Title: Accounting for Human Connectivity in Social-Ecological Systems

**Or**

Human Connectivity in Social-Ecological Systems

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**One Sentence Summary:** Fostering resilience in social-ecological systems requires that management account for the links resource users create when they are dependent on multiple components of an ecosystem.

**Main Text:**

Balancing human well-being and ecological integrity is one of the fundamental goals of conservation and natural resource management. However, despite the growing focus on measuring and valuing human well-being, alongside ecological indicators such as biodiversity and ecosystem services (REFs), we still have not fully addressed the complex and adaptive ways in which humans make a living and gain sustenance from ecosystems.

This challenge is particularly acute in commercial fisheries, where the dynamics of marine ecosystems and the well-being of fishermen are inherently tied to one another. The desire to account for connections between fish and fishermen is present, as seen in numerous policy directives including the recently released NOAA Fisheries Climate Science Strategy and Ecosystem Based Fisheries Management (EBFM) technical reports (*3*, *4*). But while these policies call for the incorporation of the complexity and adaptive nature of these social-ecological systems into ocean management, attention to food-web interactions dominates, marginalizing the equally complex human networks resulting from how people participate and shift effort among fisheries. Developing new and innovative methods to understand these complex systems and their dynamics is therefore a critical and largely unaddressed step towards moving EBFM from theory to practice and ultimately advancing sustainability science (2). To this end, this paper presents an analysis of socioeconomic connectivity of the commercial fisheries in the California Current ecosystem, illustrating the diverse intra-fishery connectivity that exist in coastal communities along the west coast of the United States, and elsewhere in the world. We focus on the California Current ecosystem because the natural science to support EBFM in this region is cutting-edge, yet little work has been done to account for human connections among fisheries that exist in the region.

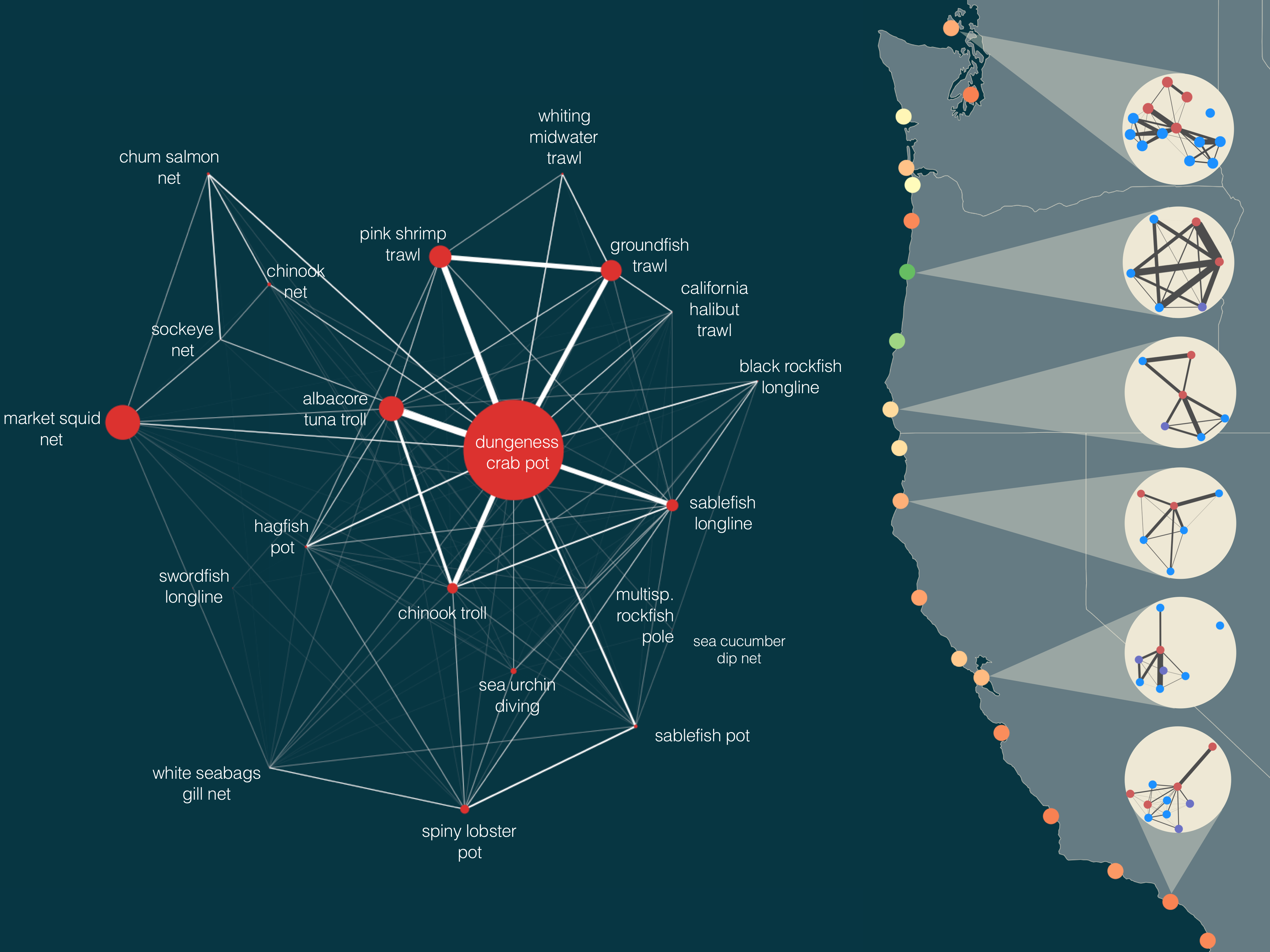
To improve understanding of human connectivity among fisheries for policy makers, stakeholders and managers, we developed and applied a novel approach to build and describe what we term “participation networks”. Participation networks are comprised of nodes, in this case fisheries, and edges connecting them, weighted by the density of the vessel linkages between any two fisheries(Materials and methods are available as supplementary materials at the Science website). This is similar to quantifying the adaptive capacity of communities (Eddie Allison REF) and identifying alternative sources of livelihood (Cinner + Bodin Ref). In doing so we find (i) general, consistent social linkages among fisheries that are currently unaccounted for in existing fisheries policy and management; (ii) that people diversify across jurisdictional and institutional boundaries (state and federal fisheries); and (iii) while there appears to be scale-invariant motifs in these networks, we find variation in the composition and structure from community to community suggesting heterogeneity in both the impact upon fishing communities, and their ability to deal with environmental, management, and/or market shocks.

This study presents a first effort to systematically measure human connectivity among commercial fisheries. Management must account for these connections in order to optimize benefits across fisheries, especially when ecologically distant taxa are transitively connected by the people who fish for both of them. For example, on the US west-coast a closure in the crab fishery could have cascading ecological impacts on numerous other fisheries because 75% of the Dungeness crab fishermen are generalists, participating in an average of four other fisheries in a given year. Such generalism suggests that fishermen will shift their effort from one fishery to another, in order to maximize or satisfy their income needs. This would likely result also in cascading management effects, as policy makers play catch-up with fishermen as they redistribute their effort.

These participation networks also point to the value of cross-scale and trans-boundary governance institutions (*5*). For example, the state-managed Dungeness crab fishery is tightly connected to federal fisheries, that is on average crab fishers make 30% of their annual revenue on non-crab fisheries, and 99% of these non-crab fisheries are federally managed. While governance institutions that acknowledge cross-scale and trans-boundary issues are not without precedent, as on the US West Coast where Pacific hake are jointly assessed and managed by the US and Canada, attention is rarely paid to the human connectivity of fisheries across jurisdictions.

Last, quantitative measures of these participation networks provide the means to evaluate policy efficacy. For example, across coastal communities in the US California current, network complexity varies five-fold. Simply naming this variability can help policymakers determine the spatially heterogeneous social and ecological effects of coast-wide management action, for example the recent implementation of catch shares in the groundfish fishery.

We have focused here on the importance of human connectivity to advancing marine policy for the US, but its importance extends to other systems in other places around the world. For example, most marine systems support a diversity of industrial and subsistence fishing fleets, each extracting different living resources (REF). So too for lentic and terrestrial systems, where people gain income and sustenance from numerous natural sources (REF). As a consequence, measuring and designing policies that account for both ecological and human connectivity will help us live sustainably now and in a future under climate change and human population growth.



**Fig. 1. Human connectivity of commercial fisheries in the California Current Ecosystem.** Fisheries in the California Current are strongly connected by human participation. Some fisheries, notably the Dungeness crab-pot fishery, dominate the coast-wide network. The human connections among fisheries also frequently connect ecologically distant species, i.e. Dungeness crab and Albacore Tuna or benthic groundfish and pink shrimp. Examining networks generated for port groups, we find that these networks vary in their structure in the number of fisheries (nodes), the heterogeneity in fishery size, and strength of interconnections. These differences in structure may correspond to differences in community resilience. We color ports using one potential metric of network resilience to highlight this heterogeneity. On the right port groups are colored by their adaptive capacity and show port-level participation networks with nodes colored by management jurisdiction (federally managed fisheries are blue, state managed are red, fisheries where both state and federal have a role in management, i.e. nearshore rockfish, are purple). For visual clarity we only include fisheries that had at least 3 vessels participating, and accounted for, on average, 25% of a vessel’s annual income (Materials and methods are available as supplementary materials at the Science website).

**References and Notes:**

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Supplementary Materials:

Materials and Methods

References (*6-10*)

Supplementary Materials:

**Materials and Methods:**

Data

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). These commercial landings accounted for approximately 2.7 million metric tons of 228 species, resulting in 3.7 billion dollars in revenue (adjusted to 2009 levels) by a total of 6,862 vessels. We discard any fisheries for which vessel-identifying information is unavailable, which precludes analysis of patterns of individual participation. This primarily affects bivalve fisheries (i.e. pacific oyster and geoduck fisheries in Washington).

Date preparation

To examine patterns of participation, we grouped landings into distinct fisheries. Fisheries are defined as harvest assemblages caught with a specific gear (*6*, *7*). 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 (*8*). In order to treat the landings dataset uniformly, we applied a métier analysis to this landing data (*9*) to build a set of fisheries.

Constructing Participation Networks

Fisheries are linked by fisher-mediated interactions. If a vessel *k* fishes in two fisheries *i* and *j*, they are linked in vessel *k*’s yearly strategy. Thus changes in fishery *i* can change the cost-benefit decisions for vessel *k* fishing in fishery *j*. The weight of the interaction between the two fisheries is determined by the density of the vessel linkages between fishery *i* and *j*. For a vessel *k*,link density scales with the amount of total revenue derived between the two fisheries *Rijk* and the evenness with which the vessel that participates in both fisheries *i* and *j,* but the more fisheries vessel *k* participates in, the smaller contribution to each fishery. So each vessel contributes to the link weight between fishery *i* and *j*. This results in a fishery-participation network

One limitation of using vessels as a proxy for individual fishermen is that it’s impossible to know if vessels changed hands. With a short enough time series, the risk of this might be slight, but with 8 years of data, it’s probable that at least some vessels were transferred. This is especially likely because some major changes occurred (i.e. the chinook salmon troll fishery closed and the general economic recession in 2008-2009; implementation of individual-transferable quotas in groundfish trawl fishery in 2011). Grouping across years, and across possible transfers in those cases, would smear the patterns of participation and obscure common subsets of fisheries that co-occur. To address the problem of vessel transfer, I split up vessels into vessel-year replicates.

To examine regional participation networks, we grouped landings by port-group. These port groups have been constructed to combine together ports that are part of the same fishing community (i.e. all San Diego-area ports).

Calculating Resilience

Using the universal resilience function from Gao et al. (*10*), for each network we calculated , where is the average edge weight across all, is the edge symmetry (here, because networks are undirected, symmetry is equal to one) and is the edge heterogeneity measured as variance in edge weights divided by .