**CHAPTER TWO**

**Management scale in commercial fisheries on the US west coast: Mapping fisheries connectivity on the US West Coast**

*Abstract*

*Introduction*

Social Ecological Systems (SES) has become an important way to understand linked problems of sustainable use of natural resources and human well-being (ostrom, others?).

This contrasts to historic focus on the biological to provide managers with sound science.

With the shift to SES, there has been a corresponding recognition that the social dynamics of these linked systems can be crucial to better understanding the effects of perturbations, be it from ecological, economic or management changes (tavoni – to some extent M. Smith and the Branch paper on markets driving fishery dependent stock assessments). This appreciation of the importance of social dynamics for driving ecological change comes at the same time that conservation is shifting to incorporate and value human well-being alongside ecological integrity (i.e. biodiversity, intact habitat protection). However empirical data capturing fine scale social dynamics and their interactions with ecological systems is still largely absent, and many have noted in the conservation movement that the major failing of this new framing of “nature and people” is that there exist few empirical measures of social dynamics, of which human well-being is derived.

Of SESs, commercial fisheries may be the most straightforward to conceptualize and so a promising place to start empirically examining links between social and ecological dynamics. Fishermen directly depend on the fish they harvest, and are equally vulnerable to changes form the social sphere (economics, management) as they are from ecological perturbations (stock collapses, range shifts). Further, commercial fishing is a major driver of ecological dynamics in these systems, and so quantifying the dynamics of harvest is equally important for understanding how to manage these foodwebs.

Federal fisheries management in the US is essentially made up of a series of fisheries management plans (FMPs). These FMPs detail the conditions under which someone may participate in the fishery in question, i.e. owning a license, using a specific gear, and/or catch limits. These FMPs therefore essentially define what’s commonly thought of as a “fishery”, which is a group of fairly homogenous vessels harvesting a common pool of species (i.e. the sablefish long-line fishery or the non-whiting groundfish trawl fishery). This definition of a fishery is a useful ecological unit, as this is the group of vessels exerting effort/causing harvest mortality for a relatively homogenous group of species under management. Vessels participating in a fishery could be crudely thought of as predators in a predator-prey system. Yet despite managers being required to manage species (i.e. to prevent the depletion of the stock), managers manage people, not fish. And it’s not at all clear that a fishery as currently conceptualized is the best construct for organizing how management manages the people doing the fishing, nor how it understands their well-being.

This is especially relevant as human well-being is a target alongside that of ecological integrity increasingly in conservation (new conservation, mace) but in fisheries management in particular. In the United States, the Maguson Stevens Act enshrines this priority in National Standard 8, that “*Conservation and management measures shall…take into account the importance of fishery resources to fishing communities in order to (a) provide for the sustained participation of such communities, and (b) to the extent practicable, minimize adverse economic impacts on such communities”*. In the US, fishing communities are legally defined by how dependent people are on commercial fishing for economic livelihoods ([national register](http://www.fisheries.noaa.gov/sfa/laws_policies/national_standards/documents/national_standard_8_cfr.pdf)), and correspondinglymost of the work focused on understanding fishing communities in the US has focused on the interdependence between fisheries and other occupational sectors (NOAA tech memo - vulnerability indices). While useful, these approaches lack a way to directly link to the scale of the fishery, to that of the fishing community (often approximated to that of the port).

Using landings data for the US West coast commercial fisheries, I develop a novel methodological framework, which I term “participation networks” to provide insights into the role of human-connectivity of fisheries in commercial fishery systems. Network approaches have long been a valuable tool to understand interactions among communities of species (i.e. foodwebs). In this context, I developed and applied a novel network modeling approach to build participation networks and analyze the patterns of fisheries participation and their interrelationships at different levels of aggregation (i.e. port, state and coastwide). To analyze these participation networks I have used two measures that have direct analogies to food-webs. The first is a measure of node centrality have been used to identify “keystone” species in food-webs, those that if removed from the food-web would lead to a disproportionately large impact on the whole system. Applied to the participation networks, measures of centrality identify “keystone fisheries”, those that most vessels would participate in (and possibly gain most of their revenue from) at some point of the year. These fisheries are likely ones that, regardless of ecological function or vulnerability, may from a human perspective, have high management importance. The second measure is that of modularity, which describes the presence of groups of well-connected realized fisheries. Network modularity is an important property of any complex system (Levin), providing resilience to perturbation by isolating effects to subcomponents. Here, modules in the participation networks identify groups of similar vessels, based on what they do on the water, that can be used to identify discrete management units. These first order properties of the participation networks are may be key to quantifying how any perturbation – a management or environmental change – will effect the whole marine social-ecological system.

*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 commercial landings accounted for XXXX tons of YYYY species, resulting in XXXXX revenue by XXXX vessels.

**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, I 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 I specify our rational for these choices.

For our distance metric I 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 I 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, I were not able to perform clustering using a single matrix containing all pairwise similarities. To obtain manageable matrix sizes I used one year of landings (2010) which I 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, I 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 I could use to compare the results. To address this issue, I 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 I did not bound our clusters spatially, temporally, or by vessel characteristics, I 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).

**Building participation networks across scales**

To represent connectivity among realized fisheries at the port level I built undirected, weighted networks where nodes each represented a realized fishery. If the graph is written as an adjacency matrix **G***,* then the element *gij* is the number of vessels that landed catch in both vertex *i* and vertex *j* over a given period. Thus nodes are connected (*gij > 0)* when vessels participate in both and 0 otherwise (Fig. 1)*.*  Node size is proportional to the number of vessels that participated in the fishery between 2009 and 2013. Landing data was aggregated at the port, state and coast wide levels to build participation networks. Here I focus on the major ports on the US west coast, defined as those which account for the top 90% of revenue coast wide. To focus on major fisheries and to protect confidentiality I filter networks and drop nodes in which fewer than three vessels participate and retain only fisheries responsible for the top 99% of revenue at a given scale.

**Measuring Centrality**

While many measures of network centrality exist, here I chose simple measures which have clear interpretations. Centrality of each node in a network was measured in two ways, by node strength and eigenvalue centrality. Node strength is a generalization of degree for weighted networks. Degree, or the number of connections to a given node, is an intuitive measure where the more connected a node is, the more central we assume to be in the network. To make use of the information contained in edge weight I calculate node strength (Barrat et al. 2004) where node strength of node *i* is

in a graph with *N* total nodes (Barrat et al. 2004). Because networks can vary orders of magnitude in the total number of vessels moving among nodes, I normalize this value by the sum of all edge weights in a graph, thus providing a measure ranging between 0 and 1 where 1 indicates that all connections in the network were to node i, and 0 means that no connections involved node *i*, and it grows that such that larger edges drive up the score. Fisheries with node strength of fishery *i* (*si*) close to one are fisheries that consistently are connected to the majority of other fisheries in the network and/or are involved the strongest connections present. Thus these fisheries that score highly in node strength across all port networks can be thought of as fisheries that are consistently central (i.e. strongly connected to most of the nodes in the network) in all the networks in which they appear.

This measure of node strength, while intuitive, only takes into account the local structure of each node. To incorporate both node strength and network structure I calculate betweenness. Betweenness centrality was developed to capture whether nodes connected two relatively distant parts of a network {Freeman:1979ve}. This metric is particularly useful in cases where we wish to know something about traffic or how information flows across a network, both of which are relevant when we think about fisheries participation. This metric is calculated as the number of shortest paths which travel through a given node *b(v)*.

where is the number of shortest paths between node *s* and node *t* and is the number of shortest paths that pass through vertex *v*. Because betweenness will scale with network size, and participation networks can vary ins ize, I normalize this value by dividing by the number of pairs of nodes *((N-1)(N-2)/2*) that do not include *v*, so that *b* is in the interval *[0, 1]*. To incorporate weights of edges I sum the edge strength such that shortest paths that involve edges with larger weights contribute more to betweenness scores.

**Measuring modularity**

Modularity was determined by looking for distinct communities in port participation networks in the top ten ports by revenue. Communities have long been of interest for biological and social networks, however they are difficult to define formally. Most recent approaches consider that a partition of the nodes of a graph represent true structure if the proportion of edges inside the community is large when compared to the number links between them and the rest of the graph. I use this definition here and define communities as groups of fisheries more tightly connected to one another than the rest of the network. These were identified using the walktrap algorithm as implemented in *igraph* {Pons:2005uh}. The algorithm’s name comes the observation that random walks on networks often get “stuck” in densely connected subgraphs. The algorithm proceeds to build an agglomerative dendogram by computing pairwise distances among all nodes and merging adjacent (i.e. sharing at least one edge) nodes/communities to form larger groupings. The weight of the edge *ij* is converted to distance by averaging all edge weights and dividing by edge weight *ij*. At each step, a pair of edges is merged based on the move that results in the greatest reduction the variation in the mean squared pairwise distance within the candidate community. This process is repeated until all communities are fused to a single large entity. To choose the optimal partition, the modularity *Q* of each partition *P* is calculated as

where *ec* represents the edges inside community *C* and *ac* is the number of edges between the community and the rest of the network {Pons:2005uh}. i At each step the modulary is computed, and the partition with the largest modularity is chosenthe multiplying the edge of a graph E Letting a random walker move through the network results in candidate networks which are evaluated and merged based on a modularity score

*Results*

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

Applied to the landing ticket data, my 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 I examined (Table 1). These fisheries include well-studied, but not quantitatively described sectors such as the dungeness crab pot (Botsford and Wickham 1978), spiny lobster pot (Kay et al. 2012), and red urchin diving (Smith and Wilen 2003).

**Participation Networks**

I found differences in the number and interconnectedness of fisheries across ports (Fig. 3). At the port level participation networks had between 1 and 11 fisheries (nodes) and between 0 and 47 edges with a median of 6 and 7, respectively. Fisheries in these networks were connected to anywhere between 0 and 10 other fisheries with a median of 3 connections. Linkage density for these networks varied between 0 and 4.27 and is variation is exemplified by participation networks in Santa Barbara, CA, Port Orford, OR, and Crescent City, CA (Figs. 3a-c). Santa Barbara was characterized by a complex participation network, with more than double the average link density of Port Orford (see Appendix for all port participation networks).

Participation networks at the state level had between 8 and 17 nodes and between 19 and 103 edges in total. The median degree of fisheries in these networks was 7, although they ranged between 2 and 16 connections. Similar to port level networks, we also found differences in the number and interconnectedness of fisheries amongst states. California had the highest linkage density, followed by Oregon and Washington.

The differences in these networks, with California’s participation network having more than double the nodes (fisheries) than either Oregon or Washington, is striking. The California participation network has a median degree of 14 compared to 6 and 4.5 of Oregon and Washington, respectively. This difference in number and interconnectivity is likely due to the presence of more purse-seine, pelagic fisheries and invertebrate pot fisheries (i.e. market squid seine, herring, sardine and spiny lobster, red urchin and rock crab respectively) that are not as dominant fisheries in Oregon or Washington.

**Centrality – keystone fisheries and measures of management importance**

In contrast to typical portrayals of fleets as independent units of fishing effort, virtually all fisheries were connected to at least one other fishery by vessel participation. These connections varied, but some clear patterns emerged. The Dungeness crab pot fishery was consistently central in both node strength and betweenness centrality. Large node strength suggests that the Dungeness crab pot fishery is much more connected than the rest of the nodes in a given network, which implies that many different fishing strategies likely include Dungeness crab pots as a component. High scores of betweenness suggest that the different strategies employed by those participating in Dungeness crab pot fishery are diverse, such that the population involved in Dungeness crab pot fishing is highly heterogeneous. Interestingly, aside from the Dungeness crab pot fishery, the betweenness centrality identifies a largely non-overlapping set of fisheries as consistently central in networks, with many more fisheries identified as peripheral. Herring seine (NET\_5) for example has relatively high median betweenness centrality but middling node strength. This suggests that while the fishery may be less commonly participated in than crab, it connects a diverse group of fisheries.

**Modularity – management units**

At the port scale, I find anywhere from 2 to 7 communities in the port participation networks. The make up of these communities, while varying in size, often have common memberships. The most common membership is a Dungeness crab pot and Albacore tuna Troll fishery (4/10 networks) followed by DTS trawl and pink shrimp (3/10 networks). Pelagic fisheries, i.e. purse seine fisheries for market squid, sardine, herring and mackeral often were interconnected (i.e. Trinidad, CA: Fig 5) and there seems to be a possible replacement of Dungeness crab with spiny lobster pots as a central fishery in southern California ports. Another common combination was albacore and salmon troll fishing, a not unexpected combination given the similar ecology of target species (highly mobile, pelagic) and gear used for these fisheries (troll).

In general communities seemed partially determined on geography and vessel size. Composition of participation networks, and these characteristic communities of fisheries, varied between southern California and further north along the coast. Southern California ports participation networks had communities dominated by market squid, no Dungeness crab fisheries, and sometimes contained sea cucumbers, California halibut and red sea urchin diving. Northern participation networks, by contrast, were dominated by dugenness crab pot fisheries groundfish trawl and pink shrimp trawls, and contained sablefish pots and longline fisheries not present in southern networks.

*Discussion*

1. Fisheries are highly connected, this is contrasted with typical depiction of fleets and underscores need for ways to map fisheries to how people participate in them, and how we relate that to the scale of fishing communities. [Fig 2] In this chapter I have developed a novel framework for linking fisheries to fishing communities and a way to visualize and analyze this interactions.
2. California fisheries are really different looking than Oregon and Washington. This is the first time such regional examination in fisheries participation and connectivity has been demonstrated to my knowledge. [Fig 3] Aside from management likely differing between states, it may also be in part due to ecology and to geography. Ecologically the California Bight is a meeting of ecosystems and is extremely species rich. Geographically the shelf gets narrow in CA, and so many more typically deep water species are available for harvest much closer.
3. Identify Dungeness crab as a fishery of “management importance”. Everyone fishes in it, and so even if it’s doing well, it may be worth proactively spending a great deal fo resources on it since it’s central to so many people’s livelihood strategies [Fig 4]. However the regional variability in the fisheries participation networks is worth considering, since few southern port participation networks contain Dugenness crab, instead being replaced by spiny lobster pot fishing.
4. Identify characteristic combinations of fisheries, which helps move towards operationalizing the goal of making management match the scale of the system in which it’s embedded. [Fig 5] There are common combinations of fisheries that appear among these participation networks: pelagic purse seining dominated by market squid purse seine, combining pink shrimp and DTS trawl, albacore and chinook trolling. In the northern part of the coast, Dugeness crab and everything, in the south, spiny lobster and everything.
5. These linkages emphasize the importance of taking a systems perspective in these complex and highly interconnected systems. Further there are a few combinations which of fisheries that from an ecosystem perspective would not expect to be tightly linked. The linkage between albacore tuna troll and crab, for example, are two single species fisheries that are ecologically disparate (pelagic and benthic) and managed under two different systems (state for albacore as a highly migratory species and state). [Fig 5]

This is the first time to my knowledge that the diversity and evenness of fisheries participation and interconnectivity has been examined across ports or states. This work has highlighted, in particular, that fisheries are not comprised of specialist fleets, and there appears to be strong regional variation in participation structure and network, with California differing dramatically from Oregon and Washington.

This analysis has also highlighted the centrality of the Dungeness crab pot fishery across scales and along the coast. This fishery is central is most networks in that it is both highly connected to many other fisheries and that it forms a central node in these networks rather than existing on the periphery. This suggests that a diversity of fishermen overlap in the crab fishery, as opposed to say the DTS and pink shrimp trawl fisheries where it’s largely the same population doing both. This is likely because much of the participation in west coast fisheries is constrained by vessel size. Much like gape size in marine ecology, large vessels could technically participate in any fishery, however frequently in hook and line and troll fisheries, the revenue doesn’t outweigh the costs of fuel. The Dungeness fishery, however, mixes both large and small vessels and thus is unique in it’s composition.

The issue of scale is one familiar to the biological management of commercial fisheries, stock complexes (species commonly caught together), for example are also frequently managed together. Defining and shifting management to multi-species, and now ecosystem-level approaches have necessitated a great deal of research on how species interact and depend on one another. We lack an analogous concept for the social side of these systems, despite the fact that it’s a well known fact that fishermen often participate in multiple fisheries, thereby connecting them.

However, there are second order properties of the participation networks that are worth considering too. In particular, not only are the links between realized fisheries heterogeneous, they are changing over time as fishers/vessels re-tool and learn new skills. Thus another key property is the transitivity of the participation networks. Transitivity describes multi-step connections, and these are particularly important when considering how information and adaptive capacity may flow through these networks

, and provides a basis for hypothesis generation about the importance of the topology of these networks for how stabhow management changes in one fishery may affect others.

Without a way to link changes in management at the scale of the fishery to the the heterogeneity of participation across and examine the connections within the fishing communities themselves, specifically how fisheries are related and interconnected with one another.

Examining how fishermen participate in any one of these fisheries forms the study of “fleet-dynamics,” a sub-discipline of fisheries science. Central to these studies is determining empirically when and where fishermen fish and developing theoretical frameworks to predict if and when this spatial allocation of effort should be important for accurate prediction of ecological dynamics. However, these approaches currently lack a way to examine system-level measures of the whole set of fisheries and their interrelations. Furthermore, I also perceive a need for a comprehensive and readily understandable way to capture and illustrate how fisheries are connected to one another by the vessels that move between them. In this chapter, I develop a novel methodological framework to provide insights into the role of human-connectivity of fisheries in commercial fishery systems. Network approaches have long been a valuable tool to understand species interactions in ecological systems (i.e. foodwebs). In this context, I developed and applied a novel network modeling approach to illustrate and analyze the patterns of fisheries participation and their interrelationships at different levels of aggregation (i.e. port, state and coastwide). Key advantages to using a network analysis to examine fisheries participation are that it provides measures of how each fishery relates to the other fisheries as well as it enables systematic measures of fisheries participation at scales larger than that of the individual.

Here, I have used two measures that have direct analogies to food-webs: (1) measures of node centrality have been used to identify “keystone” species in food-webs, those that if removed from the food-web would lead to a disproportionately large impact on the whole system. Applied to the participation networks, measures of centrality identify “keystone fisheries”, those that most vessels would participate in (and possibly gain most of their revenue from) at some point of the year; (2) measures of modularity, which describes the presence of groups of well-connected realized fisheries. Network modularity is an important property of any complex system (Levin Refs), providing resilience to perturbation by isolating effects to subcomponents. Here, modules in the participation networks identify groups of similar vessels, based on what they do on the water, that can be used to identify discrete management units. These first order properties of the participation networks are key to quantifying how any perturbation – a management or environmental change – will effect the whole marine social-ecological system. However, there are second order properties of the participation networks that are worth considering too. In particular, not only are the links between realized fisheries heterogeneous, they are changing over time as fishers/vessels re-tool and learn new skills. Thus another key property is the transitivity of the participation networks. Transitivity describes multi-step connections, and these are particularly important when considering how information and adaptive capacity may flow through these networks.

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 and (ii) describe networks of fisheries participation for entire communities (ports). The novel results from this work suggest that the Dungeness crab fishery is a “keystone fishery” and that there are a number of common modules that appear regardless of scale of analysis that may be appropriate management units. Overall I find a wide range in the size and complexity of these networks, suggesting that some ports may be more resilient than others to perturbations.