	2	473.907	650.557	13.894	933.920
Pr(>F)	2	0.00000	0.00000	0.000	0.00000

Table S4: Tukey's HSD table for differences in Future P(marine heatwave)

Source	Group	Difference	adjusted p value
fishery	sea_cucumber-lobster	0.0090626	0.0494427
fishery	urchin-lobster	0.0149556	0.0000016
fishery	urchin-sea_cucumber	0.0058930	0.2840727
ssp	ssp126-Historical	0.2068923	0.0000000
ssp	ssp245-Historical	0.2110530	0.0000000
ssp	ssp585-Historical	0.2135038	0.0000000
ssp	ssp245-ssp126	0.0041607	0.6821577
ssp	ssp585-ssp126	0.0066116	0.2916535
ssp	ssp585-ssp245	0.0024508	0.9135664

Table S5: Largest cumulative marine heatwave intensity (°C Days) observed for each TURF.

RNPA of Economic Unit	Year	Lobster	Sea Cucumber	Sea Urchin
0203000278	2015	950.17	-	-
0203000302	2015	822.83	818.44	818.44
0203000351	2015	939.12	-	-
0203002829	2015	794.85	-	-
0203004726	2015	845.84	845.84	845.84
0203005673	2015	755.16	-	755.16
0203006168	2015	903.78	-	-
0203007901	2015	768.87	-	-
0203008305	2015	729.3	-	-
0203008990	2015	741.31	-	721.39
0203009261	2015	824.58	-	-
0203010715	2015	826.63	-	-
0203014063	2015	779.77	-	-
0203126974	2015	773	-	-
0301000089	2015	933.56	933.56	-
0301000097	2015	911.87	-	-
0301000105	2015	936.11	936.11	-
0301000113	2015	924.96	-	-
0305000036	2015	809.06	-	-
0305000051	2015	765.58	-	-
0305000101	2015	741.68	-	-
0310000013	2015	974.58	-	-
0313000028	2015	912.74	-	-
0313000036	2015	955.94	-	-
0203008149	2015	-	677.57	677.57
0203008875	2015	-	783.46	782.97
0203014550	2015	-	766.65	766.64
0203126677	2015	-	708.39	708.49
0203127444	2015	-	782.03	-
0203004577	2015	-	-	749.29
0203004866	2015	-	-	697.56
0203008610	2015	-	-	716.24
0203008826	2015	-	-	677.49
0203009105	2015	-	-	783.46
0203009527	2015	-	-	755.16
0203009949	2015	-	-	839.38
0203009956	2015	-	-	818.44
0203011457	2015	-	-	741
0203011499	2015	-	-	741.9
0203012646	2015	-	-	755.16
0203014691	2015	-	-	782.4
0203014717	2015	-	-	761.28
0203126552	2015	-	-	818.44

Table S6: Post-hoc testing via Tukey's HSD for differences in future probability of extreme events across fisheries and SSPs

Source	Group	Difference	adjusted p value
fishery	sea_cucumber-lobster	0.0090626	0.0494427
fishery	urchin-lobster	0.0149556	0.0000016
fishery	urchin-sea_cucumber	0.0058930	0.2840727
ssp	ssp126-Historical	0.2068923	0.0000000
ssp	ssp245-Historical	0.2110530	0.0000000
ssp	ssp585-Historical	0.2135038	0.0000000
ssp	ssp245-ssp126	0.0041607	0.6821577
ssp	ssp585-ssp126	0.0066116	0.2916535
ssp	ssp585-ssp245	0.0024508	0.9135664

Table S7: Re-analysis of landings data from Free et al., 2023.

State	Before	After	Difference	% Diff
California	13923586.3	9994508	-3929077.93	-28.218864
Oregon	196358.4	0	-196358.36	-100.000000
Washington	1255091.5	1316600	61508.96	4.900755
British Columbia	6524642.7	7988360	1463717.34	22.433678