**INTRODUCTION**

Here, we have developed a novel classification to: (i) calculate vessel-level participation in individual fisheries and (ii) determine emergent diversification of a vessel’s revenue and participation across fisheries. We found that the majority of vessels examined were generalists, defined as those participating in, and receiving most of their revenue from more than one commercial fishery.

**METHODS**

**Description of Data Sources**

We collected vessel landings tickets for all commercial landings on the US west-coast between 2006-2014 from the Pacific Fisheries Information Network (PacFIN) database ([www.psmfc.org](http://www.psmfc.org/)).

**Defining Realized Fisheries**

Fisheries 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 analysis to this landing data (Deporte et al. 2012) to build a set of realized fisheries. A métier analysis identifies realized fisheries by clustering the species composition of landings. This methodology requires choices in the way similarity among trips are measured, a clustering algorithm for grouping similar trips together, and a constraint that the methods can scale across hundreds of thousands of landings. In the following we specify our rational for these choices.

For our distance metric 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. 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 *B* is defined as

|  |  |
| --- | --- |
|  | (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 realized fisheries as groups of trips with similar target assemblages using the infoMap community detection algorithm (Rosvall and Bergstrom 2008). This algorithm examines networks for subgraphs more interconnected to one another than the network in which it is embedded. To generate the required network we transformed the distance matrix into a similarity matrix by subtracting the distance metric’s upper limit (i.e. ) from each pairwise distance. The result is a weighted, undirected network where trips are connected by edges proportional to their similarity. However, because our dataset contained 340,466 unique trips, it was computationally intractable for us to perform clustering using a single matrix containing all pairwise similarities. To obtain manageable matrix sizes we used one year of landings (2010) which we split by gear. Pairwise distances among trips and community detection were calculated within each gear partition, which grouped trips into target assemblage categories. To classify the 2009, 2012 and 2013 trips to fisheries, we assigned each unclassified trip to the same realized fishery as the 2010 trip to which it was closest in multi-dimensional space using a k-nearest neighbors algorithm.

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 realized fisheries 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 Vessel 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. We 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).

/Users/efuller/Desktop/CNH/Analysis/Metiers/writing/draft/fig1.pdf

**RESULTS**

**Realized Fisheries of the US West-coast**

Applied to the landing ticket data, 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 temporal and spatial structure (Fig. S2a, b). This structure showed strong agreement with the 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 key realized fisheries, listed as target assemblage-gear pairs are: Dungeness crab-crab pot, market squid-purse seine, albacore tuna troll, groundfish bottom trawl, pink shrimp-trawl, sablefish-long line, salmon-troll, sardine-purse seine, spiny lobster-pot, and red urchin-diving, and included sectors which have been well-studied, but not quantitatively described prior to now, for example the dungeness crab pot (Botsford and Wickham 1978), spiny lobster pot (Kay et al. 2012), and red urchin diving (Smith and Wilen 2003) (Table 1) realized fisheries.

**Vessel 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).

**DISCUSSION**

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 (Anderson et al. 2015). Mapping these social-ecological connections have 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 often 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 static (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). Specifically, for the US west-coast, we have found that the majority of vessels are generalists.

Changes in system characteristics, be it management, ecology or markets, have been previously shown to affect fishing participation. For example, Hentati-Sundberg et al. (2014) has shown how Swedish commercial fishermen have grown increasingly specialized as management became more restrictive and Steneck et al. (2011) document how Maine fishermen have increasingly become dependent on a single species due to interactions among markets and ecological conditions. Here, we found that along the whole the US west-coast, greater than 60% of commercial fishing vessels were generalists, participating in more than one realized fishery. The revenue of each of these generalists is thus tied to multiple fisheries, effectively connecting them and setting up the potential for linked social/economic dynamics and coupled ecological dynamics of target species. The social implications of generalist fishing practices 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 increased revenue diversity have less variable revenues (Kasperski and Holland 2013). Further work is need 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 of one particular fishery.