Fisheries connectivity and the effects of management on an interconnected marine socio-economic system

Emma Fuller1, Jameal Samhouri2, Joshua Stoll3, James Watson4

1Department of Ecology and Evolutionary Biology, Princeton University, USA

2Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, Washington, USA

3School of Marine Sciences, University of Maine, Orono, Maine, USA

4Stockholm Resilience Center, Stockholm University, Sweden

# Abstract

# Introduction

Ecosystem based fisheries management (EBFM) focuses on interactions, both between species and species and the biophysical environment. Because of the focus on interactions, EBFM is often described as managing an ecosystem as a whole, rather than individual species. This approach recognizes that other species, abiotic conditions, and human harvest are all drivers of system dynamics and seeks to manage them holistically. As such, much work on EBFM has been to build food webs, and to account for how abiotic conditions may drive species interactions from the bottom up.

The push for EBFM also comes at a time when the importance of considering the role people have in food webs is growing: increasingly, natural-resource management and conservation efforts are framing approaches in terms of ecosystem services and characterizing ecosystems more broadly as social-ecological systems (millenium ecosystem assessement). 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 (ref, IEA?).

These efforts to model both social and ecological dynamics represent progress but tend to have higher resolution for the ecological components of these systems and lower resolution for the social or economic interactions. In particular, these fleets are largely modeled as independent populations of vessels with no exchange among fisheries. Yet just as predators can couple disparate food chains (refs -serengeti), there is evidence that that vessels strategically enter and exit fisheries depending on markets, regulations and ecological conditions (jonas, holland kasperski, sethi) and that multiple fleets target the same species (Colemen et al. 2004). This lack of realism is problematic both because uncertainty in how vessels respond to changes in management has been identified as a major source of uncertainty in fisheries science (Fulton et al. 2011) and because mapping the flows of ecosystem services and incorporating “human dimensions” is often an explicit goal of management (ref, IEA?). Quantifying and understanding the human connectivity in marine systems, i.e. how vessels link fisheries together by contemporaneous participation, therefore represent an important frontier to EBFM science

In this paper we contribute to this knowledge gap by presenting an approach for measuring the connectivity of fisheries at both the vessel and community levels and use it to evaluate how a change in management related to changes in these linkages across the entire commercial fishing sector on the west coast of the United States (US). Towards this objective, we developed a novel classification method to identify distinct fishing practices used by fishers along the US west-coast and constructed a comprehensive database of commercial fisheries participation. Specifically, the classification method was used to: (i) calculate vessel-level participation in individual fisheries, (ii) determine emergent diversification of a vessel’s participation across fisheries, and (iii) describe networks of fisheries participation for entire communities (ports). We found that the majority of vessels examined were generalists, defined as those participating in more than one commercial fishery between 2009 and 2013. In addition, the interconnectedness of fisheries participation varied strongly across ports. Using these individual and community-level measures of fisheries diversification, we evaluated how the introduction of the Pacific Trawl Rationalization (catch share) program in the federal groundfish fishery in 2011 influenced vessel-level participation in the fishery, along with the diversification of vessels and ports as a function of their participation in the fishery.

**Methods**

**Description of Data Sources**

We used landings tickets that record 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/)). We restricted our analyses to vessels with an average of at least $5,000 in annual revenue and removed vessels that landed commercial catch in Alaska. We did not analyze landings from 2011, a management transition year in which catch shares were established. We also removed landings from vessels that participated in the California Halibut trawl fishery due to concerns about inconsistencies in landing tickets. This left 2,413 vessels that were responsible for approximately 93% of the total revenue and biomass commercially landed during this period.

**Defining Fishing Practices**

In the following we use terms *fishing practice* and *fishery* interchangeably. Fisheries are defined as harvest assemblages caught with a specific gear {vanPutten:2012bj, Boonstra:2014dh}. The Pacific Fisheries Management Council (PFMC) has developed a set of sector-based definitions similar to this approach for the federally managed groundfish landings (www.pcouncil.org), but no equivalent exists for non-groundfish fisheries {NorthwestFisheriesScienceCenter:vj}. In order to treat the landings dataset uniformly, we applied a métier-like analysis to this landing data {Deporte:2012kq}.

A métier analysis identifies fishing practices by clustering the species composition of landings. This methodology requires choices in the way similarity among trips are measured, an algorithm for grouping similar trips together, and a requirement that it can scale across hundreds of thousands of landings. In the following we specify and briefly outline our rational for these choices.

For our distance metric we used the Hellinger distance *D* {Legendre:2012uq} to calculate the similarity in revenue profiles between trips and generated a pairwise distance matrix. This distance metric has the benefit that it is asymmetric, where the presence of a species in both trips is considered more informative than the absence of a species. The Hellinger distance between the species composition of two fishing trips *A* and *C* is defined as

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| --- | --- |
|  | (1) |

where *ai* is the fraction of revenue derived from species *i* on trip *A*, *bi* is the fraction of revenue derived from species *i* on trip *B*, and *S* indicates the total number of species collected in both trips. With this metric, trips *A* and *B* become increasingly similar (and the Hellinger distance declines) as the proportion of revenue attributable to each of the *S* species becomes increasingly matched.

We identified groups of trips with similar target assemblages using the infoMap community detection algorithm {Rosvall:2008fi}. This algorithm examines networks for subgraphs more interconnected to one another than the network in which it is embedded. To generate the required weighted, undirected network we transformed the distance matrix into a similarity matrix by subtracting the distance metric’s upper limit () from each pairwise distance.

. However, because our dataset contained 340,466 unique trips, it was computationally intractable for us to construct a single matrix containing all pairwise similarities. To obtain management matrix sizes we used one year of landings (2010) and we split by gear. Pairwise distances among trips and community detection were used within each gear partition, which grouped trips into target assemblage categories. To classify the 2009, 2012 and 2013 trips to fishing practices, we assigned each unclassified trip to the same fishing practice as the 2010 trip to which it was closest in multi-dimensional space.

A challenge in testing the effectiveness of this classification method, and part of the reason for its need, is that there is not an independent classification of US west coast fisheries that we could use to compare the results. To address this issue, we tested the reliability of our classification approach by evaluating the extent to which it identified known spatial and temporal structure of well-described US west coast fisheries and fishery sectors. Specifically, because we did not bound our clusters spatially, temporally, or by vessel characteristics, we were able to compare our emergent fishing strategies to existing sector definitions of groundfish, and groundfish impacting fisheries provided by the Northwest Fisheries Science Center Observer Program {NorthwestFisheriesScienceCenter:vj}.

**Calculating changes in vessel and community level fishing diversity**

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| Vessel revenue diversity is calculated using the effective Shannon index *H* {LouJost:2006vi}. This metric quantifies variability in the proportion of revenue *pf* derived from each fishery *f*, such that *H* for vessel *j* is calculated as | (2) |

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

To represent connectivity among fisheries at the port level we built directed, weighted networks where nodes represented a 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* we 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 we calculated the link density (number of edges divided by nodes) which scales both with network size and interconnectedness. This value can be interpreted as the average number of fisheries to which a fishery is connected (i.e. all vessels participate in both fisheries) at port *k*.

**Analysis of changes in revenue diversity and port connectance associated with catch shares implementation**

We used linear regressions to determine whether a change to catch shares management in the limited entry groundfish trawl sector was associated with a change in revenue diversity or a change in port connectance. We assigned vessels to one of three categories *Mn*. First, we defined vessels unaffected by catch shares as the *general fleet*, which included only those vessels for which we observed no commercial landings in the catch-shares affected fishery in 2009-2010 or 2012-2013 (*M1, n* = 1,878). Second, we defined *catch share participants* as those vessels that fished in the limited entry trawl fishery prior to 2011 and continued to fish by using catch share quota to land fish after 2011 (*M2, n* = 71). Third, we defined *limited entry exits* as those vessels that fished in the limited entry trawl fishery prior to 2011, but exited the fishery with the implementation of catch shares (*M3, n =* 35, Fig. 2). By comparing the general fleet to vessels affected by catch shares (*catch share participants* and *limit entry exits*) we’re able to control for inter-annual variation in revenue diversity.

For each vessel and for each port (henceforth we drop the indices for vessel and port for brevity)we calculated change in revenue diversity as the difference in revenue diversity before (*Hpre*) and after (*Hpost*) the implementation of catch shares,

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| --- | --- |
|  | (4) |

We defined a change in connectance for each port as the difference in connectance before (*Cpre*) and after (*Cpost*) the implementation of catch shares,

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| --- | --- |
|  | (5) |

Thus a value of zero for Δ*H* or Δ*C* indicated there was no change in revenue diversity or connectance 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.

If catch shares allowed vessels to be more flexible in their fisheries participation, we would expect that catch share participants would, on average, demonstrate increased revenue diversity after the implementation of catch shares. To this end, we conducted a linear regression to determine the relationship between delta H and Mn. 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 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 random variation drop in diversity. Thus, we also evaluated a model in which the pre-catch share revenue diversity H\_pre of each vessel was a covariate.

To determine whether a change to catch shares management in the limited entry groundfish trawl sector was associated with a change in fishery connectance at the port level, we used a simple linear regression to compare the change in connectance between ports that were and were not affected by catch shares. Paralleling our vessel-level analysis, a port was considered a *general port* if there was no record of vessels landing groundfish with trawl gear prior to 2011 and no quota used to land commercial catches after 2011 (*P1, n* = 48). Ports were *catch share ports* if there were landings of groundfish trawl prior to 2011 and either continued to land quota after 2011 (*P2, n* = 16) or *limited entry port exits* if the ports no longer had groundfish trawl landings after 2011 (*P3, n* = 10). Thus our port level analysis paralleled the vessel-level model where we regressed the change in connectance against catch shares participation with and without connectance prior to catch shares as a covariate.

In both the vessel and port level analyses, we compared alternative models using the information theoretic approach that allows direct comparison of the models’ goodness of fit using model likelihoods {Burnham:2002wc}. 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). Here the lower the AIC, the better the model {Burnham:2002wc}. We calculated 95% confidence intervals on the model parameters by bootstrapping to determine whether the confidence intervals overlapped with zero. To do so, we randomly selected data with replacement from our vessel and port datasets until we had a dataset the same size as our original and then refit the models. This procedure was repeated 10,000 times and the resulting distribution give the 95% confidence intervals for each parameter.

**Results**

**Definitions of realized fisheries**

Our clustering algorithm identified 109 realized fisheries (Appendix, Table 1). Realized fisheries often consisted of a single species, but could also comprise assemblages of species (Fig. S1a). Whether their catch consisted of a single species or multiple species, the realized fisheries were characterized by distinct patterns of temporal and spatial structure (Fig. S2a, b). These patterns suggested strong agreement between our realized fisheries and NWFSC Observer sector designations, as did comparisons of vessel sizes and catch composition (single- vs. multi-species, Table 1).

The realized fisheries also varied by several orders of magnitude in effort (number of trips) and revenue (Fig. S1b), with a small number of fisheries accounting for the majority of effort and revenue. For example, only 10 of the 109 fisheries were responsible for 90% of ex-vessel revenue and landings (pounds) in the time period we examined (Table 1). These fisheries included sectors which have been well-studied, but not quantitatively described prior to now e.g., dungeness crab pots {Botsford:1978jy}, spiny lobster pots {Kay:2012uq}, or red urchin diving {Smith:2003bm} (Table 1).

**Changes in vessel and community level fishing diversity**

We found that between 2009-2010, 66% of commercial vessels on the west coast participated in more than one realized fishery (Fig. 3a) although the degree to which vessels diversified varied. Breaking these patterns down regionally using PFMC management regions, generalists outnumbered specialists (Fig. 3b). 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. 3c). 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. 3c).

The preceding analysis focused on fishing strategies employed by individual vessels, without consideration of how those strategies came together to create characteristic fisheries participation networks for specific ports. We found differences in the number and interconnectedness of fisheries across ports (Fig. 3a). Ports had anywhere between 0-7 fisheries connected. This variation is exemplified by participation networks in Santa Barbara, CA and Neah Bay, WA (Fig 3ab). Santa Barbara was characterized by a complex participation network, with more than double the average fishery connectance of Neah Bay. The ports had a spectrum of vessels landing at them and we found that there was a positive, but not a significant, relationship between vessel and port level diversity (Fig S3).

**Analysis of changes in revenue diversity and port connectance due to catch shares**

We find that at the vessel level the model that best explained changes in revenue diversity following catch shares implementation included a term for pre-catch shares diversity (*H*pre) and catch shares category (*Mn*) (Table S1). This suggests that the changes in revenue diversity are best explained by both pre-catch shares diversity and relationship to catch shares. Vessels with higher participation diversity prior to catch shares were more likely to show a reduction in diversity following catch shares (Fig 4a). Between the period before (2009-2010) and after (2012-2013) catch shares, vessels in the general fleet showed a modest, but significant, 2.6% increase in fisheries diversification (*Hpre* =1.52 to *Hpost* =1.57, p < 2e-16). However, we found that catch share participants demonstrated a four-fold higher (12%) increase in diversification as compared to vessels in the general fleet (*Hpre* =1.77 to *Hpost* =1.98, p = 5.22e-05) while limited entry exit vessels declined in diversity by 21% (*Hpre* = 2.0633 to *Hpost* = 1.62953, p = 0.0207). We also found the limited entry exits and catch share participants were 16% more diverse than vessels in the general fleet prior to 2011 (two sided t-test, 1.76 to 1.52, p = 0.00279).

At the port level, the model that best explained changes in port connectance following catch shares implementation included only a term for port level connectance values prior to catch shares. Ports with higher connectance values prior to catch shares were more likely to show a reduction in connectance following catch shares, however examining a port level model which includes the equivalent catch share categories as the vessel level model, we find qualitatively similar results, despite lack of significance (Fig. 4b).

**Discussion**

As we continue to move along the management spectrum towards system-level approaches, there is widespread recognition that we need to identify better ways to account for the interconnectivity within and between the human and ecological dimensions of marine systems {Anderson:2015et}. This is particularly important in fisheries, where socioeconomic or ecological changes in one fishery often have cascading affects that ultimately influencing others. Yet despite this recognition, social dynamics continue to be poorly characterized and as such fishing fleets are often represented as homogenous or monolithic forms {Field:2004ui} even though they are highly heterogeneous and continually change in size, effort levels, and composition as numerous exogenous and endogenous forces influence them. Acknowledging this issue, we use this paper to investigate the socioeconomic connectivity within and across fisheries on the west coast of the US.

We find that more than 60% of vessels participating in west coast fisheries are generalists. Each of these generalists is socioeconomically connected to multiple fisheries, effectively connecting fisheries on the west coast. This is the first time to our knowledge that these connections have been documented. This finding runs counter to conventional ways of thinking about the human dimension of fisheries. Historically, theoretical models of fishing routinely define fleets as homogenous groups of specialist vessels focusing a set of species with a particular gear and ignoring the other fisheries in which the vessels may participate {Schaefer:1954vr, Mangel:1982vb, but see Martin:2008uf}. Following these formulations, most empirical analyses have also taken a similar approach {vanPutten:2012bj}. Even those advocating for EBM, with a focus on systems-level analyses and species interactions, commonly treat fleets as unconnected {Field:2004ui}. This gap is problematic as fisher behavior ultimately mediates how changes in management translate into changes in the marine environment {Fulton:2010jw}.

The social implications of this generalism have been most directly related to reduced exposure to financial risk {Kasperski:2013gb, Sethi:2012kj}. Previous work has demonstrated that vessels with increased revenue diversity have less variable revenues, and that changes in management have been associated with reduced revenue diversity in these fisheries {Kasperski:2013gb}. Thus measuring revenue diversity across vessels before and after a management change helps to understand how changes in system characteristics affect one facet of human well-being.

There is also a large literature demonstrating the importance of accounting for apparent competition, where the competition between two species is obscured by the predation by a common predator. Failing to account for apparent competition has resulted in being unable to predict the impact of extinction in a food web {Holt:1977up}. Similarly, failing to account for the socioeconomic connectivity among fisheries may result in changes in one fishery unexpectedly affecting the participation in a fishery targeting a species which is ecologically unconnected. Dungeness crab and albacore tuna fisheries on the US west coast provide an appealing, but untested example. Here, we find these two fishing practices to be commonly connected by vessels at the port level, yet are unrelated ecologically. Examining changes in revenue diversity and vessel participation after the recent closure of the Dungeness crab fishery in Washington and Oregon would be an excellent test of these results. Perturbations, whether they be environmental or due to a management change, will ripple through these networks, and that the topology of these networks (from port to port) will largely determine how individual fishers experience these perturbations.

In addition to revealing connectively across fisheries, we examined the effects of a catch share program on vessels and communities. We define a *fishing portfolio* as the group of fisheries a vessel combines within a time period (in this case two, two year periods 2009-2010 and 2012-2013). We found that the implementation of catch shares is associated with a minority (6%) of vessels leaving commercial fishing altogether while 66% of vessels continued to participate in the affected fishery. Of vessels which continued fishing in the affect fishery, only 13% of vessels continued to participate with fishing participation unchanged. A third group consisted of vessels that exited catch shares but continued to fish commercially (28%). These vessels showed a mixed response, with increased and decreased fishing diversity observed. We also found that these changes at the vessel-level qualitatively matched the patterns of participation among fisheries at a community level.

If previously documented relationships between vessel participation diversity and revenue variability hold, catch shares thus has reduced these vessels’ exposure to risk. It is important to note, however, that not all groundfish trawl boats made the transition into the catch shares regime. Most analyses of the impacts of catch shares have focused on the vessels that continue fishing, assuming that vessels that exit also exit commercial fishing. This work demonstrates that the majority of vessels continued fishing, albeit in other fisheries. Closely examining what happens to trawlers that exited groundfish fisheries, and whether these patterns in of connectivity can predict new entries is an important next step for this work as we seek to more fully account for the socioeconomic connectivity of the system.

Overall, it should be cautioned that our time series is short, and fishing fleets will continue to adjust to the management changes. We also recognize that there are many possibly appropriate scales at which to conceptualize a “fishing community” and that these communities are affected by much more than just fisheries. Similarly we also recognize that fishermen frequently have employment outside of the fishing industry, vessels constitute more than one person. To more fully include the social aspects of these social-ecological systems all these issues need additional attention. An important next step would be to develop fishing portfolios, or characteristic combinations of fisheries that vessels participate in annually, in order to better map changes in marine species abundance and range to changes in fishing livelihoods.

**References**:

{papers2\_bibliography}