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

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# Abstract

# Introduction

Ecosystem-based management (EBM) and its many variants have become the approach du jour of ocean and coastal conservation and stewardship, appearing prominently in an array of highly visible policy documents

(Pew Oceans Commission 2003; President Barack Obama 2010; Commonwealth of Australia 1998; Canada 1996; European Commission 2008; Secretariat of the Convention on Biological Diversity 2004). The shift towards EBM is motivated by a combination of real and perceived concerns, including conflict between ocean users (Crowder and Norse 2008), poor coordination across governing bodies (Norse 2010), failure to adequately sustain living marine resources through single-species management (Jackson et al. 2001; Worm et al. 2006), and increasing recognition of the complex, non-linear, and coupled human-natural interactions within marine systems (Wilson, Hayden, and Kersula 2013). However, despite the increasing emphasis on EBM, the transition from EBM in theory and policy to practice has been slow (Pitcher et al. 2009). This slowness, in part, underscores the technical and scientific challenges that underlie EBM and the uneven, sometimes contradictory, and difficult task of understandings of the often complex social-ecological context of marine ecosystems (Evans and Klinger 2008).

In the last decade, numerous efforts have been waged to better define (Slocombe 1998; EPAP 1999; Pikitch et al. 2004; McLeod et al. 2005) and forward EBM (Curtin and Prellezo 2010; SPC 2010; Pomeroy et al. 2013). This progress is often cast as a sharp departure from traditional, single-species management regimes (Chapin, Kofinas, and Folke 2009), though there have been challenges to the “apparent duality” between existing fisheries management and proposed EBM strategies (Link 2002), with an argument that there is a “gradient of approaches” along the continuum of management decisions that exist. Aswani et al. (2012) offer a similar view, arguing that EBM “is best thought of as an expansion of customary management and integrated coastal management, rather than a paradigm shift.”

Much of the research on EBM has sought to illuminate the connectivity within and between the biotic and abiotic components of these systems, using sophisticated modeling approaches such as OSMOSE (Shin and Cury 2004), Ecopath/Ecosim (Christensen and Pauly 1992), and Atlantis (Fulton et al. 2011). For example, the latter is used in the integrated ecosystem assessment (IEA) framework proposed by (Levin et al. 2009) and adopted by the National Marine Fisheries Service to guide management decisions. Atlantis, like others, can be used to model simple trophic interactions and more highly complex ecological structures (Flower et al. 2013). These efforts represent definitive progress along the conceptual gradient of EBM (Link 2002), but focus almost exclusively on the ecological components of these systems, without explicit consideration of the social or economic influences that interact across time and space. Quantifying and understanding human connectivity in marine systems therefore represent an important frontier to EBM science.

In this paper we contribute to this knowledge gap by presenting an approach for measuring the socioeconomic connectivity of fisheries at both the vessel and community levels and use it to evaluate how a change in management is associated with 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. 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**

Fishing practices are defined as harvest assemblages caught with a specific gear (van Putten et al. 2012; Boonstra and Hentati Sundberg 2014). 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 (Northwest Fisheries Science Center 2015). In order to treat the landings dataset uniformly, we applied a métier-like analysis to this landing data (Deporte et al. 2012). In the following we use terms *fishing practice* and *fishery* interchangeably.

A métier analysis identifies fishing practices by clustering the species composition of landings. We used the Hellinger distance *D* (P. Legendre and Legendre 2012) to calculate the similarity in revenue profiles between trips and generated a pairwise distance matrix. The Hellinger distance between the species composition of two fishing trips *A* and *C* is defined as

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where *ai* is the fraction of revenue derived from species *i* on trip *A*, *ci* is the fraction of revenue derived from species *i* on trip *C*, where there are *S* total species. With this metric, trips *A* and *C* become increasingly similar (and the Hellinger distance declines) as the proportion of revenue attributable to each of the *S* species becomes increasingly matched.

We transformed the distance matrix into a similarity matrix by subtracting the distance metric’s upper limit () from each pairwise distance and used these similarities to generate a weighted, undirected network where nodes were fishing trips and edge weights were pairwise similarity. We used the infoMap community detection algorithm (Rosvall and Bergstrom 2008) and identified groups of trips with similar target assemblages. 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 overcome this challenge we used…

one year of landings (2010) that we split by gear which resulted in manageable matrix sizes (between 1,700 and 31,000 rows/columns). Pairwise distances among trips and community detection were used within each gear partition, which grouped trips into target assemblage categories. To make the final assignment of fishing practice, we linked the species-composition clusters to gear used for the trip. 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 (Northwest Fisheries Science Center 2015).

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

Vessel revenue diversity is calculated using the effective Shannon index *H* (Lou Jost 2006). *H* for vessel *j* is calculated as

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where *F* is the number of realized fisheries and *pf* is the proportion of revenue derived from fishery *f*. We define specialist vessels are 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,A🡪B* in which an edge *A🡪B* was the number of vessels participating in fishery *A* and *B* divided by the total number of vessels that participated in fishery *A*. Similarly, edge *B🡪A* is the number of vessels participating in both fisheries divided by the total number of vessels that participated in fishery *B* (Fig. 1)*.*

To measure port-level revenue diversity we developed a network metric that increases with the number of fisheries present and the evenness of participation. Common network topology measures such as shortest path and centrality metrics capture the evenness of connectivity across the network but don’t reflect the difference between a port with many or few nodes (fisheries). To address these concerns we developed an index of average fishery connectance *C* for each port *k* defined as the sum of *E* total edge weights *w* present in network *Gk* divided by the number of nodes *V* in *Gk* .

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|  | (3) |

Because edge weights are constrained to be between 0-1, this value can be interpreted as the average number of fisheries to which a fishery is fully 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

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We defined a change in connectance for each port as

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Thus a value of zero for Δ*H* or Δ*C* indicated there was no change in revenue diversity or connectance for 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 fit the following linear regression,

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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 of each vessel was a covariate as

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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 with

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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 and Anderson 2002). 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 and Anderson 2002). 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 and Wickham 1978), spiny lobster pots (Kay et al. 2012), or red urchin diving (Smith and Wilen 2003) (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 (J. L. Anderson et al. 2015). 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 2004) 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 1954; Mangel 1982; but see Martin 2008). Following these formulations, most empirical analyses have also taken a similar approach (van Putten et al. 2012). Even those advocating for EBM, with a focus on systems-level analyses and species interactions, commonly treat fleets as unconnected (Field 2004). This gap is problematic as fisher behavior ultimately mediates how changes in management translate into changes in the marine environment (Fulton et al. 2010).

The social implications of this generalism have been most directly related to reduced exposure to financial risk (Kasperski and Holland 2013; Sethi et al. 2012). 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 and Holland 2013). 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 1977). 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.

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