Climate shock effects and mediation in fisheries

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Climate shocks can reorganize the social–ecological linkages in food-producing communities, leading to a sudden loss of key products in food systems. The extent and persistence of this reorganization are difficult to observe and summarize, but are critical aspects of predicting and rapidly assessing community vulnerability to extreme events. We apply network analysis to evaluate the impact of a climate shock—an unprecedented marine heatwave—on patterns of resource use in California fishing communities, which were severely affected through closures of the Dungeness crab fishery. The climate shock significantly modified flows of users between fishery resources during the closures. These modifications were predicted by pre-shock patterns of resource use and were associated with three strategies used by fishing community member vessels to respond to the closures: temporary exit from the food system, spillover of effort from the Dungeness crab fishery into other fisheries, and spatial shifts in where crab were landed. Regional differences in resource use patterns and vessel-level responses highlighted the Dungeness crab fishery as a seasonal "gilded trap" for northern California fishing communities. We also detected disparities in climate shock response based on vessel size, with larger vessels more likely to display spatial mobility. Our study demonstrates the importance of highly connected and decentralized networks of resource use in reducing the vulnerability of human communities to climate shocks.

social–ecological system | climate shock | adaptive capacity | fisheries | climate change

Climate shocks threaten food systems around the world and are expected to increase in frequency and intensity under climate change (1–5). Distinct from climate change (e.g., long-term warming), climate shocks rapidly outstrip the capacity of a system to cope by inflicting unexpected and highly concentrated damage (6). Vulnerability of communities to climate shocks varies within and across food systems, depending on the severity of the shock and the sensitivity and adaptive capacity of community members (7). Communities that form the harvesting and processing base of food systems—especially agrarian and fishing communities—are often among the most vulnerable to climate shocks (8), as their resource-based economies operate at the interface of environment and society. Marine heatwaves represent one such climate shock of growing importance, as they impact fishing communities by compromising seafood safety, shifting species distributions, and lowering recruitment and survival of fished species (9–12).

Diversifying harvest portfolios is one strategy used by fishers to manage risk (13–16). If marine heatwaves disproportionately affect a subset of species, fishers may respond by shifting participation into less affected fisheries. This response, referred to as "leakage" or "spillover" (17–21), restructures the networks that form as fishers participate in multiple fisheries (19–21). The topology of these fisheries participation networks can reveal the extent to which climate shocks lead to indirect or lasting changes in patterns of resource use within fishing communities and, by drawing on network theory, indicate the sensitivity of these communities to perturbations (18).

The 2014–2016 North Pacific marine heatwave (12, 22) was a climate shock that led to a massive harmful algal bloom (HAB), contaminating Dungeness crab with biotoxins and compelling state managers to coordinate fishery closures along the entire US West Coast (23). In California, where the Dungeness crab fishery represents ∼26% of all annual fishery revenue (California Department of Fish and Wildlife; https://wildlife.ca.gov) and supports >25% of all commercial fishing vessels (Pacific Fisheries Information Network; http://pacfin.psmfc.org), the HAB significantly delayed the 2015–16 commercial Dungeness crab fishing season (24). California Dungeness crab landings for the 2015–16 season reached only 52% of the average catch from the previous 5 y, spurring Congress to appropriate >$25 million in federal disaster relief funding (25). Dungeness crab fishers reported shifting participation to alternative fisheries during the 2015–16 season to offset socioeconomic impacts (26, 27); however, to date there has been no quantitative demonstration of spillover from the Dungeness crab fishery, or analysis of how the resulting changes in fisheries participation networks may have varied geographically and persisted after the closures were lifted.

Our study examined the impact of the 2015–16 Dungeness crab fishery closures (hereafter 2016 closures) on patterns of resource use in California fishing communities. We considered seven fishing communities representing a total of 2,516 individual fishing vessels (Table 1). We found significant changes in fisheries participation network topology during the 2016

Significance

Climate shocks are increasingly disruptive to global food systems, with far-reaching consequences for resource-based communities. Yet quantitative assessments of community impacts rarely account for economic connectivity between alternative resources. We show that patterns of resource use influence the sensitivity of US West Coast fishing communities to unprecedented fishery closures in the wake of a recent climate shock. Patterns of participation in commercial fisheries were significantly altered during the fishery closures, but rebounded to preexisting states after closures were lifted, indicating community-level resilience to this particular perturbation. Our study provides evidence that more complex networks of resource use buffer the impact of climate shocks, and reveals strategies that alter emergent patterns of resource use in affected fishing communities.

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Table 1. Ports of landing and vessel counts for the seven California fishing communities included in this study

Region	Fishing community	Ports of landing	Total annual vessels, 2008–17	Dungeness crab vessel counts (large/small), 2015	Dungeness crab vessel proportions, 2015
North	Crescent City	Crescent City, Other Del Norte County	109 ± 16	68 (40/28)	0.75
	Eureka	Eureka, Fields Landing, Trinidad, Other Humboldt County	150 ± 24	77 (34/43)	0.51
	Fort Bragg	Albion, Point Arena, Fort Bragg, Other Mendocino County	237 ± 96	41 (22/19)	0.12
	Bodega Bay	Bodega Bay, Bolinas, Point Reyes, Tomales Bay, Other Sonoma/Marin County	208 ± 77	105 (56/49)	0.44
	Total		*753 ± 149*	*291 (152/139)*	*0.36*
Central	San Francisco	Alameda, Berkeley, Oakland, Princeton/Half Moon Bay, Richmond, San Francisco Sausalito, Other San Francisco Bay/San Mateo County	388 ± 97	221 (121/100)	0.49
	Monterey Bay	Santa Cruz, Monterey, Moss Landing, Other Santa Cruz/Monterey County	286 ± 83	47 (15/32)	0.14
	Morro Bay	Avila, Morro Bay, Other San Luis Obispo County	187 ± 26	30 (17/13)	0.14
	Total		*567 ± 98*	*298 (153/145)*	*0.30*

The number and proportion of commercial Dungeness crab fishing vessels in the given community is reported for the 2015 crab year. "Total annual vessels" reports the mean annual number of active commercial vessels in the given fishing community, with SD, for crab years 2008 to 2017.

closures, which corresponded with a severe reduction in fishing activity, spillover of fishing effort from the Dungeness crab fishery, and spatial variation in pre-shock network topology. Our analysis captured changing patterns of resource use during a severe climate shock, and demonstrated how this emergent social outcome in fishing communities can be predicted by pre-shock network metrics and related to the adaptive strategies of community member vessels. We discuss the implications of fishery management measures for adaptive decision making and network structure, and provide recommendations for sustainable fishery management during climate shocks.

Evaluating Change in Fisheries Participation Networks

Our analysis used historical landings data and network methodology to quantify the sensitivity of fishing communities to perturbations in the Dungeness crab fishery. We then related expected sensitivity to changes in network topology during and after the 2016 closures, and qualitatively linked those changes to adaptive responses by Dungeness crab vessels. We used a shore-based definition of fishing communities as port groups (18, 28), with vessels landing catch in a given port group as proxies for fishers. We defined fishing community sensitivity as the magnitude of change in fisheries participation network topology caused by a perturbation.

Participation Network Framework. We used two types of participation networks to 1) quantify patterns of resource use in fishing communities, and 2) deconstruct Dungeness crab vessel activity. In both networks, nodes are fisheries, with edges connecting pairs of fisheries based on shared vessel participation. Undirected fisheries participation networks show participation by all vessels in a fishing community, with nondirectional edge weights defined by the number of vessels participating in, and the evenness of revenue generation from, pairs of connected fisheries (18). Directed networks capture spillover from the Dungeness crab fishery during and immediately after the 2016 closures; edges, weighted by the number of vessels, indicate Dungeness crab vessel movement out of fisheries in which they participated during the previous season and into alternative fisheries, to a different fishing community, or out of the California commercial fishing industry for the 2015–16 fishing season.

Drawing on >286,000 landing records, we constructed directed and undirected networks for each Dungeness crab season. We refer to each season using "crab years," from November through October of the following year; the 2016 crab year corresponds to the 2015–16 fishing season (i.e., November 2015 to October 2016). To observe behavioral responses during and immediately after the 2016 closures, we further subdivided each crab year into an early season and a late season, delineated by the dates of the 2016 closures (*SI Appendix*, Table S1). The early season spanned from the typical Dungeness crab fishing season start date (November 15 or December 1) to when the 2016 closures were lifted, and the late season encompassed the remainder of the crab year (Fig. 1 and *SI Appendix*, Table S1). Spatial variation was observed at a regional level, with fishing communities clustered into northern and central regions (Table 1 and *SI Appendix*, Fig. S1).

Quantifying Patterns of Cross-Fishery Participation. We examined three aspects of participation network topology that network theory relates to the ability of individuals and communities to respond to a perturbation (*SI Appendix*, Table S2). The first is overall connectedness, or fisheries connectivity, measured using edge density. In a fisheries context, greater connectivity suggests more flexibility in fishers' participation (18, 29) and thus a greater capacity to adapt to a perturbation without leaving the fishing industry. The second is the degree to which the network is divided into subgroups, quantified by modularity. Modularity is inversely related to sensitivity, because more modular networks tend to limit perturbations to the subgroup in which they occur (18, 30). The third is the degree to which the network is concentrated around a central fishery, represented by network centralization (31). Networks with high centralization display little sensitivity to a perturbation unless the perturbation impacts the central node. Modularity and centralization were calculated using network edge weights (*SI Appendix*, Table S2); we also calculated unweighted modularity and centralization, as well as mean degree for a size-scalable alternative to edge density, and report these results in the *SI Appendix*.

Participation networks are highly dynamic over time in both size and structure (*SI Appendix*, Figs. S2–S4), and can be influenced by a number of social and ecological factors. We used generalized linear models to attribute topological changes during the 2016 crab year to the 2016 Dungeness crab fishery closures, with network metrics as the response variables. Since the Dungeness crab fishery experienced shortened seasons prior to the 2016 crab year (*SI Appendix*, Table S3), we captured the effect of the 2016 closures using a closure duration (D) categorical predictor variable. The 2016 closures represented the highest level of closure duration. We also included network size, crab year, community, and region as predictor variables in our nested models (*SI Appendix*, Tables S4 and S5).

Results

Network-Based Expectations of Community Vulnerability. Prior to the 2016 closures, patterns of fishery participation in California varied substantially between regions (Fig. 1 and *SI Appendix*, Fig. S3). Networks for the northern region fishing communities of Crescent City, Eureka, Fort Bragg, and Bodega Bay were composed of fewer fisheries; more highly centralized around Dungeness crab; had lower size-scaled fisheries connectivity (mean degree); and exhibited less modularity than the central region fishing

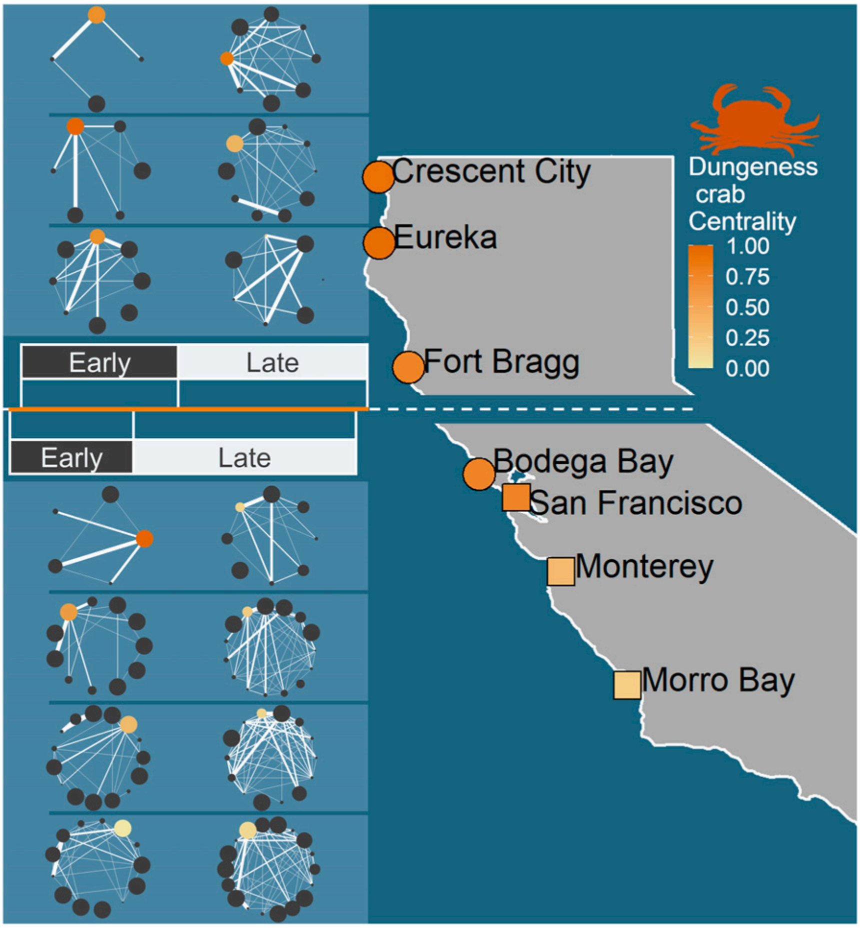

Fig. 1. The seven California fishing communities included in this study and their pre-shock fisheries participation networks. Pre-shock early (*Left*) and late (*Right*) networks represent a 3-y average (crab years 2013 to 2015) of participation prior to the 2016 fishery closures. The Dungeness crab fishery node is shaded orange in each network according to its betweenness centrality, a measure of importance (note that nodes are not consistently positioned across networks). The timeline shows the relative duration of the early and late seasons for fishing communities in the two California management districts (above/below timeline). Point color on the map indicates average Dungeness crab betweenness centrality across the early and late seasons, and point shape indicates whether the fishing community was considered part of the northern region (circle) or the central region (square) for this study.

communities of San Francisco, Monterey, and Morro Bay. These regional differences were particularly pronounced during the early season, when the majority of Dungeness crab landings occur (32, 33). In the late season, northern region networks were more complex and less centralized, lessening most topological differences between regions (*SI Appendix*, Fig. S3). Network theory predicts that fishing communities in the northern region would be more vulnerable to a perturbation in the Dungeness crab fishery due to higher sensitivity (centralization, modularity) and lower adaptive capacity (fisheries connectivity, network size), particularly during the winter months of the early season.

Northern Region Impacts during the Shock. Patterns of fishery participation during the early season were significantly more affected by the 2016 closures in the northern region than in the central region. Networks of fishing communities in the northern region saw significant declines in fisheries connectivity (edge density; −58%) and reduced concentration of participation around a single fishery (centralization; −31%) (Fig. 2*A* and *SI Appendix*, Table S6).

These network changes represent three strategies undertaken by northern region Dungeness crab vessels to cope with, or adapt to, the 2016 closures: vessel dropout, spatial mobility, and spillover into alternative fisheries. The majority of Dungeness crab fishing vessels in the northern region (56.4 ± 16.7%) discontinued all fishing in California during the 2016 closures. Early season vessel dropout was relatively consistent between large (≥40 ft) and small (<40 ft) vessels. Landing catch in a different community, representative of spatial mobility, was mostly undertaken by large vessels, particularly those that spent the previous crab year fishing in Eureka and Crescent City (Fig. 3). Dropout and spatial mobility could have decreased fisheries connectivity if vessels that stopped fishing entirely or moved to a different fishing community would normally have participated in multiple fisheries during the early season.

The observed declines in fisheries connectivity were also tied to vessels that remained active within the same fishing community. Approximately 87% and 84% of active small and large vessels, respectively, concentrated participation in a single alternative fishery and thus did not contribute to fisheries connectivity during the early season of the 2016 crab year. During the early season of the previous crab year, 61% of these vessels spread participation across multiple fisheries (Dungeness crab and others). Spillover resulting from the 2016 closures was concentrated primarily in the sablefish and mixed rockfish/lingcod fisheries (Fig. 3), although northern region Dungeness crab vessels participated in a total of 16 alternative fisheries. Because vessels that normally would have concentrated participation in the Dungeness crab fishery dispersed into different alternatives, network centralization declined.

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Central Region Impacts during the Shock. Fisheries connectivity and centralization in the central region increased by 32% and 16%, respectively, during the early season of the 2016 crab year (Fig. 2*A*). These changes were significantly different from the declines that occurred in the northern region during the closures (Fig. 2*A* and *SI Appendix*, Table S6).

Smaller changes in fisheries connectivity and centralization in the central region are consistent with network theory: lower reliance on the Dungeness crab fishery, represented by lower preshock Dungeness crab centrality (Fig. 1), translated to less sensitivity to the loss of access to Dungeness crab. Increases in fisheries connectivity within central region fishing communities coincided with an increase in the diversity of fishery participation by Dungeness crab vessels, particularly in Monterey (n =18 active vessels). While northern region Dungeness crab vessels exhibited more single-fishery participation during the early season of the 2016 crab year compared with the previous year, the proportion of active Dungeness crab vessels participating in two or more fisheries in the central region more than doubled between the 2015 and 2016 early season (from 9% to 20%).

Lower reliance on the Dungeness crab fishery also makes it possible for dynamics external to the Dungeness crab fishery to have an equal or greater effect on patterns of resource use in central region fishing communities. Dungeness crab vessels represented only 14% of all commercial fishing vessels in Monterey and Morro Bay (Table 1), and the majority of central region Dungeness crab vessels stopped fishing entirely during the early season (72.5 ± 0.1%). Therefore, even as concentrated participation in the Dungeness crab fishery was replaced with a number of alternative fisheries, decentralizing participation among Dungeness crab vessels, at a community scale these effects were relatively weak.

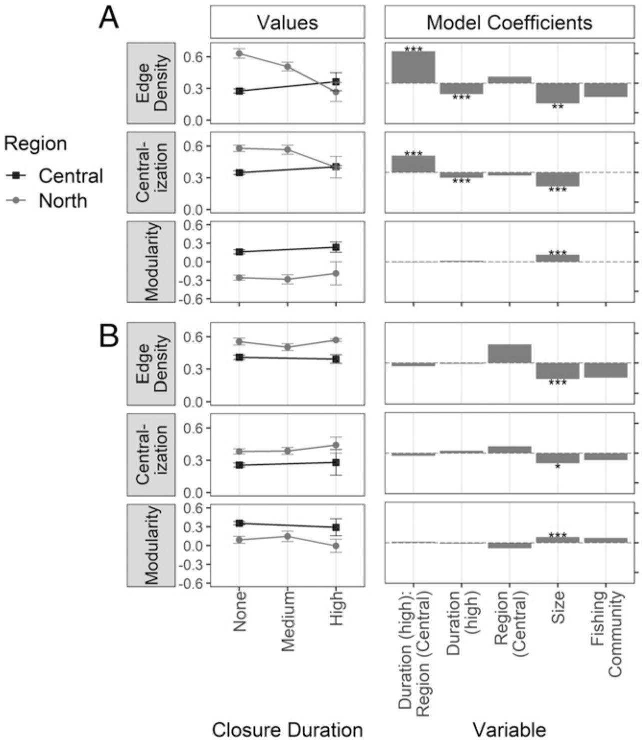

Fig. 2. Mean value and SE at each closure duration level (*Left*) and coefficients from the generalized linear models (*Right*) for each network metric in the early (*A*) and late (*B*) seasons. Coefficients for edge density and centralization are on the logit scale. The *Duration (high) : Region (central)* term describes the change to the coefficient of the *Duration (high)* term when observing central region, compared with northern region, networks. For example, the coefficient for *Duration (high) : Region (central)* in the model for early season edge density (*A*, *Top*), is positive; this indicates that observing a network from the central region compared with the northern region makes the negative association of the 2016 closures with edge density more positive. Significance is indicated above each column. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

California Impacts Immediately after the Shock. We observed minimal, nonsignificant effects of the 2016 closures on late season patterns of fishery participation (Fig. 2). None of the network metrics for either region exhibited significant change during the late season, although increases in centralization in the northern and central regions were significant when not weighted by revenue (unweighted centralization; *SI Appendix*, Table S7). Increased centralization was likely from the concentration of participation in the high-revenue Dungeness crab fishery after the closures were lifted, at a time when fishers would normally have been prioritizing a variety of other fisheries, such as Chinook salmon (*SI Appendix*, Fig. S5).

Discussion

As climate shocks become more frequent and intense under climate change, it is increasingly critical to predict, rapidly assess, and reduce the vulnerability of natural resource-based communities. For fishing communities, vulnerability to resource loss can be closely tied to access to alternative fisheries, an important source of adaptive capacity (13, 15). In this study, we found significant changes in patterns of fishery participation in response to fishery closures, forced by a heatwave-associated HAB. Greater changes in northern California fishing communities corresponded with greater sensitivity (increased specialization or network centralization), less adaptive capacity (lower fisheries connectivity and smaller network size), and heightened exposure (longer duration fishery closures). Patterns of fishery participation mostly returned to their predisturbance state following the opening of the Dungeness crab fishery, indicating community-level resilience to this singular perturbation. This study quantified the impact of a climate shock and subsequent management measures on natural resource use in fishing communities, and revealed the underlying behavior of fishing vessels.

A challenge in predicting community response to anthropogenic and environmental perturbations lies in quantifying community sensitivity and adaptive capacity (7). Network metrics help us do this, serving as indicators of system sensitivity (centralization, modularity) and adaptive capacity (network size, connectivity) in the face of perturbations (18, 34, 35). We can therefore interpret our results through the lens of network theory and the vulnerability framework (7) to provide a forward-looking glimpse into an alternative state under climate change, in which more frequent marine heatwaves and HABs (36, 37) cause the loss of key resources for California fishing communities. On the one hand, minimal spillover and topological changes to fisheries participation networks following the 2016 closures suggest that patterns of fishery participation in California were resilient to this climate shock. However, if Dungeness crab vessel owners and operators were to permanently adopt the alternative fishing strategies observed during the 2016 closures, then our results imply that the northern fishing communities could become more vulnerable to secondary social and ecological perturbations. Even as participation becomes more evenly spread across existing fisheries, the sharp decline of fisheries connectivity (captured here with edge density) predicts a lower capacity for individuals to switch between fisheries. For the central region fishing communities, a more diverse portfolio of early season fishery participation could buffer the impacts of future perturbations if diversification were adopted as a long-term adaptive strategy (as was done by Pacífico Norte fishers; ref. 38); however, it is important to note that the lower reliance on Dungeness crab

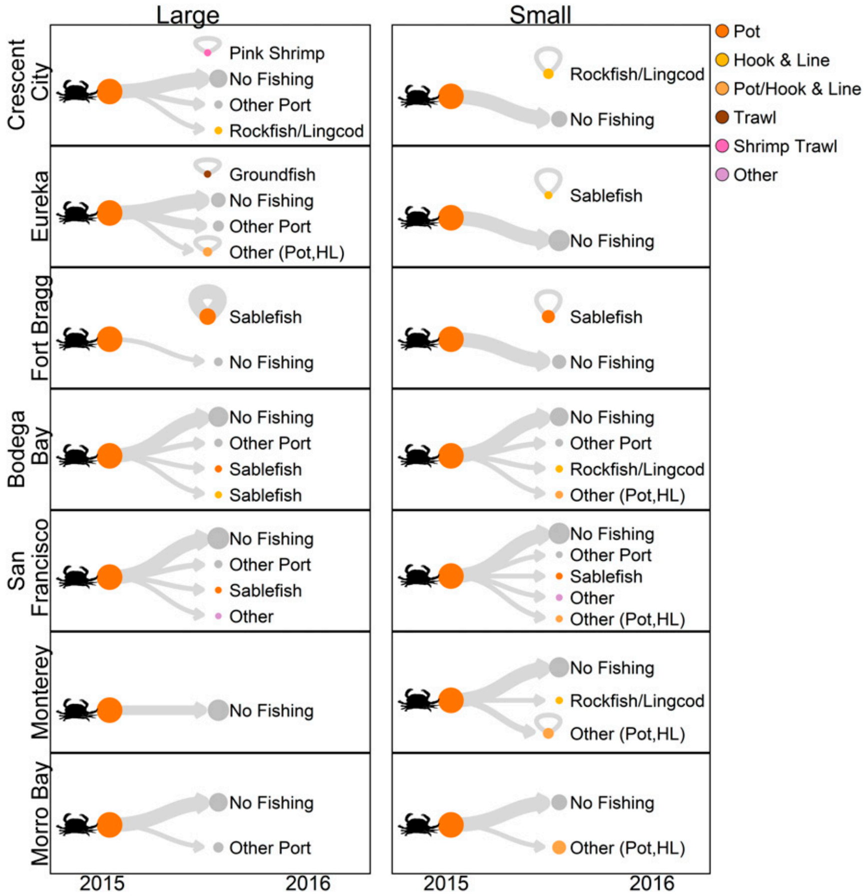

Fig. 3. Changes in early season fishery participation by large (*Left*) and small (*Right*) Dungeness crab vessels from the 2015 to the 2016 crab year. Edges show the flow of vessels out of the 2015 Dungeness crab fishery (left of each network graph, labeled with crab icon) into 2016 alternatives (right of each network graph). Self-loops were included if Dungeness crab vessels participated in a non-Dungeness fishery during both crab years; otherwise, the directed edge represents new early season participation in the 2016 alternative. Edge-weight is proportional to the number of Dungeness crab vessels that undertook the indicated shift in participation. Node size is proportional to the number of Dungeness crab vessels participating in each fishery during the associated crab year (*x*-axis). When multiple fisheries using pot or hook-and-line gear had fewer than three participating vessels, we collapsed the fisheries into a single "Other (Pot, HL)" node; the "Other" node is a similar aggregate but with fisheries using any gear type. We added two nonfishery nodes to indicate whether a vessel stopped fishing altogether during the 2016 Dungeness crab closures ("No Fishing") or stopped fishing at the given fishing community but was recorded landing catch at another California port ("Other Port").

in the central region is also a key factor in maintaining low community vulnerability to secondary perturbations. The ability to reallocate fishing effort conferred by diverse harvest portfolios reduces variation in annual fishing revenue (15) and is critical for individual adaptation not only to climate shocks, but also to fishery management changes (e.g., catch share programs ; refs. 20 and 21). More generally, diversification is a fundamental tenet of resilience theory for social–ecological systems, which emphasize strategies that integrate over variability, shocks, and reorganization to sustain species, economies, and livelihoods (39).

There can be many counterincentives to diversification, however, especially when common species are highly valuable (16) or when there are high barriers to access for certain resources (e.g., permitting structures, capital, knowledge; ref 14). In fisheries, concentration of effort into a single, highly lucrative fishery can result in a "gilded trap" (16, 40). Most notably observed in the Maine American lobster industry, this type of social trap is formed as social drivers increase the value of the resource, even as the resource itself moves closer to an ecological tipping point (16). Our research and community interviews (41) suggest that Dungeness crab might be considered a gilded trap for northern California fishing communities and associated coastal communities. While economically lucrative for fishers and fishing-related industries in the short term, a focus of effort on Dungeness crab increases vulnerability to climate shocks during the winter months when there is little existing activity in other fisheries. The Dungeness crab fishery is presently at risk not only from seafood safety concerns, but also from the bycatch of protected species (42) and the effects of ocean acidification on early life history stages (43). Escape from social traps in resource-based economies requires incentives and policies that address the underlying socioeconomic conditions and behavior reinforcing the trap. This can be a complex undertaking that requires careful investment in institutional capacity at multiple scales (44, 45).

These community patterns summarized in fisheries participation networks emerge from decisions made by individuals, which in turn are influenced by community-scale properties. The vessel activity that we describe highlights how the impacts of climate shocks are likely to be felt unequally within fishing communities, in California and beyond (27, 46). Differences in adaptive capacity during the 2016 closures were related to vessel size, with larger vessels conferring a greater ability to move out of closed areas to fish; we observed a greater proportion of large vessels than small vessels moving between fishing communities, particularly during the longer closures in the northern region. Our

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findings agree with those of Jardine et al. (27), who used a 3-y baseline of Dungeness crab landings at the same California fishing communities to show that large Dungeness crab vessels were more mobile than small vessels in the 2016 crab year. Fishers with smaller vessels instead relied on alternative fisheries to remain active in-place. This discrepancy arose despite state management measures that seek to restrict mobility during fishery closures, requiring vessels landing Dungeness crab outside a delayed district to wait 30 d before fishing within the delayed district (California Fish and Game Code § 8279.1). Recent amendments (47), motivated in part by vessel movement during the 2016 crab year, may limit the feasibility of spatial redistribution as a strategy to cope with future climate shocks.

Yet, moving to a location where social and ecological conditions are more favorable may be more effective than reliance on strategies to remain active in-place, such as shifting effort to alternative fisheries. Keeping pace with shifting species ranges and abundance under climate change often requires resource users to modify the spatial distribution and intensity of their efforts (48, 49). In addition, the adoption of limited entry and catch share programs may make it increasingly difficult to remain active in-place by accessing alternative fisheries. For example, on the US West Coast, the 2012 Pacific groundfish trawl rationalization and 2002 Pacific sablefish permit stacking programs restricted access to certain groundfish and sablefish fisheries. This led to historically active vessels exiting the affected fisheries (50) and higher costs to new participants (51). A comprehensive comparison of climate adaptation through in-place strategies as opposed to movement must also account for access to diverse employment opportunities beyond fishing (often captured by education and economy size; refs. 52 and 53). Extending participation networks to include nonfisheries job participation (i.e., "livelihood landscapes;" ref. 31) provides this more holistic view of in-place adaptive capacity and may capture co-occurring effects of climate shocks across food systems (5). Livelihood landscapes also focus on individuals or households and so can speak to the heterogeneity in capacity and agency among fishers, something not captured with vessel-level data.

While some individuals move or modify behavior in response to climate shocks, others are unable to access viable alternatives and must simply absorb the impact and rebuild. This "duck-and-cover" strategy is particularly common in fishing and agrarian communities following major storms (54, 55). In the California Dungeness crab fishery, a surprisingly high proportion of large and small Dungeness crab vessels adopted this duck-and-cover strategy and ceased all fishing activity during the 2016 closures. Most vessels waited out the closures in port (26, 41), despite later evidence that alternative fishing activities contributed significantly to fishers' income loss recovery (56). The prevalence of this strategy, and adaptive actions more broadly, may be best understood as the outcome of nested decision making processes at both individual and institutional levels (57). On the US West Coast, HAB monitoring and associated fishery closures are implemented by state and tribal governments; as a result, the structure and effectiveness of early warning systems and communication with stakeholders varies by region (58). California fishers have requested more reliable and clear communication by scientific and regulating institutions during future HAB events to facilitate more effective decision making (41). Communication and prediction are both important for climate shock preparedness and, more generally, in "climate-ready" fisheries management (59).

Another key consideration for developing climate-ready fisheries management is how to facilitate fishing effort spillover in such a way as to increase adaptive capacity and achieve a net decline in vulnerability. Fishers are creative problem solvers with a long history of adapting to challenging conditions (29), but they must also be supported by governance systems. This will require coordination and partnership between governing institutions; in our study system, the Dungeness crab fishery is managed at the state level, but alternatives during the 2016 closures consisted of both state- and federally-managed fisheries. Also needed is careful consideration of unintended outcomes that may arise from improving mobility between fisheries, such as increased or novel interactions with protected species (42) and other ocean use sectors, the potential for overcapitalization of remaining open access fisheries, and incentivization of a "roving bandit" strategy of sequential overharvesting across a participation network (60). When designing governance measures to temporarily facilitate spillover during a climate shock, combining networks of economic and ecological connectivity among fisheries, and considering networks that represent different types of fishery participants, could help to assess direct and indirect social and ecological impacts (19).

Our findings suggest that management approaches that account for connectivity and spillover between fisheries during a climate shock are more likely to anticipate, and potentially mediate, impacts on fishing communities. The impacts of climate shocks are a materialization of underlying risk and vulnerability (61) in fisheries and other components of food systems. Quantifying connectivity between alternative resources can capture these impacts and uncover sources of sensitivity and adaptive capacity in highly dynamic, resource-based communities—a critical step toward achieving sustainability in the face of climate shocks and long-term change.

Materials and Methods

Data. Fisheries landings and vessel registration data for the 2008 to 2017 crab years were retrieved from the Pacific Fisheries Information Network (PacFIN; http://pacfin.psmfc.org) database. Landings data were filtered to include commercial landings from 30 California ports of landing, or seven port groups, where Dungeness crab is an important source of revenue (Fig. 1 and Table 1). Since we expected to find length-based differences in adaptive capacity (27), we used registration data to calculate vessel length in feet (*SI Appendix*) and classified vessels ≥40 feet long as large vessels and those <40 feet long as small vessels (13).

Defining Fisheries and Fishing Communities. We defined fisheries by grouping PacFIN fish tickets based on gear type, species composition of catch, and ex-vessel revenue using a métier analysis (62) modified from Fuller et al. (18). In short, we ran the infoMap community detection algorithm (63) implemented in the R package igraph (64) on data from fish tickets collected during the 2011 and 2012 crab years (chosen because they occurred in the middle of our pre-shock study period). The remaining fish ticket data were matched to the infoMap-processed fish tickets using a *k*-nearest-neighbor (KNN) approach. Fish tickets that failed to be assigned métiers with KNN (i.e., those that recorded unique species/gear combinations) were compiled across crab years and rerun through the infoMap algorithm. Fish tickets are linked to vessels, which formed the foundation of our participation analyses. Thus our definition of a fishing community was a set of vessels that land their catch at a given shore-based port group. We used vessels as proxies for fishers owing to the limitations of available data (18, 50), not because of the notion that a collection of vessels better characterizes a community than a group of people. Although this was an imperfect approximation, it did allow us to track changes in harvesting practices through time, across vessel sizes and geographic regions.

Constructing Networks. Participation networks summarized cross-fishery participation for all vessels in a fishing community. If a single fishing vessel recorded catch in multiple fishing communities within a single crab year, it was considered a member of each fishing community. We used the network framework of Fuller et al. (18), in which the weight of a nondirectional edge between fisheries *i* and *j* represents a measure of fisheries connectivity that is proportional to the number of vessels participating in both fisheries and the evenness with which each vessel generates revenue from fishery *i* v. fishery *j*. We constructed directed networks to observe changes in fishery participation by Dungeness crab vessels in each fishing community. A "Dungeness crab vessel" was defined as any fishing vessel that recorded at least one commercial Dungeness crab landing in California in the 2015 crab year (n = 477 unique vessels).

Generalized Linear Models. We evaluated a series of nested models (*SI Appendix*, Table S4) and chose the most informative model using an F-test. Participation network size varies through time and across fishing communities, and certain network metrics, such as edge density and centralization, are known to be dependent on network size. To distinguish between a meaningful signal of change and variability related to network size, we conservatively included network size (N) as a predictor variable based on results from a Spearman rank correlation test (65) between each metric and the number of nodes in the network (*SI Appendix*, Table S5). Standardized residuals and Q-Q plots were used to assess normality, linearity, and homoscedasticity assumptions, and the model was tested for sensitivity to outliers detected with Cook's distance.

Data Availability. Confidential vessel-level landings and registration data may be acquired by direct request from the California Department of Fish and Wildlife, subject to a nondisclosure agreement. Aggregated, nonconfidential data to construct network graphs, network metrics data used as input for the generalized linear models, and R code are available on GitHub (DOI: 10.5281/zenodo.4177949).

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