Defining the economic scope for ecosystem-based fishery management

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The emergence of ecosystem-based fisheries management (EBFM) has broadened the policy scope of fisheries management by accounting for the biological and ecological connectivity of fisheries. Less attention, however, has been given to the economic connectivity of fisheries. If fishers consider multiple fisheries when deciding where, when, and how much to fish, then management changes in one fishery can generate spillover impacts in other fisheries. Catch-share programs are a popular fisheries management framework that may be particularly prone to generating spillovers given that they typically change fishers' incentives and their subsequent actions. We use data from Alaska fisheries to examine spillovers from each of the main catch-share programs in Alaska. We evaluate changes in participation—a traditional indicator in fisheries economics—in both the catch-share and non–catch-share fisheries. Using network analysis, we also investigate whether catch-share programs change the economic connectivity of fisheries, which can have implications for the socioeconomic resilience and robustness of the ecosystem, and empirically identify the set of fisheries impacted by each Alaska catch-share program. We find that cross-fishery participation spillovers and changes in economic connectivity coincide with some, but not all, catch-share programs. Our findings suggest that economic connectivity and the potential for cross-fishery spillovers deserve serious consideration, especially when designing and evaluating EBFM policies.

networks | ecosystem-based fisheries management | catch shares | spillovers | leakage

Ecosystem-based fisheries management (EBFM) has revolutionized the way we think about and manage ocean resources (1). A key characteristic of EBFM is broadening the scope of policy evaluation and design beyond the typical single-fishery focus—a need that has been recognized and for which methods and models have been advanced on the ecological side (2). However, just as fisheries within an ecosystem can be ecologically connected [e.g., through complex food-web interactions (3, 4)], they can also be economically connected if fishers participate in multiple fisheries (5–7).

If fishers consider more than one fishery when deciding where, when, and how much to fish, there is potential for economic and, in turn, ecological outcomes in multiple fisheries to be jointly determined. More generally, mismatches between the scope of fisheries policy and the scope of policy impacts have led to calls for integrated social–ecological system models that account for system linkages between the resource units and between the resource and socioeconomic characteristics (8). Despite these calls, little work has been done to integrate socioeconomic motivations and outcomes and operationalize models that include socioeconomic factors into EBFM frameworks (9).

Economic connectivity of fisheries is particularly relevant if fishers react to a policy change in one fishery (henceforth, the target fishery) by changing their effort allocation in other fisheries. In this context, "leakage" or "spillover" of policy impacts into nontarget fisheries is said to occur. Fishers may adjust effort along the extensive margin—e.g., which fisheries to participate in, if any—and/or the intensive margin—e.g., how much effort to allocate to each of the fisheries they participate in (Fig. 1). Leakage has the potential to generate both negative and positive impacts. For example, negative impacts can include a loss in economic efficiency and increased pressure on species in fisheries that effort moves into (7, 10). However, leakage can also generate positive impacts as it can be a means through which fishers maintain a diverse portfolio of fishing effort, which has been shown to help fishers and fishing communities mitigate risk and smooth incomes (11–14).

Understanding and evaluating leakage across economically connected fisheries is essential to accurately estimate the full impact of a policy change in a manner consistent with best-practice impact evaluation (15). Specifically, failing to account for leakage can result in inaccurate predictions of postmanagement changes (5), evaluations that do not capture changes in all impacted entities, and biased estimates of impact in the target fishery if other fisheries are used as controls (16). Nevertheless, most economic modeling and evaluation of fisheries policy are single-fishery focused.

Several recent studies have investigated cross-fishery spillovers from a theoretical (17) and/or empirical (6, 7, 10, 18–21) perspective; however, these studies investigate leakage using a limited, predetermined set of fisheries in which leakage can occur. In practice, fisheries compose a complex and connected system, and the scope of leakage is not immediately clear. To our knowledge, the scope of leakage from a single-fishery policy has yet to be

Significance

Ecosystem-based fisheries management provides a framework for incorporating ecological linkages between fisheries into policymaking. However, relatively little attention has been given to economic linkages between fisheries: If fishers consider multiple fisheries when deciding where, when, and how much to fish, there is potential for management decisions in one fishery to generate spillover impacts in other fisheries. We evaluate changes in participation and economic connectivity of fisheries following the implementation of Alaska's catch-share programs. Catch shares are increasingly used worldwide and typically implemented and evaluated on a single-fishery basis. We provide evidence that changes beyond the catch-share fishery have occurred, suggesting that spillovers should be considered when designing and evaluating catch-share policies.

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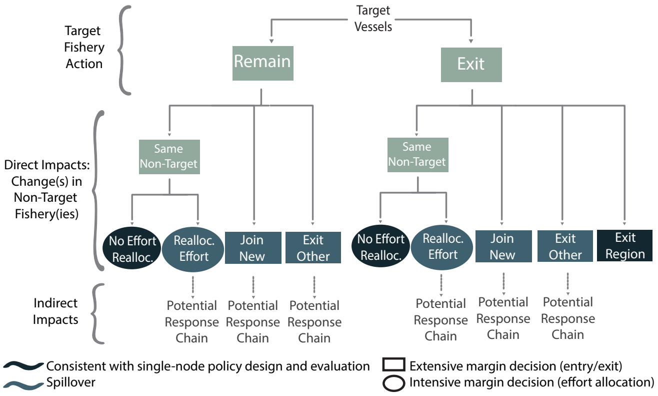

Fig. 1. Typology of responses to management change. Vessels exiting or remaining in the target fishery after the policy change may adjust their participation in other fisheries (direct impacts). These actions can lead to a subsequent chain of spillover, or indirect, impacts in nontarget fisheries and/or the network at large. Outcomes consistent with single-node policy design and evaluation are shown in black; outcomes consistent with spillover are shown in dark teal.

empirically estimated. Further, no studies to date have explored the extent to which a change in one fishery has changed the economic connectivity of other fisheries, which can have implications for the socioeconomic resilience and robustness of the ecosystem (22, 23).

Although there are many types of policy changes that could generate spillover, we examine spillovers following the implementation of catch-share programs—which allocate individual shares of a species' total allowable catch to fishers—to understand whether a single-fishery policy analysis is too narrow to capture the full scope of policy impacts. We explore spillovers in response to catch shares for three primary reasons. First, catch-share programs are increasingly used worldwide and therefore an important policy to explore from a management perspective (24). Second, catch shares are typically implemented and evaluated on a single-fishery basis—in direct contrast to EBFM's ecosystem scale. Finally, many catch-share programs have an objective to address excess participation (or overcapacity) in the catch-share fishery (25, 26), which raises the question, Where does the excess participation go?

Several studies have examined the margins of change associated with catch shares (27–31), including the effects of limits on quota transferability within catch-share programs, which are often implemented to meet social objectives (32); however, with few exceptions (7, 21), these studies focus only on the fishery (or fisheries) in which catch shares were implemented and generally do not consider the potential implications of leakage. In contrast, we estimate the scope of leakage (i.e., the set of impacted fisheries), changes in participation beyond the catch-share fishery, and changes in economic connectivity that coincide with catch-share implementation. To explore changes in economic connectivity between fisheries we use network analysis, which has been used in a variety of fisheries-related applications to understand system connectivity and complexity (22, 33–35).

We evaluate leakage coinciding with the six major Alaska catch-share programs (totaling 46–67% of annual catch volume), using commercial fishing landings data for all catcher vessels (about 6,000–8,000/y) that participated in 104 Alaska fisheries between 1991 and 2015 (see *SI Appendix* for more details). The catch-share programs vary in terms of their objectives, program design (e.g., transferability of quota and limits on harvest activities in other fisheries), and fishery characteristics (26, 36). A subset of vessels is active in multiple fisheries each year, the total generally decreasing over time from 4,063 in 1991 to 1,350 in 2015. Vessels also exit and enter new fisheries each year, the total generally decreasing over time and ranging from 173 to 869. We identify significant changes in non–catch-share fishery participation and network connectivity that coincide with some, but not all, catch-share programs, suggesting that economic connectivity and the potential for leakage deserve serious consideration when designing and evaluating EBFM policies.

Measuring Economic Connectivity and Leakage

We use networks to represent the aggregate behavior of individual fishers and the economic connectivity of the Alaska fishery system. We measure both fishery-level outcomes and—analogous to the literature on ecological connections between species in the EBFM literature (4)—the economic connectivity of the entire fishery system. We generate two types of networks for each year in our sample: (*i*) a network of cross-fishery participation and (*ii*) a network of year-to-year migration of fishing effort between fisheries (*SI Appendix*, Figs. S4–S7). In each network, nodes represent fisheries. Each edge in the participation network represents the number of vessels active in each of the two connected fisheries. Each edge in the migration network represents the number of vessels exiting the edge-origin node and entering the edge-destination node.

To measure leakage associated with catch-share programs, it is necessary to link fisher actions to changes in network attributes. Fishers can take several actions in response to a policy change, which may or may not be consistent with a single-fishery policy scope. The suite of actions related to participation, entry, and exit (Fig. 1 and Table 1) is applicable to both fishers in the target fishery and fishers in the nontarget fisheries that experience leakage directly from the target fishery, thereby creating a potential chain reaction of indirect leakage throughout the

Table 1. Fisher actions, network attributes, and network metrics

Actions		Participation		Cross-fishery participation (*iii*): weighted degree/ centrality	Migration (*iv*): weighted out-degree/centrality	Leakage?
Target fishery	Other fisheries	Target (*i*) node size	Nontarget (*ii*) node size			
Exit	N/A	—	0	0	0	No
Exit	Exit	—	—	—	0	Yes
Exit	Enter	—	+	—/+	+	Yes
Exit	No change	—	0	—	0	Yes
Remain	Exit	0	—	—	0	Yes
Remain	Enter	0	+	+	0	Yes
Remain	No change	0	0	0	0	No

Symbols are used to represent whether, all else being equal, a change in the network metric will occur given the fisher action ("0" is used to represent no change) and, if a change will occur, whether the metric will increase (+) or decrease (—). N/A refers to the case where a fisher participates only in the target fishery before the policy change and makes no adjustments that involve other fisheries postpolicy change.

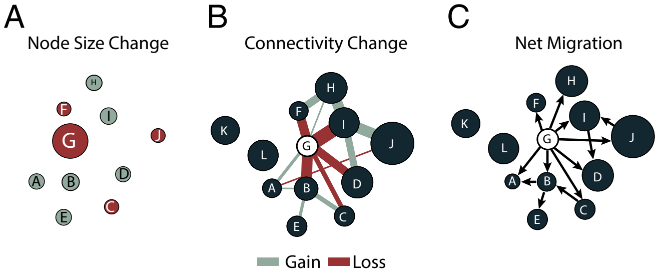

Fig. 2. Policy impacts on networks. (*A*–*C*) Three ways in which leakage from a single-fishery policy (in fishery G) may manifest on networks.

network. We focus on four types of network attributes that can experience change (Fig. 2): (*i*) participation in the target fishery (Fig. 2*A*), (*ii*) participation in the nontarget fisheries (Fig. 2*A*), (*iii*) cross-fishery participation (Fig. 2*B*), and (*iv*) migration of participants between fisheries (Fig. 2*C*). All else being equal, fisher actions that result in network changes of type i but not types $ii-iv$ do not change nontarget fishery participation or the economic connectivity between fisheries and are therefore consistent with a single-fishery policy scope. Not all changes may take place, however, and only one of these changes ($ii-iv$) is required for leakage to occur.

Network attributes can be measured via network metrics, which we also link to fisher actions (Table 1). Node-level metrics characterize a fishery's direct and indirect connectivity to other fisheries in the network. Weighted degree is a measure of a node's strength or direct connectivity to other fisheries and is calculated as the sum of all edge weights connected to a node. In the cross-fishery participation network, a fishery's weighted degree measures the extent to which fishers also participate in other fisheries. In the migration network, a fishery's weighted degree (hereafter called weighted out-degree for clarity) measures the extent that fishers exit and enter other fisheries. Weighted degree and out-degree can change with catch shares reflecting a change in direct connectivity, through cross-fishery participation or migration of participants, of the catch-share fishery to other fisheries. Weighted closeness centrality is a measure of a node's strength and position in the network and is based on a fishery's average distance—i.e., the shortest path—to all other fisheries. Closeness centrality measures the extent to which a fishery is both directly and indirectly connected to other fisheries. In the participation network, a fishery with high centrality is relatively important to the ability of fishers to distribute effort across fisheries (22). In the migration network, out-centrality identifies fisheries that play an important role in facilitating the flow of exit and entry across fisheries (in Fig. 2, G has a high out-centrality and is the origin of much of the entry and exit observed in the network). An increase in a fishery's centrality with the onset of a catch-share program indicates that catch shares have heightened a fishery's role in the cross-fishery participation and/or migration patterns of fishers.

Results

We test for structural breaks that coincide with catch-share implementation in the participation and economic connectivity (weighted degree, weighted out-degree, weighted centrality, and weighted out-centrality) time series for the target fisheries of the six major Alaska catch-share programs. Changes in both the cross-fishery participation and migration networks coinciding with some catch shares are also visually evident (Fig. 3).

We find evidence of a decrease in catch-share fishery participation, with four of the six fisheries exhibiting a significant reduction in the rate of change in participation following program implementation, ranging from 37 percentage points (halibut) to 99 [Bristol Bay king crab (BBKC)] percentage points (Table 2). While the reduction in the American Fisheries Act (AFA) pollock fishery is statistically significant, the estimated effect is small compared with estimated placebo effects generated by reassigning the catch-share implementation year, suggesting that the estimated effect may not stem from catch-share implementation. The rockfish fishery is the lone fishery that experienced an increase in participation with catch shares, although the change is small in absolute terms.

Under the null hypothesis that catch shares generate only changes consistent with a single-fishery policy scope, implementation should have no independent influence on the economic

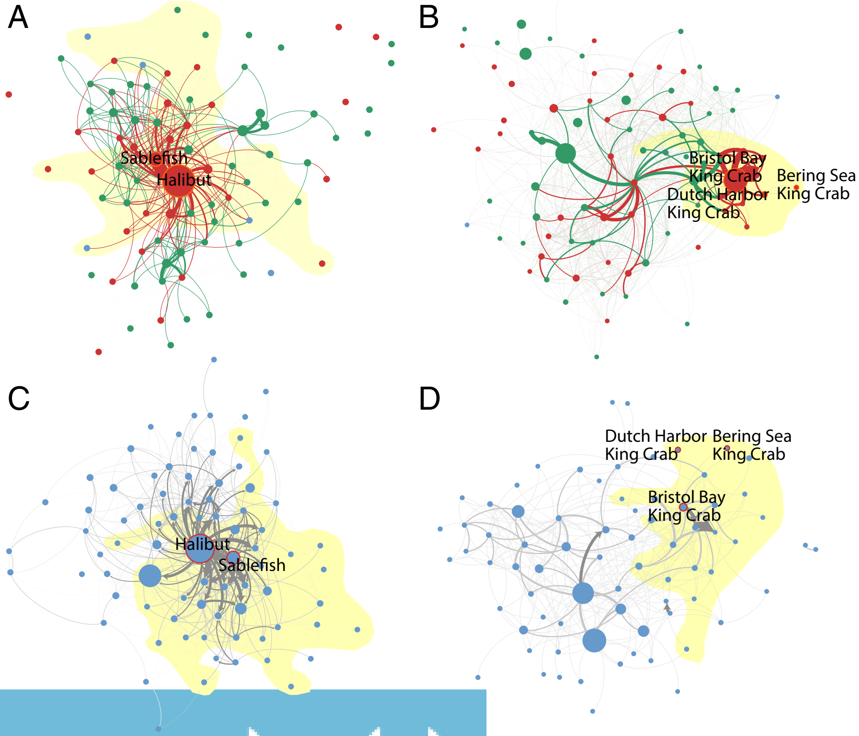

Fig. 3. (*A*–*D*) Changes in cross-fishery participation (*A* and *B*) and migration (*C* and *D*) networks: halibut/sablefish (1994–1995, *A* and *C*) and Bristol Bay king crab (2004–2005, *B* and *D*) catch-share programs. For both networks, yellow shading represents the scope of leakage and catch-share fisheries are circled in orange. Networks for the remaining catch shares are in *SI Appendix*. In the cross-participation network (*A* and *B*), node size represents the change in number of active vessels in the fishery between the 2 y (red, loss; green, gain; blue, no change); edge thickness corresponds to the change in the number of active vessels participating in each of the connected fisheries. In the net migration network (*C* and *D*), node size represents the number of active vessels in the fisheries the year before catch-share implementation. Edge thickness (or weight) corresponds to the net number of vessels migrating from one fishery to another. The arrows are drawn to represent vessels exiting the fishery at the arrow origin and becoming active in the fishery at the arrow destination. When no arrows are visible, the flow is clockwise from origin to destination.

Table 2. Structural break test results for catch-share fisheries

		Catch-share fishery, year implemented					
Network	Network metric	Halibut IFQ, 1995	Sablefish IFQ, 1995	AFA pollock, 2000†	BB king crab IFQ, 2005	BS snow crab IFQ, 2006	Rockfish coops, 2007
	Node size	−0.37*** (0.00)	−0.38*** (0.00)	−0.10*** (0.17)	−0.99*** (0.00)	−0.65*** (0.00)	0.11*** (0.16)
Cross-fishery	Weighted degree	−0.34*** (0.00)	−0.35*** (0.00)	−0.33*** (0.00)	−1.03*** (0.00)	−0.12* (0.58)	0.060 (0.53)
Cross-fishery	Weighted centrality	0.031 (0.71)	0.027 (0.71)	0.21*** (0.13)	−0.17*** (0.32)	−0.19*** (0.25)	0.13* (0.26)
Migration	Weighted out-degree	1.06*** (0.00)	0.84*** (0.00)	0.040 (0.88)	1.42*** (0.16)	1.09*** (0.08)	−2.44*** (0.11)
Migration	Weighted out-centrality	0.67*** (0.00)	0.53*** (0.00)	0.27 (0.54)	0.69 (0.58)	0.30*** (0.33)	−0.55** (0.53)

P values from placebo tests are in parentheses.

*$P < 0.10$; **$P < 0.05$; ***$P < 0.01$. BB, Bristol Bay; BS, Bering Sea; IFQ, individual fishing quota.

† The program implementation date was 1999, but applied to catcher vessels in 2000.

connectivity measures. Thus, rejecting the null hypothesis of no structural break for any of these metrics implies that leakage coincides with catch-share programs. Time series from the cross-fishery participation network suggest that catch-share implementation did result in leakage: The null hypothesis of no structural break in weighted degree is consistently rejected for three of the fisheries that experienced a reduction in participation (Table 2). Decreases in weighted degree indicate that the primary source of leakage is from fishers leaving the target and/or other fisheries, as opposed to remaining in the target fishery and joining new fisheries. While the reduction in weighted degree for the Bering Sea snow crab (BSSC) fishery is statistically significant, the estimated effect is small compared with the estimated placebo effects, suggesting that the estimated effect may not stem from the catch share. It is worth noting, however, that the BSSC fishery experienced a large decrease in weighted degree the year before catch-share implementation, which is likely due to (*i*) catch shares being implemented in the BBKC fishery the year before, which coincided with a large decrease in BBKC participation, and (*ii*) many of the fishers that exited the BBKC fishery also having participated in the BSSC fishery. Although changes in direct connectivity of some fisheries are evidenced by changes in weighted degree, placebo tests suggest that the relative positioning of the catch-share fisheries, as measured by centrality, does not experience significant change.

The existence of leakage is further supported by the migration network (Table 2). Three of the six catch-share fisheries exhibit a significant increase in weighted out-degree after catch-share implementation, ranging from 84% (sablefish) to 109% (BSSC), suggesting that catch shares induced fishers to exit the target fisheries and enter new fisheries. There is also evidence of changes in migration patterns, specifically the position of the catch-share fishery in the network of migration, as measured by the weighted out-centrality. The sign and significance of the out-centrality coefficients suggest that the halibut and sablefish fisheries exhibit increasing centrality, reflecting an increasing role facilitating the flow of exit and entry across fisheries after catch-share implementation.

To estimate the scope of leakage and further investigate changes in participation and economic connectivity throughout the network, we use a cluster-detection algorithm (37) to statistically partition the network into clusters of fisheries that exhibit high levels of connectivity within the cluster, but relatively low connectivity outside it. We identify separate clusters for each network and for each catch-share year. The cluster of fisheries that contains the catch-share fishery represents the scope of leakage (Fig. 3). The halibut and sablefish catch-share fisheries are contained in the same cluster and have the largest scope of leakage relative to the other catch-share programs—34 or 67 fisheries, depending on the network. Moreover, both the halibut and sablefish fisheries are central to the cluster, suggesting that these two fisheries are the origin of the network change (38). The BBKC and BSSC fisheries have smaller scopes of leakage (ranging from 13 to 19 fisheries) and are also central to their own respective clusters. The AFA pollock and rockfish fisheries are in relatively small clusters (the rockfish fishery was the only fishery in its cluster for the migration network) and neither one is central to its own cluster, suggesting that changes in the cluster should not be attributed to catch-share implementation in these fisheries.

To estimate the scale of leakage that occurred in the cluster, we test for a structural break in the network metrics for the fisheries contained in the cluster (Table 3). Coinciding with the drop in participation in the halibut, sablefish, and BBKC fisheries, we observe a significant increase in total participation in other fisheries within their respective clusters. There is less evidence of a change in connectivity of other fisheries in the cluster in the cross-fishery participation network, with the exception of a decrease in connectivity of fisheries within the BBSC catch-share program cluster. Several catch-share programs significantly influenced the scale of migration of vessels throughout the clusters: On average, weighted out-degree in other fisheries increased by 50% and 59% with catch-share implementation in the BBKC and halibut/sablefish clusters, respectively. Moreover, significant increases in out-centrality corresponding to the halibut/sablefish and BBSC catch-share programs indicate an increase in migration throughout the network.

Discussion

We demonstrate that fishery policies have the potential to have spillover impacts beyond the target fishery; thus, the economic connectivity of fisheries is important to consider when designing and evaluating fishery management policy. Moreover, spillover impacts are likely to be heterogeneous, and therefore the economic, ecological, and institutional specifics of the network must be taken into consideration to avoid unintended consequences. Indeed, our analysis of Alaska fisheries networks shows that changes to economic connectivity and migration patterns coincide with the implementation of some, but not all, catch-share programs. Further, the scope of leakage and the degree to which other fisheries exhibit changes in economic connectivity differ across catch-share programs. The halibut and sablefish catch-share programs exhibit the largest scope and scale of leakage, followed by the BBKC and BSSC fisheries; in contrast, the AFA pollock and rockfish catch-share programs did not

Table 3. Structural break test results for catch-share cluster fisheries

		Catch-share fishery				
Network	Network metric	Halibut/ sablefish IFQ	AFA pollock	BB king crab IFQ	BS snow crab IFQ	Rockfish coops
Migration	Cluster participation	0.080*** (0.04)	0.023 (0.71)	0.12*** (0.06)	−0.09*** (0.21)	—
Cross-fishery	Weighted degree	−0.22** (0.21)	0.19 (0.42)	0.12 (0.32)	−0.42* (0.12)	−0.31 (0.16)
Cross-fishery	Weighted centrality	−0.10** (0.46)	0.26** (0.13)	0.01 (0.90)	−0.31*** (0.04)	−0.00 (0.84)
Migration	Weighted out-degree	0.59*** (0.04)	−0.10 (0.67)	0.50** (0.05)	0.44 (0.29)	—
Migration	Weighted out-centrality	0.29*** (0.04)	0.082 (0.54)	−0.25 (0.16)	0.43*** (0.04)	—

The rockfish fishery is the only fishery in the migration network cluster, and therefore no hypothesis testing is conducted. *P* values from placebo tests are in parentheses. $^*P < 0.10$; $^{**}P < 0.05$; $^{***}P < 0.01$. IFQ, individual fishing quota.

generate much (if any) leakage. Moreover, estimates for the rockfish program also tended to be opposite to those for other fisheries.

There are several potential explanations for the heterogeneous effects across catch-share programs, as leakage from a single-fishery policy will generally depend on socioeconomic, biological, and institutional factors. For instance, the degree to which fishers are able and willing to substitute between fisheries in response to a policy shock could depend on the type of gear used, the fishing area, and the species harvested in other fisheries. Previous work has shown that fishers in Alaska are more likely to jointly permit in fisheries that share the same area and gear (35); thus, policies implemented in fisheries that do not share gear type and fishing areas with many other fisheries are not likely to generate much leakage. This is true of the rockfish and AFA pollock fisheries, both of which harvest with trawl gear in the Bering Sea and Western/Central Gulf of Alaska, respectively, where there are relatively few other fisheries that use the same gear. In contrast, the halibut and sablefish fisheries use long-line gear and are primarily prosecuted in the Central/Eastern Gulf of Alaska, where there are several other fisheries that share the same gear. Indeed, the halibut and sablefish fisheries were relatively more connected to other fisheries than the AFA pollock and rockfish fisheries before catch-share implementation, suggesting a preexisting difference in substitution possibilities between the two sets of fisheries. Fishers' ability to substitute between fisheries will also depend on the nature of the catch-share program, as well as the regulatory environment of other fisheries. For example, quota transferability restrictions—which exist to varying degrees in all Alaska catch-share programs—and/or limited entry regulations in other fisheries may act as barriers that impede policy spillovers from the target fishery. Similarly, sideboard limits—which limit the ability of catch-share participants to participate in other fisheries—also restrict catch-share leakage from occurring. In fact, the four catch-share programs with the least amount of leakage (i.e., BBKC, BSSC, AFA pollock, and rockfish) had some form of sideboard limits introduced alongside catch shares, suggesting that there was already some awareness in the management system of the potential challenges of spillovers. Finally, the extent of leakage from a catch-share program will also depend on the initial conditions of the catch-share fishery. For example, overcapacity was relatively less of a concern in the rockfish fishery, which may partially explain why estimates of the scope and scale of leakage for the rockfish fishery were either insignificant or opposite to those for the other catch-share fisheries.

Our analysis of catch-share leakage exploits network theory to understand policy impacts (39). However, further research challenges must be overcome before spillover effects from past and future single-fishery policies can be fully predicted and management goals that may be influenced by spillover evaluated. Chief among them is how to reconcile individual-, vessel-, and community-level analyses and outcomes that show the benefits and risks of fishery portfolio diversification (11–14, 31) with the current scope of policymaking, which is typically the fishery. A better understanding of other types of leakage is also warranted, such as those related to social factors—e.g., employment and community well-being (40)—and distributional impacts—e.g., small- vs. large-scale operators. One opportunity is to explore linking these scales within EBFM frameworks.

This work also raises questions about the appropriate scale for EBFM, specifically the possibility that there is a mismatch between the scales of ecological and economic connectivity. Our analysis includes all Alaska fisheries and is arguably one of the larger analyses of fishing policy outcomes to date. Although not investigated here, there is also evidence that spillover may occur between fishing regions or countries and therefore an even broader scope may be appropriate (21, 41).

Additionally, more work is needed to integrate economic connectivity into models of socio-environmental systems more broadly. Although we emphasize system change in response to a particular policy (catch-share programs), the concepts and methods developed could be extended to other policy changes and also ecological changes, such as a rapid stock collapse or slower disturbances (e.g., climate change). Furthermore, the economic connectivity modeled here can be viewed as an analog to work on ecological system structure and linkages emphasized under EBFM (4); future work could link the economic and ecological networks (42), potentially also including other social factors—such as information sharing and governance—to develop integrated socio-environmental models suitable for assessing the impact of policy and/or ecological system shocks.

Materials and Methods

We use confidential Alaska region commercial fishing data collected by the Alaska Department of Fish and Game. The dataset includes one record per landing for all commercial fishing trips made by catcher vessels in the Alaska region, about 500,000 records per year, from 1991 to 2015. The landings database is comprehensive for catcher vessels, but not for catcher processors that process their catch at sea; thus we focus only on catch-share programs that were implemented in fisheries with catcher vessels and remove all catcher processor records from the analysis. Each record in the landings database includes a vessel identifier and the permitted fishery in which harvesting took place. In total, there are 104 fisheries, defined as a unique area/species/gear combination (*SI Appendix*).

We test for a structural break in the time series of participation and the network metrics (node size, weighted degree, weighted out-degree, weighted centrality, and weighted out-centrality), thereby controlling for background trends stemming from changes in biological, economic, and other processes. We estimate a time-series regression model for a given fishery as

$$\ln(V_t) - \ln(V_{t-1}) = \beta_0 + \beta_1 D_t + \beta_2 t + \beta_3 t^2 + e_t, \qquad [1]$$

where V denotes the network statistic, D_t denotes an indicator variable equal to one for the year immediately after catch-share implementation and zero otherwise, t represents year, and e_t represents an idiosyncratic error. Testing for a structural break immediately after catch shares were introduced is equivalent to testing the null hypothesis of $\beta_1 = 0$. Note that this specification looks for a structural break in the flow of, or first difference in, the time series. Since the migration network is already the first difference in networks, metrics from the migration network are not first differenced when estimating Eq. **1**. Standard errors are computed using the Newey–West variance estimator (43). We also compare our estimates of β_1 to a reference distribution of placebo effects, which are generated by iteratively reassigning the catch-share intervention year and reestimating Eq. **1**. If the original estimate of β_1 is small relative to the distribution of placebo effects, then we have less confidence that the effect is from catch-share implementation (44, 45). We also consider lagged impacts that take place in the first few years following catch-share implementation (see *SI Appendix* for additional details).

To estimate the scope of leakage, we apply a cluster-detection algorithm to the net-migration network and to year-to-year changes in the cross-participation network. We assign fisheries to clusters for each of the catch-share programs for the year in which the program was introduced to maximize modularity, which measures the extent to which clusters, or densely connected groups of nodes with only sparse connections between groups, exist in the network (46).

Within each cluster, we test whether participation and network metrics exhibit a structural break at the time of catch-share implementation for the fisheries contained in the cluster to estimate the scale of leakage. To estimate a change in cluster participation, we follow Eq. **1** but use the total number of participants that were active in at least one fishery in the migration cluster beyond that/those the catch share was implemented in. To test for changes in economic connectivity, we estimate a panel-regression model for a given cluster that is identical to Eq. **1**, except that we exploit the longitudinal nature of the data and allow for fishery-specific fixed effects $\beta_{0,i}$. To explore whether cluster-level structural breaks can be attributed to catch-share implementation, we identify the central node(s) within each cluster based on closeness centrality. Centrality of nodes is recognized as a means of identifying the optimal seeding nodes (38), and we use it to identify the conceptual opposite—i.e., the origin of the network change. Therefore, to the extent the catch-share fishery has the highest centrality, we attribute the structural breaks within the cluster to the catch-share fishery.

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