Title:

Human Connectivity in Social-Ecological Systems

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**One Sentence Summary:** Fostering resilience requires that resource managers account for the social and ecological links 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 valuing this balance, tractable methods for achieving this goal are still lacking (*1*). This challenge is particularly acute in commercial fisheries, where the well-being of fishermen is inherently tied to the distribution and abundance of numerous marine species. Accordingly, the need to manage for human well-being has received considerable attention in marine policy directives. In the US, for example, both the NOAA Fisheries Climate Science Strategy (*2*) and Ecosystem Based Fisheries Management (EBFM) policy (*3*) call for increased research on coastal communities and their linkages to ocean ecosystems. Despite this focus, 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 (*4*). To this end, this paper presents an analysis of human connectivity for the commercial fisheries in the California Current ecosystem, illustrating the diverse inter-fishery connectivity that exists in coastal communities along the west coast of the United States. 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.

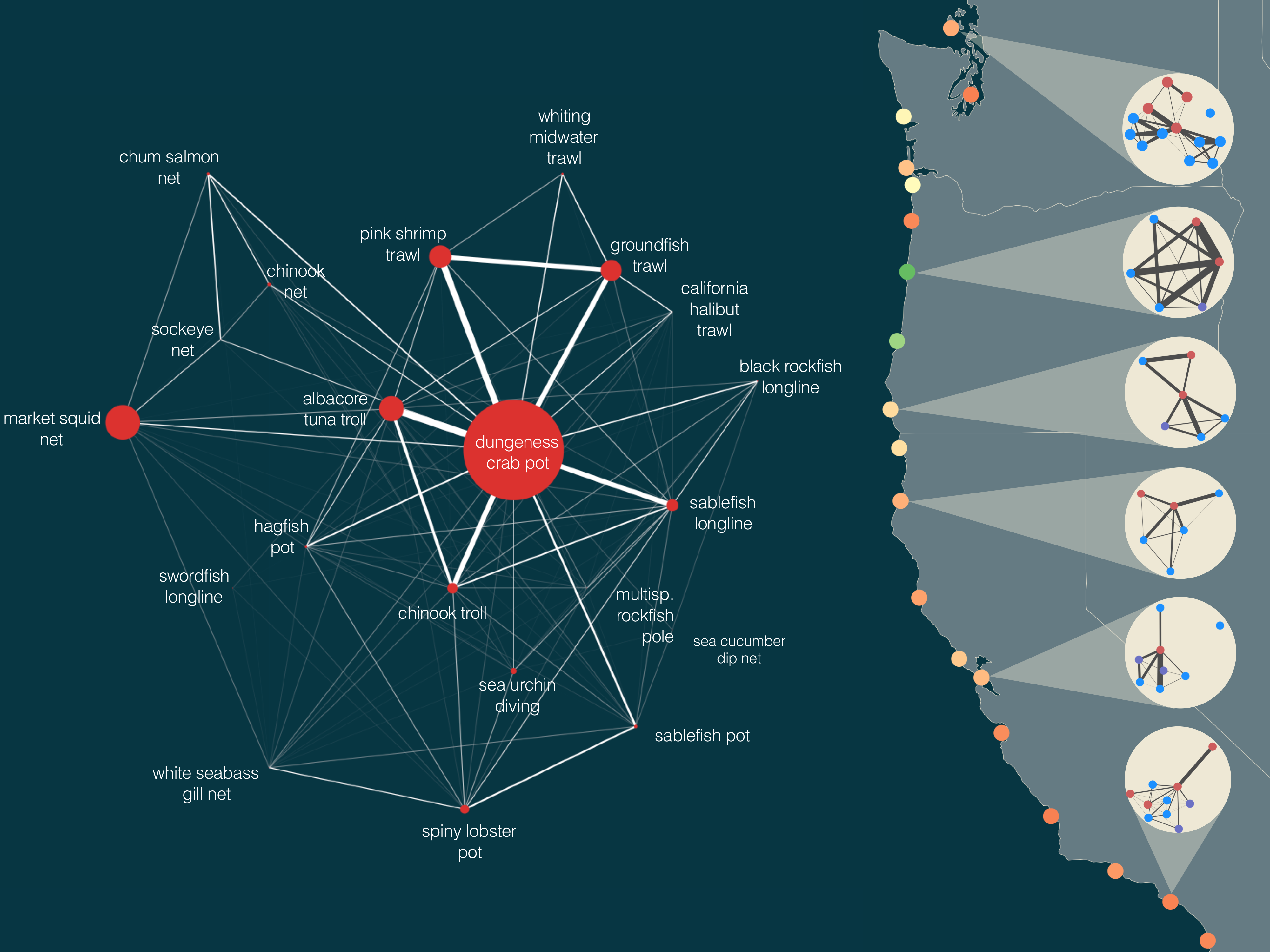
To improve understanding of human connectivity among fisheries for policy makers, stakeholders and managers, we developed and applied a novel approach to build and describe what we term “participation networks”. Participation networks are comprised of nodes, in this case fisheries, connected by the vessels that participate in both (Materials and methods are available as supplementary materials at the Science website). This network approach is most similar to identifying different sources of income that people use to support their livelihoods (5), but rather than examining how people move across occupational sectors, it focuses on the multitude of interactions that comprise a single social-ecological system, allowing linkages to be drawn between species and the people who depend on them. This approach also allows us to take advantage of metrics developed to assess network resilience (see main text Figure, colored markers; *6*). Such network statistics allow us to calculate how coastal communities might respond to perturbations, for example climate change or a change in management. In building and systematically measuring the human connectivity among commercial fisheries we find (i) general social linkages among fisheries that are currently unaccounted for in existing fisheries policy and management (see figures S4-S21 in Supplement); (ii) that people diversify across jurisdictional and institutional boundaries (state and federal fisheries); and (iii) while there appears to be general patterns in these networks, we find variation in the composition and structure from community to community suggesting heterogeneity in their ability to deal with environmental, management, and market shocks (see main text Figure; range of network topologies along the coast, Figures S2-S3).

These patterns suggest that management must account for these connections, in order to maintain benefits across fisheries, especially when ecologically distant taxa are transitively connected by fishermen. 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 (e.g., tuna, groundfish, salmon, crab). Such generalism suggests that fishermen will shift their effort from one fishery to another, in order to maximize or satisfy their income needs. This could cause 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 (*7*). For example, the state-managed Dungeness crab fishery is tightly connected to federal fisheries. 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, formal management structures that recognize human connectivity of fisheries across jurisdictions are the exception, not the rule.

Last, quantitative measures of these participation networks provide the means to evaluate policy efficacy. Participation networks of the coastal communities in the US California current vary in both composition and topology, with the most complex networks having four times the connectivity of the simplest ones (Monterey/Santa Cruz compared to Crescent City and Bodega Bay respectively, Figure S2). Recognition of this variability can help managers anticipate the extent to which coast-wide policy change will create similar or different social and ecological consequences from place to place. For example, due to the varying degree of human connectivity to fisheries across coastal communities on the US West Coast the social and ecological consequences of the recent implementation of catch shares in the groundfish fishery will likely be heterogeneous.

Despite the growing focus on valuing, and therefore measuring, human well-being alongside ecological quality indicators (i.e. biodiversity, ecosystem function), we still lack clear ways to operationalize these goals (1) and fisheries are no exception. Here we have presented participation networks, which provide a tractable, generalizable method to advance our understanding of coastal communities and their linkages to the ocean. By making use of existing data this approach allows quick adoption by government agencies tasked with policy design. We have focused here on the importance of human connectivity to advancing marine policy for the US, but its significance extends to other systems in other places around the world. For example, marine systems often support a diversity of industrial, recreational, and subsistence fishing fleets, each extracting different living resources (*8*). Examining the overlap among different groups of harvesters could help identify keystone management species: stocks that, independent of their ecological importance, form a major component of harvesters’ livelihoods (i.e., Dungeness crab in this analysis). This research is also relevant where people gain income and sustenance from freshwater and terrestrial sources, interacting with multiple components of multiple ecosystems (*9*). We hope that by quantitatively illustrating human connectivity across institutions, habitats, and trophic levels, we can stimulate the development of policies that recognize and embrace this complexity to better human well-being and ecological sustainability.

***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 on the right, we find that these networks vary in the number of fisheries (nodes) 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 (see supplementary materials for additional metrics). 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).*

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Supplementary Materials:

Materials and Methods

Figures S1-S3

Table S1

Supplementary Text

References (*10-17*)