**CHAPTER TWO**

**The effects of a management action on the broader marine socio-ecological system**

*Abstract*

There is widespread recognition that ecosystem-based management requires an understanding of the connectivity within and between the human and ecological subcomponents of marine systems. Mapping these social-ecological connections have resulted in considerable insight, often by identifying drivers unobservable from social or ecological studies alone. This connectivity is particularly important in fisheries, where socioeconomic or ecological changes in one fishery often have cascading effects that ultimately influence another. Yet despite this recognition, social dynamics are often missing and fishing fleets are usually represented as homogenous, specialist, and static. My results highlight that on the contrary commercial fishing fleets on the US west coast are highly heterogeneous with the majority of vessels being generalists, and that a change in management is associated with a shift in patterns of participation across fisheries.

*I**ntroduction*

Ecosystem based fisheries management (EBFM) focuses on interactions between species and on the ecological effects of the biophysical environment (REF). Due to a focus on these interactions, EBFM is often described as managing an ecosystem as a whole, rather than individual species. This approach recognizes that the food-web, abiotic conditions, and human harvest are all drivers of system dynamics and seeks to manage them holistically. As such, much work on EBFM has focused on building models of food-web dynamics, and to account for how abiotic conditions may drive species interactions. Interest in EBFM also comes at a time when the importance of human behavior is being recognized, natural-resource management and conservation efforts are increasingly framing approaches in terms of ecosystem services and characterizing ecosystems more broadly as social-ecological systems (SESs; Millennium Ecosystem Assessment 2005, Carl Folke's papers?). EBFM dovetails with these trends and advises managers that human impacts should be included both to better represent the ecological impacts fisheries have and to capture livelihoods and human well-being derived from harvest (Levin et al. 2009).

These efforts to model both social and ecological dynamics of commercial fishery systems represent progress. However, in general there has been a bias towards studying ecological dynamics, with less focus on social or economic interactions. This is especially true of fishing fleets, which are largely modeled as independent populations of specialist vessels with no exchange among fisheries. Yet just as generalist predators can couple disparate food chains through broad diet preferences (Baskerville et al. 2011), there is evidence that vessels are often generalists: strategically entering and exiting fisheries depending on short term fluctuations in market, regulatory and ecological conditions (Hentati-Sundberg et al. 2014; Kasperski and Holland 2013; Sethi, Reimer, and Knapp 2014); and that multiple fleets target the same species (Coleman et al. 2004). Ignoring these details is problematic because (1) how vessels respond to changes in management is a major source of uncertainty in fisheries science (Fulton et al. 2010) and (2) because an often stated management goal is precisely to map the flows of ecosystem services and to incorporate “human dimensions” (Mace 2014; Levin et al. 2009). Therefore, quantifying and understanding “fisheries connectivity” is important if we are to transform ecosystem-based fisheries management from a concept that is biased towards understanding food-web connectivity only, into a more holistic systems-based fisheries management, where the interactions within and between both social and ecological subcomponents are understood and quantified.

The introduction of the Pacific Trawl Rationalization (catch share) program in the federal groundfish fishery in 2011 (cite the Federal Register) is just the kind of decision that is likely to create a cascade of social and ecological effects (Essington et al. PNAS, Costello et al. Science). Previous work examining the participation of vessels across fisheries has shown that in the absence of catch shares, management can act as a driver of fishing specialization (Hentati-Sundberg et al. 2014; Kasperski and Holland 2013) and lead to inefficiencies. A catch shares system guarantees each fisher an individual and tradeable quota, in theory ending the race to fish (CITE). It has also been shown that catch shares make fisheries more “efficient”, that is poor performing fishermen generally sell their quota to more successful fishermen. In the long run though, there is evidence to suggest that catch shares can lead to diminished participation in a fishery (REF). It is thus unclear how quota guarantees and changes in efficiency together influence entries and exits from fisheries, overall participation, and consequent diversification and connectivity among fisheries.

Here I use US west coast fisheries as a case study to develop a novel classification to: (i) describe participation of fishing vessels in fisheries with distinct ecological compositions, (ii) characterize the diversity of revenue streams and and participation across fisheries for individual vessels, and (iii) describe networks of fisheries participation for entire communities (ports). Our detailed study of fishery connectivity highlights the heterogeneous and dynamic nature of the social component of marine systems. In so doing, it underscores the gains to be had by incorporating such detail into existing conceptual and mathematical frameworks for EBFM.

*Methods*

**Description of Data Sources**

I collected vessel landings tickets for all commercial landings on the US west-coast between 2009-2013 from the Pacific Fisheries Information Network (PacFIN) database ([www.psmfc.org](http://www.psmfc.org/)). These data were filtered for vessels with an average of at least $5,000 in annual revenue and I further removed vessels that landed commercial catch in Alaska. I did not analyze landings from 2011, a management transition year in which catch shares were established. In doing so I restricted our analysis to fisheries landings before and after the implementation of catch shares. I also removed landings from vessels that participated in the California Halibut trawl fishery due to concerns about inconsistencies in landing tickets (REF?). This left 2,413 vessels that were responsible for approximately 93% of the total revenue and biomass commercially landed on the US west-coast during this period.

**Calculating Changes in Vessel and Community Level Fishing Diversity**

Vessel revenue diversity is calculated using the effective Shannon index *H* (Jost 2006). This metric quantifies variability in the proportion of revenue *pf* derived from each realized fishery *f* (identified from the clustering approach described above), such that revenue diversity *H* for vessel *j* is calculated as

where *F* is the number of realized fisheries. I define specialist vessels as those that land in a single realized fishery (*H* = 1) and generalist vessels are vessels that land in more than realized fishery (*H* > 1).

To represent connectivity among realized fisheries at the port level I built directed, weighted networks where nodes represented a realized fishery, and the strength of the connections between nodes represented the number of vessels that landed catch in both over a given period. More formally, for each port *k* I built a network *Gk,X🡪Y* in which an edge weight between two nodes *X* and *Y* was the number of vessels participating in fishery *X* and *Y* divided by the total number of vessels that participated in fishery *X*. Similarly, is the number of vessels participating in both fisheries divided by the total number of vessels that participated in fishery *Y* (Fig. 1)*.*

To measure port-level fisheries connectivity I calculated the link density (*LD,* number of edges divided by nodes) which scales both with network size and interconnectedness. Because the network is directed, this value can be interpreted as two times the average number of fisheries to which a fishery is connected (i.e. all vessels participate in both fisheries) at port *k*.

In order to test whether realized fishery participation at the vessel or port level changes as a function of the implementation of catch shares, I assigned vessels and ports to one of three categories: *M1*, *M2* or*M3*. *M1*: vessels (ports) unaffected by catch shares were termed the *general participants*, which included only those vessels (ports) for which I observed no commercial landings in the catch-shares affected fishery in 2009-2010 or 2012-2013 (*nvessels* = 1,878, *nports* = 52). *M1*: *catch share participants* were those vessels (ports) had landings in the limited entry trawl fishery prior to 2011 and continued to have catch share quota landings after 2011 (*nvessels* = 71, *nports* = 16). *M3*:, *limited entry exits* were those vessels (ports) that landed in the limited entry trawl fishery prior to 2011, but had no landings using catch shares quota after 2011 (*M3, nvessels =* 35, *nports* = 10, Fig. 2). By comparing the general participants to vessels (ports) affected by catch shares (*catch share participants* and *limit entry exits*) I were able to control for exogenous inter-annual variation in revenue diversity present in both groups of vessels.

**Effects of Catch Shares on Revenue Diversity and Fisheries Connectivity**

We used linear regressions to determine whether a change from limited-entry to catch-shares management in the limited entry groundfish trawl sector was associated with a change in revenue diversity at the vessel level and/or a change in fisheries connectivity at the port level. For each vessel and port (henceforth I drop the indices for vessel and port for brevity) *I* calculated the change in revenue diversity as the difference in revenue diversity before (*Hpre*) and after (*Hpost*) the implementation of catch shares as *ΔH = Hpost – Hpre*. I defined a change in fisheries connectivity for each port as the difference in link density before (*Cpre*) and after (*Cpost*) the implementation of catch shares as *ΔC = Cpost – Cpre*. Thus a value of zero for Δ*H* or Δ*C* indicated there was no change in revenue diversity or fisheries connectivity for a given port, respectively, between the two periods, and a positive value indicated the vessel or port increased the evenness and/or the number of fisheries from which it received revenue.

At the vessel level, if catch shares allowed more flexibility in fisheries participation, I would expect that catch share participants would, on average, demonstrate increased revenue diversity after the implementation of catch shares. To this end, I conducted a linear regression to determine the relationship between Δ*H* and the three vessel categories *M1* (general participants), *M2* (catch share participants) and *M3* (limited entry exits). However, the ability to change diversity between two periods is related to the starting period diversity. For example, if a vessel is a specialist (i.e. *H* = 1), then it is impossible for that vessel to have a drop in diversity and any random variation will bias *ΔH* upwards. Similarly, if a vessel was maximally diversified, then the vessel could either remain the same or with a random drop in diversity. Thus, I also evaluated a model in which the pre-catch share revenue diversity *Hpre* of each vessel was a covariate.

At the port level, I used similar regressions to those employed at the vessel level, to determine whether a change to catch shares management in the limited entry groundfish trawl sector was associated with a change in fishery connectivity. Thus I also regressed Δ*C* against catch shares participation with and without *Cpre* to catch shares as a covariate.

In both the vessel and port level analyses, the Akaike Information Criterion (AIC) was used to find the most parsimonious model which balanced both the goodness of fit, as measured by likelihood, and model complexity, as measured by the number of parameters (Burnham and Anderson 2002). I calculated 95% confidence intervals by randomly selected data with replacement, from both the vessel and port datasets, and repeated this procedure 10,000 times.

*Results*

**Vessel and Community Level Fishing Diversity**

We found that between the start of 2009 and the end of 2010, 66% of commercial vessels on the west coast participated in more than one realized fishery (Fig. 2a) although the degree to which vessels diversified varied. Breaking these patterns down regionally using PFMC management regions, generalists outnumbered specialists (Fig. 2b). The distribution of diversity varied among the generalists, from vessels that were highly specialized, but had a few landings in additional fisheries to those that fished in many fisheries evenly (Fig. 2c). Notably, the majority of diversified vessels revenue was dominated by revenue from a single fishery (71%), with very small percentages coming from alternatives. However almost a quarter (24%) of diversified vessels were participating in at least two fisheries equally, with some vessels (4%) participating evenly in more than three fisheries (Fig. 2c).

We also found differences in the number and interconnectedness of fisheries across ports (Fig. 3). Ports had between 0 and 7 fisheries that were connected. This variation is exemplified by participation networks in Santa Barbara, CA, Eureka, CA, and Oakland, CA (Figs. 3a-c). Santa Barbara was characterized by a complex participation network, with more than double the average link density of Eureka (see Appendix for all port participation networks). Most ports had a spectrum of vessels landing at them and I found that there was a positive, albeit weak, relationship between vessel and port level diversity (Spearman’s correlation 0.185, p < 2.2e-16, Fig S3).

**Effects of catch shares management on individual vessel diversification and community-level participation networks**

Two-thirds (66%) of vessels that operated in the catch shares affected fishery continued to participate in it following the implementation of catch shares, while only a minority (6%) of vessels left commercial fishing altogether. Of vessels which continued fishing in the catch-shares fishery, 87% of vessels adjusted their fishing participation, entering or exiting new fisheries. A third group consisted of vessels that exited catch shares but continued to fish commercially (28%) (Fig 4). These vessels showed a mixed response, with increased and decreased fishing diversity observed.

Over our study time period, vessels that continued to fish became more diversified on average (Fig 4). Vessels that participated in catch shares, post 2011, saw an increase in their revenue diversity that was twice that for vessels which exited the catch share fishery. Notably, the change in revenue diversity was strongly explained by the revenue diversity the vessels had prior to the implementation of catch shares (in 2009-2010). Vessels with higher (lower) participation diversity prior to catch shares were more likely to show a reduction (increase) in diversity following catch shares (Table S2).

At the port level I found that ports that there was a non-significant increase in fisheries connectivity by approximately 5% on average (two sided t-test p-value = 0.3287), and this was predicted by previous fisheries connectivity (*Cpre*) (Table S1, S2). However, the model which best explained the change in fisheries connectivity did not include terms for a port’s relationship to catch shares (*Mn*).

*Discussion*

There is widespread recognition that ecosystem-based fishery management requires an understanding of the connectivity within and between the human and ecological subcomponents of marine systems (Anderson et al. 2015). Mapping these social-ecological connections has resulted in considerable insight, often by identifying drivers unobservable from social or ecological studies alone (Brashares et al. 2004; Lade et al. 2015). This connectivity is particularly important in fisheries, where socioeconomic or ecological changes in one fishery can have cascading effects that ultimately influence others (Steneck et al. 2011; Lade et al. 2015). Yet despite this recognition, social dynamics are often missing and fishing fleets are usually represented as homogenous and non-interacting (Field 2004). Our results highlight that on the contrary fishing fleets are highly heterogeneous and continually changing in size, effort level, and composition, as numerous exogenous and endogenous forces influence them (Opaluch and Bockstael 1984). More generally, this study highlights a perhaps underappreciated aspect of social-ecological systems: as in food webs and social networks, the consequences of environmental and management changes are determined large part by the connectivity between nodes.

We found that the majority of vessels on the US west coast engage in multiple fisheries and that the implementation of the Pacific Trawl Rationalization program appears to have changed patterns of participation across fisheries. Greater than 60% of commercial fishing vessels were generalists, participating in more than one realized fishery. The revenue of each of these generalists was thus tied to multiple fisheries, effectively connecting them and setting up the potential for linked social-ecological dynamics that were previously invisible. The social implications of generalist fishing practices with corresponding diversified revenue portfolios have been most directly related to reduced exposure to income risk (Kasperski and Holland 2013; Sethi, Reimer, and Knapp 2014), with previous work identifying that vessels with more diverse revenue streams have less variable revenues (Kasperski and Holland 2013). In contrast to US west coast fisheries, Steneck et al. (2011) has documented how Maine fishermen have increasingly become dependent on a single species due to interactions among markets and ecological conditions. In addition, Hentati-Sundberg et al. (2014) and Stoll et al. (2016) have shown how commercial fishermen in Sweden and the Gulf of Maine respectively have grown increasingly specialized as management became more restrictive. Thus, while many forms of management can be constraining, reducing the portfolio of fisheries prosecuted by individual fishermen, catch shares management may expand portfolios. Further study is needed to determine whether the ubiquity of generalists on the US west-coast is indicative of systemic risk-adverse behavior, and whether revenue diversity confers a general resilience in fishermen’s revenues to perturbation, such as diminished catch due to exogenous environmental factors or a change in management or markets of particular fisheries.

Much of the previous research on fishery diversity and revenue variability (REFs) has focused primarily on the impacts of catch shares on the vessels that have continued to operate within the fishery of interest, assuming that vessels that exit also exit commercial fishing entirely. Our analysis shows that for the US west-coast, the majority of vessels that participated in the groundfish fishery prior to the implementation of catch shares, continued to operate after the management change albeit in other realized fisheries. This highlights the need to quantify how a management change, or any other perturbation, is felt throughout the marine social-ecological system as vessels/individuals reorganize their participation across realized fisheries.

The redistribution of fishing effort across a fisheries participation network is directly analogous to (changes in) predation pressure in a food-web. Specifically, if I think of vessels as predators, then the realized fisheries that they participate in are their prey. As I have shown, there are many specialist vessel/predators, but the majority of fishermen/vessels are generalist predators with a broad diet preference. In natural systems, a predator’s diet preference is largely determined by the physiological adaptations of the predator. Here, the analogy extends to the gear and skill that each vessel has.

This is relevant when considering the redistribution of fishing effort across participation networks. Vessels geared and skilled at harvesting certain sets of species, will not immediately start harvesting other target species that require completely different gear and skills. This is reflected in the different realized fisheries that any one vessel participates in over a given year, and in general it is related to the topology of the participation networks.

For example, if there is a pair of species that are unconnected ecologically (i.e. there is no link between them in the food-web), but there are vessels that harvest both (i.e. there is a link in the participation network between these species’ realized fisheries), then there is a transitive link. As a consequence, a management change that affects vessel participation in one fishery, will affect that status of the (ecologically unconnected) stock of the other species. Dungeness crab and albacore tuna fisheries on the US west coast provide an appealing (but currently untested) example. Here, I find these two realized fisheries to be commonly connected by vessels at the port level, yet these species do not interact directly in the ocean. Examining changes in revenue diversity and vessel participation in the albacore tuna fishery after the recent closure of the Dungeness crab fishery in Washington and Oregon would be an excellent test of how connectivity influences fisheries participation. In general, environmental or management perturbations will ripple through these participation networks, and that their topology as well as the adaptability of fishermen, will largely determine their economic impacts.

In conclusion, our results highlight the need to consider fisheries as connected and dynamic entities. Not only does EBFM need to acknowledge the links between species in food-webs, but there needs to be an equal emphasis on the connectivity between fisheries, based on the participation of vessels, and on the economic consequences of the topology of the participation networks. I have shown that fishery participation is heterogeneous, varying greatly from place to place, and dynamic, responding to the implementation of catch shares in the groundfish fishery. If I can broaden the conceptual and mathematical models of marine systems to include such properties, then I will be truly on our way to developing systems-based fisheries management, which is likely to lead to better performing governance institutions in the future.

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*Figures*

../../Desktop/CNH/Analysis/Metiers/writing/draft/fig2.pdf

**Figure 1.** Distribution of revenue diversity at the vessel level measured as the effective shannon index of revenue plotted in three different ways: A) coastwide, B) by management region, and C) breakdown of generalism for each management sector. I defined generalists as vessels that landed in more than one realized fishery. I found that generalists outnumbered specialists (A, B), although the degree of generalism varied (C).

**../../Desktop/CNH/Analysis/Metiers/writing/draft/fig4.pdf**

**Figure 2.** I map the ways that a vessel can respond to the implementation of catch shares. Vessels that were directly affected by catch share implementation are those that fished in the limited entry (LE) groundfish fleet between 2009-2010. After 2011, vessels either continue to participate in the groundfish trawl fishery by landing with quota, or leave the catch share fishery and either leave commercial fishing entirely or continue to fish in other commercial fisheries. The width of the bar in the decision tree is proportional to the absolute number of vessels which follow a given path given by the number. Percentages are relative to each decision point. I find that very few vessels which stopped fishing in the groundfish fishery actually left commercial fishing altogether, and vessels which participated in catch shares changing their participation across fisheries.

../../Desktop/CNH/Analysis/Metiers/writing/draft/fig5.pdf

**Figure 3.** Estimated effects of catch shares on revenue diversity for vessels, bars represent 95% confidence intervals. Vessels that participate in catch share increase in revenue diversity more than either the general participants or those that exited catch shares. At the port level the best supported model does not include a term for participation in catch shares.

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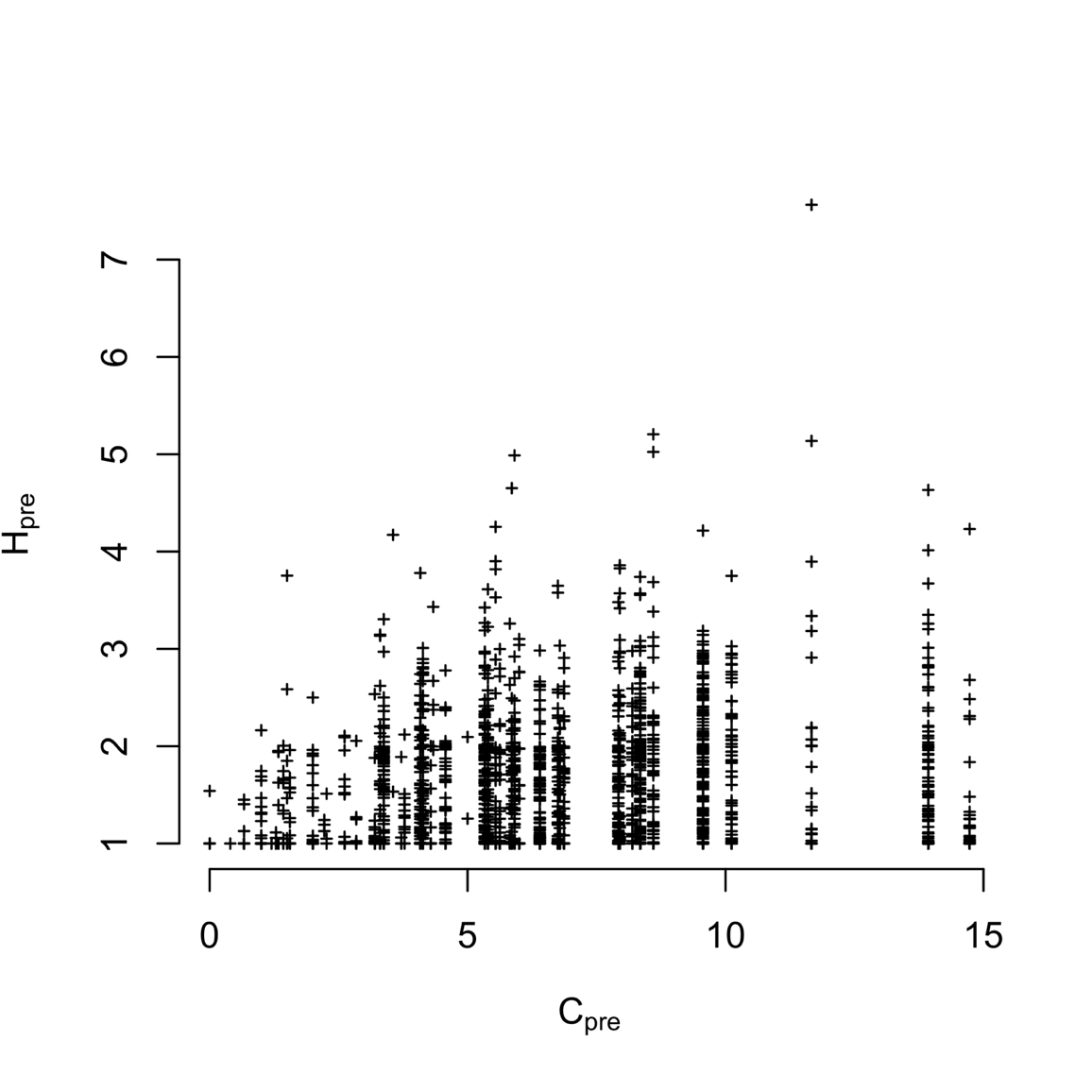
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*Supplemental information*

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**Figure S1.** Plotting vessel participation diversity (H, 2009-2010) against port connectivity (C, 2009-2010). I find vessel and port level diversity weakly correlated (Spearman’s correlation 0.1849745, p < 2.2e-16). But the most diverse vessels tend to be found in the most diverse ports.

**Table S1.** Akaike Information Criterion (AIC) values for the models with and without terms for catch shares. Values for the best model at each level are in boldface.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *Level* | *Hpre* | *Catch shares* | *No. Parameters (K)* | *AIC* | *ΔAIC* | *Adjusted R2* |
| *Vessel* | *Yes* | *No* | *1* | *3140.767* | *30.916* | *0.2392* |
|  | ***Yes*** | ***Yes*** | ***2*** | ***3109.851*** | ***0*** | ***0.2471*** |
|  | *No* | *Yes* | *1* | *3643.718* | *533.867* | *0.01007* |
| *Port* | ***Yes*** | ***No*** | ***1*** | ***184.1367*** | ***0*** | ***0.8866*** |
|  | *Yes* | *Yes* | *2* | *186.5804* | *2.4437* | *0.8858* |
|  | *No* | *Yes* | *1* | *325.8152* | *141.6785* | *0.2404* |

**Table S2.** Coefficient values for two best fit models for each scale of analysis

|  |  |  |  |
| --- | --- | --- | --- |
| *Level* | *Variable* | *Best model* | *Second best* |
| *Vessel* | *Hpre* | *-0.46 (0.02)* | *-0.46 (0.10)* |
|  | *General fleet* | *0.74 (0.03)* | *0.74 (0.03)* |
|  | *Catch share participant* | *0.27 (0.07)* | *-* |
|  | *Limited entry exit* | *-0.24 (0.10)* | *-* |
| *Port* | *Cpre* | *-0.67 (0.03)* | *-0.66 (0.03)* |
|  | *General fleet* | *-* | *0.29 (0.27)* |
|  | *Catch share participant* | *-* | *0.19 (0.28)* |
|  | *Limited entry exit* | *-* | *0.33 (0.33)* |
|  |  |  |  |