Multiplex social ecological network analysis reveals how social changes affect community robustness more than resource depletion

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Network analysis provides a powerful tool to analyze complex influences of social and ecological structures on community and household dynamics. Most network studies of social–ecological systems use simple, undirected, unweighted networks. We analyze multiplex, directed, and weighted networks of subsistence food flows collected in three small indigenous communities in Arctic Alaska potentially facing substantial economic and ecological changes. Our analysis of plausible future scenarios suggests that changes to social relations and key households have greater effects on community robustness than changes to specific wild food resources.

multiplex networks | food sharing | mixed subsistence–cash economies | climate change | social–ecological systems

Globally, while millions of people combine subsistence- and market-based activities for their livelihoods, they are increasingly exposed to substantial perturbations from both climate change and globalization (1–4). Mixed subsistence–cash economies are characterized by strong human–landscape connections, in which social relations facilitate flows of food and other resources among households (5). Early termed the moral economy (6), cultural norms of sharing and cooperation enable risk sharing, improve food security, improve health and equity outcomes, and contribute to group identity and cohesion (7–10). Embedded social relations have been termed the "capital of the poor" (11) as they allow flexible access to resources in times of stress and rapid change (12–16). Yet inequities can emerge as cooperative institutions are stressed (17, 18) and effects of specific exposures on people, social relations, and landscapes are uncertain (3, 4, 19).

The indigenous Alaskan communities considered here represent two ethno-linguistic groups occupying distinct ecological zones with differential access to marine and terrestrial resources: coastal Iñupiat and interior Athabascan Gwich'in (*SI Appendix*, Fig. 1). Common to all three communities are (*i*) exposure to significant ecological and economic change, (*ii*) substantial reliance on subsistence production of local wild foods, (*iii*) engagement in the market economy, and (*iv*) a strong focus on social relations. Within communities, households are characterized by strong heterogeneity in roles and degree of subsistence engagement (20, 21). Although many challenges face Arctic communities (22, 23), we focus on three frequently cited scenarios: changes in resource abundance or distribution due to climate, shifts in cultural practices related to sharing and cooperation, and loss of key productive households. Specifically, climate change could affect access to critical species or entire species groups. Engagement in the cash economy and high food and fuel costs could displace dependence on social relations (2). Sharing and contributions have been described as particularly vulnerable to these changes (24, 25). Finally, loss of highly productive key households—it is well documented in Alaska that 30% of rural households produce 70% of food and redistribute widely to others (20)—could reduce resources flowing to second- and third-order neighbors.

It is well documented that structural properties of networks influence behaviors and outcomes in a wide range of systems: social networks, food webs, landscapes, power grids, and the internet (26–30). In its simplest form, a network consists of entities of interest (nodes) and the interactions (edges) between nodes. In the real world, a pair of nodes often have many different kinds of interactions. This scenario creates, analytically speaking, a layered network, or a "multiplex," where each layer represents a different type of interaction.

Mindful of the central role of social relations in mixed economies, we use data about subsistence food flows to explore structural properties of cooperation and sharing networks. We use network connectivity as an indicator of social–ecological-system robustness under different social and ecological change scenarios. To represent interdependencies among ecological services and social relations, we employ a network approach using self-reported, reciprocal, weighted flows of food and resources between individual households, in two dimensions. The first

Significance

Social capital ties are ubiquitous in modern life. For societies with people and landscapes tightly connected, in variable or marginal ecosystems, and with unreliable market sectors, social relations are critical. Each relation is a potential source of food, information, cash, labor, or expertise. Here, we present an analysis of multiplex, directed, and weighted networks representing actual flows of subsistence-related goods and services among households in three remote indigenous Alaska communities exposed to both extreme climate change and industrial development. We find that the principal challenge to the robustness of such communities is the loss of key households and the erosion of cultural ties linked to sharing and cooperative social relations rather than resource depletion.

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Data deposition: Network datasets will be made available at https://github.com/manlius/Alaska and https://www.researchgate.net/publication/309648240_Multiplex_Networks_in_Northern_Alaska.

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dimension is ecological: core subsistence resources being harvested or distributed by households (e.g., caribou, bowhead whale, etc.; *SI Appendix*). The second dimension is social: relations between households and crews such as cooperative hunting, sharing, contributions (e.g., of labor and equipment), etc. In our multiplex networks, each node represents a household or crew in a study community, each layer represents a unique resource–relation pair (e.g., caribou sharing), and each node appears in every layer. Representing the system as a multiplex network creates connections both within layers and between layers.

Recent methodological advances using tensor mathematics make it possible to analyze the simultaneous impact of multiple types of relations (31–33) and to evaluate cumulative effects of removing particular households/crews, social relations, or resources on the entire multiplex (34, 35). Our hypotheses, then, are that the loss of specific households/crews, specific social relations, specific core species, or entire species complexes will have similar effects on network robustness. Additionally, we hypothesize that targeted removals will have stronger negative effects than random removal on network robustness.

We first explore patterns of household engagements in different resource–relation layers and then the potential effects of plausible scenarios of change. We find—contrary to much of the focus on climate change—that the loss of important social relations or the loss of key households has greater effects on community interconnectedness than the loss of core subsistence species. Using a multiplexity lens highlights possible vulnerabilities of resource harvesting and distribution networks for small-scale societies facing drivers of change and provides insights into key response mechanisms (36, 37).

Results and Discussion

Multiplex Networks. Wainwright and Kaktovik are coastal Iñupiat communities in Alaska, whose subsistence depends on bowhead, beluga, caribou, and other marine and terrestrial species. Venetie is an interior Athabascan Gwich'in community, whose subsistence centers on moose, caribou, salmon, and other riverine and terrestrial species (*SI Appendix*). The study communities are small (Wainwright has 553 people; Kaktovik, 239; and Venetie, 166), geographically isolated, and not connected to Alaska's road system.

Data were collected with comprehensive socio-economic surveys administered in person to heads of households in 2009 and 2010. Samples included 146 of 156 households (94%) in Wainwright, 70 of 85 households in Kaktovik (82%), and 84 of 89 households (94%) in Venetie. Almost all of the sampled households (90% in Wainwright, 91% in Kaktovik, and 94% in Venetie) engaged in a mixed economy, relying on a combination of wage employment and subsistence production (21).

Surveys collected inflows of wild foods to each household for 7–10 core species in each community, converted to edible pounds for analysis (Table 1). For each resource, flows through different social relations were identified initially from ethnographies, verified by community interviews and advisory groups, and then pretested. Finally, surveys collected the individual source of each subsistence food and nonfood resource from other households, from whaling crews, and from organizations, all of which are represented as nodes in the community networks. The network for Wainwright includes 218 nodes; that for Kaktovik, 164 nodes; and that for Venetie, 206 nodes. A community network, then, is represented by multiple layers of identical nodes, in which each layer represents a unique combination of ecological resource and social relation, and edges between the nodes represent the weighted value of flows of a specific resource obtained through a specific relation. The combination of all layers results in one multiplex network per community (36 layers form Wainwright's multiplex, 37 layers form Kaktovik's, and 43 layers form Venetie's; details in *SI Appendix*). Mathematically, a multiplex network can be represented by $M^{i\alpha}_{j\beta}$ (32), a rank-4 tensor: i.e., a multidimensional array in which four indexes (rank 4), node i in layer α and node j in layer β, identify a specific element of the array (*SI Appendix* and *SI Appendix*, Fig. 2).

Table 1. Summary of flows in the multiplex network, by social relation and community

	Wainwright (146 households)		Kaktovik (70 households)		Venetie (84 households)	
Social relation	Pounds	%	Pounds	%	Pounds	%
Own harvest	102,587	25	47,812	21	33,401	35
Cooperative harvest	112,116	28	42,442	19	23,067	25
Helper shares	13,294	3	10,340	5	13,702	15
Sharing	40,646	10	19,944	9	18,955	21
Trading	1,807	1	407	1	96	1
Social whaling relations (bowhead/beluga)	132,290	33	102,648	45	2,276	2
Total: all relationships	404,082	100	223,615	100	92,034	100
Total: social relationships	301,495	75	175,803	80	58,633	64

Whaling social relations include cooperative harvest, helper shares, sharing, shares (e.g., crew, towing, captains, and household), the Nalukataq (whaling feast), small (captains') feasts, and trading.

Patterns of Engagement. We began by exploring distributions of households' engagement in all possible layers of the three multiplexes, by community and by flow direction (Fig. 1). Distributions of inflow engagement (households receiving goods, supplies, or labor) were approximately normal in Wainwright and Venetie and nearly uniform in Kaktovik. Distributions of outflow engagement (households giving goods, supplies, or labor) were strongly skewed, indicating a higher degree of specialization in production of goods and services via specific resources and relations. This seems intuitively correct. Some households (specifically, elder, young, and disabled families) have less productive capacity to give significant food away or provide services, but all households may receive (5, 21). We then analyzed the relations between different layers, using Spearman correlation between in- and outgoing strengths of nodes across layers. Spearman correlation $\rho_{\alpha\beta}$ is calculated by comparing the strength s_α of households in one layer against their strength s_β in other layers,

$$\rho_{\alpha\beta}(pq) = 1 - \frac{6\sum_{i=1}^{N}[r_\alpha^{(i)}(p) - r_\beta^{(i)}(q)]}{N(N^2-1)}, \qquad [1]$$

where $p, q =$ ingoing, outgoing, or total strength and $r_\alpha^{(i)}(p)$ is the rank of node i in layer α.

Strong positive correlations indicate that households highly active in one layer are also highly active in a corresponding layer (Fig. 2). Conversely, strong negative correlations indicate that households highly active in one layer are not active, or have low activity, in another layer.

We assessed the contribution of specific resources and relations to receiving and giving patterns by fitting three two-part models for in- and outflows: comparing all resources vs. all social relations, only across resources, and only across social relations (*SI Appendix*). A two-part model is a statistical model that allows for 0 inflation, where 0 indicates nodes that do not contribute to a specific layer (38, 39). We then assessed how much of the observed variance in giving/receiving patterns is explained by each

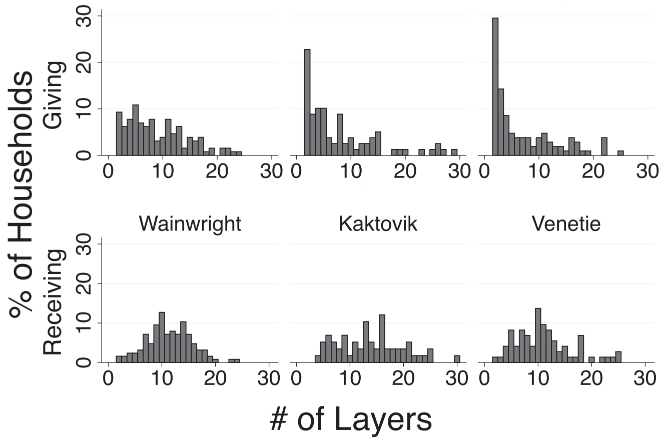

Fig. 1. Households' engagement in Arctic multiplex social networks. Shown is the percentage of households engaged in *N* different, unique, resource–social relation layers.

resource, by each social relation, and by resources and social relations using Shapley values (40, 41) (details in *SI Appendix*).

In Fig. 2, blocks of species–relation layers with high positive correlations indicate community networks characterized by households with high activity across multiple resource–relation layers. Clustering of resources (clumping of *y*-axis color codes) implies that households engage in multiple social relations across a resource or group of resources (i.e., caribou sharing, caribou cooperative hunting, etc.). If households' activities are focused on specific types of social relations (i.e., sharing or contributing), but across multiple resources, then we would expect clustering by relation types (clumping of *x*-axis color codes). Few clusters on either the *x* or the *y* axis reflect networks of households with broad engagement across resources and relations. Taken together, correlation strength and clustering patterns visually suggest important interdependencies between households across network layers (*SI Appendix*, Figs. 3–14).

In combination, patterns observed in Fig. 2 and Table 2 reflect the relative importance of households across layers and the percentage of variance in giving and receiving patterns explained by different social relations and resources. For giving relations (outflows), Spearman correlations (Fig. 2) show that Kaktovik households who give in one layer also give strongly across a wider diversity of other layers compared with households in Wainwright and Venetie. In Kaktovik, 88% of the total variance in giving patterns is explained by social relations, compared with 72% in Wainwright and 61% in Venetie (note clustering by relations in top axis of Fig. 2 and in top rows of Table 2). For social relation outflows in Kaktovik and Wainwright, contributions (CNT) and cooperative hunting (COP) explain the most variance in giving patterns whereas, in Venetie, CNT and helper shares (HSH) explain the most variance. For resource outflows, caribou (CBU) explain the most variance in giving patterns in Wainwright and Venetie, but not in Kaktovik (Table 2). Other resources are unique to specific communities [e.g., beluga (BLG), geese (GES), and seal (SEA) in Kaktovik and moose (MOO) and ducks (DUC) in Venetie]. For receiving relations (inflows), Spearman results illustrate that Kaktovik households who give strongly in one layer tend to give across many other layers (Fig. 2). Blocked and strong correlations are evident in both Wainwright and Venetie, but in different ways. Receiving patterns are more diffuse across all resources–relations in Venetie and clustered more tightly around a narrow set of layers in Wainwright. Again, disaggregating variance across resources and relations is useful (Table 2). In all three communities, social relations explain much more of the variance in receiving patterns than resources, 80% in Kaktovik, 71% in Wainwright, and 63% in Venetie (Table 2). CNT explain more variance in receiving than any other social relation (45–55%), whereas whale shares (WSH) explain 21% and 30% of the variance in receiving patterns in Wainwright and Kaktovik, respectively. This result is consistent with resource patterns, where bowhead (BOW) accounts for

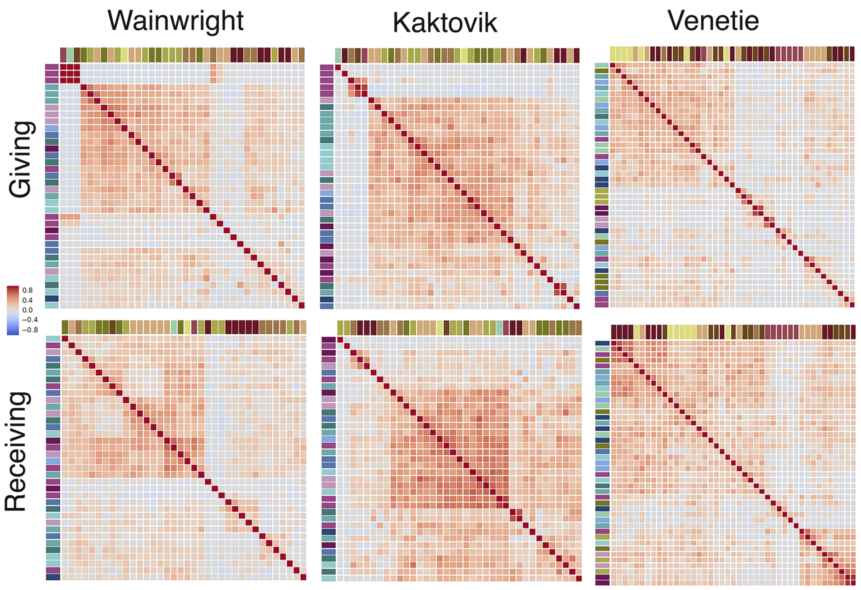

Fig. 2. Interlayer Spearman correlation matrices for Arctic multiplex social networks. Shown are interlayer correlations between any pair of layers in the three communities based on "giving" and "receiving" relationships (i.e., out- and inflows, respectively). Higher correlation indicates that it is more likely that a household that gives/receives most in one layer also gives/receives most in another layer. Axis color codes indicate species and social relationships. Color code on the left of each graph indicates whether layers relating to the same species (i.e., beluga sharing, beluga–helper shares, etc.) are clustered together, whereas the color code on the top of each graph indicates whether layers relating to the same social relationship are clustered together (i.e., caribou contributions, moose contributions, etc.).

Table 2. Percentage of variance of outflow (giving) and inflow (receiving) patterns explained by ecological and social layers of the community's multiplex networks

Type	Layer	Giving, %	Receiving, %
	Wainwright		
All	Resources	28.27	29.23
	Relations	71.73	70.77
Ecological resources	BLG	11.99	5.09
	BOW	10.77	25.35
	CBU	44.66	12.29
	DUC	13.68	25.27
	GES	8.96	19.76
	SEA	7.63	3.32
	SMT	2.31	8.93
Social relations	CNT	50.55	37.05
	COP	17.04	8.51
	CSH	2.02	2.21
	EQP	2.68	4.74
	FST	2.19	3.77
	HHS	4.22	14.07
	HSH	6.81	3.23
	SHR	8.29	3.95
	TRD	1.21	1.68
	WSH	4.98	20.79
	Kaktovik		
All	Resources	11.49	19.74
	Relations	88.51	80.26
Ecological resources	BLG	17.93	20.11
	BOW	10.99	25.56
	CBU	10.16	4.86
	CHR	3.96	4.08
	GES	29.26	22.22
	SEA	23.67	13.61
	SHP	4.02	9.56
Social relations	CNT	44.47	41.72
	COP	16.16	9.54
	CSH	3.61	2.07
	EQP	2.97	1.88
	FST	3.28	3.16
	HHS	2.67	2.88
	HSH	6.91	5.06
	SHR	6.96	3.93
	TRD	1.28	0.68
	WSH	11.69	29.07
	Venetie		
All	Resources	38.67	36.98
	Relations	61.33	63.02
Ecological resources	BLG	3.78	3.01
	BOW	1.70	1.80
	BRR	15.24	12.60
	CBU	19.29	21.16
	DUC	16.54	19.21
	GES	3.01	2.97
	GRY	2.48	3.49
	MOO	18.74	19.13
	SAL	6.53	5.16
	SEA	12.68	11.46
Social relations	CNT	55.02	56.65
	COP	9.10	15.88
	CSH	2.24	0.87
	EQP	2.62	2.05
	HSH	22.61	16.71
	SHR	7.38	6.95
	TRD	1.02	0.91

Each ecological layer includes all of the social relations associated with a specific resource. Each social layer contains all of the resources associated with a specific social relation. See *SI Appendix*, Table 2 for keys to layer codes.

25% and 26% of variance in Wainwright and Kaktovik. Venetie households are considerably less specialized. Receiving patterns are key in social relationships of CNT and HSH for help in processing wild foods and important resources are CBU but also berries (BRR) and MOO.

In summary, the correlation findings expand upon the layer distribution findings in Fig. 1. In all three communities observed variance in giving and receiving is explained primarily by key social relations. In Wainwright and Venetie the proportion of variance explained by relations compared with resources was the same whether giving or receiving (30/70% and 40/60%, respectively). In Kaktovik social relations explained around 80% of the variance for giving and 80% for receiving. Fig. 2 patterns begin to highlight the different roles of households across specific resources and social relations, particularly in Kaktovik. CNT and COP are important in all communities, and HSH are important in Venetie. Whaling is important for the coastal communities, with a broader mix of species in the interior. These flow structures affect how social and ecological changes might be experienced within communities and are the logical basis for the targeted vs. random removal scenarios.

Analysis of Network Robustness. Interconnectedness depends on household engagement in multiple resource–relation layers. We can quantify the interconnectedness of a multiplex network by counting the number of interlayer links between any pair of nodes in any pair of layers,

$$\mathcal{I} = Z^{-1} \sum_{\alpha,\beta=1}^{L} (1-\delta^{\alpha}_{\beta}) \sum_{i,j=1}^{N} M^{i\alpha}_{j\beta}, \qquad [2]$$

where Z is a normalization factor to obtain an interconnectedness between 0 (all layers are disconnected) and 1 (all layers are connected by the maximum number of allowed node–node interlayer links) and δ^{α}_{β} is the Kronecker delta. In the case of a multiplex network, nodes are allowed to interconnect only to their replicas (i.e., themselves) in all other layers, $Z = NL(L-1)$.

We use changes in interconnectedness to assess community robustness under six perturbation scenarios: random and targeted removals of households, of social relations, and of ecological resources (Fig. 3). We also assess three perturbation scenarios involving targeted removals of specific resources by category (i.e., terrestrial, marine, riverine), as might occur with rising temperatures, increasing forest fires, industrial disasters, etc. The removal of a household implies iterative losses of the ecological resources the household produces or distributes through diverse social relations. The removal of a social relation implies the iterative loss of associated resources, and the removal of a resource implies the loss of associated social relations.

Fig. 3 summarizes the results of the robustness analysis for each community. With few exceptions, removal effects were remarkably similar across all three study communities. Random removals had virtually identical effects, linear for household loss and nonlinear for social relation loss and ecological resource loss. For every scenario, random removals had less effect on interconnectedness than targeted removals, as expected. However, in every community targeted removals of resources had less effect on interconnectedness than targeted removals of households or social relations.

In Wainwright, targeted removals of 20% of households resulted in a 66% reduction in interconnectedness, whereas targeted removals of 20% of social relations (e.g., sharing, cooperative hunting, and contributions) resulted in an 80% reduction in interconnectedness. A loss of key households in Wainwright has less of an effect than in Kaktovik and Venetie (additional details in *SI Appendix*, Figs. 15–17). Targeted removals of two core ecological resources (29% of core resource layers) resulted in a 65% reduction in interconnectedness. In Kaktovik, targeted removals

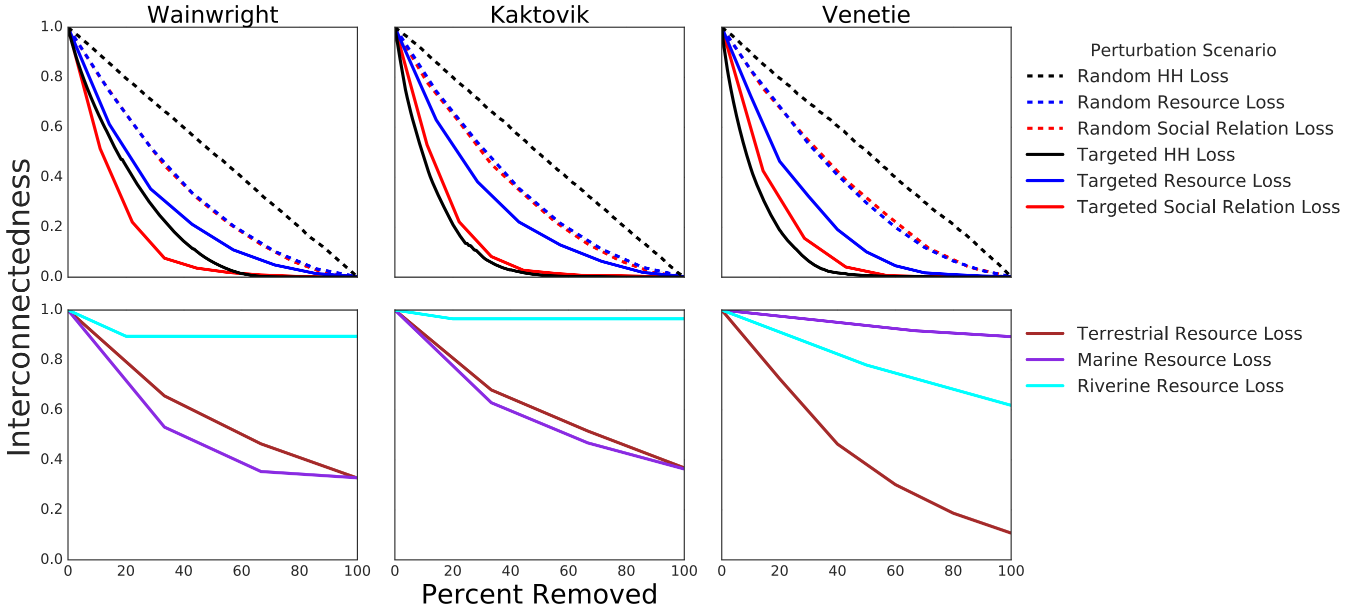

Fig. 3. Robustness of multiplex networks to perturbations. Shown are changes represented by targeted vs. random removal nodes (households) and layers (social relations, species, and species groups). Robustness patterns strongly depend on the perturbation type. Interconnectedness in the case of random removal scenarios is averaged over 100 realizations of random removal of nodes [household (HH) loss] or layers (social relation loss and resource loss).

of 20% of households resulted in an 80% reduction in interconnectedness, and targeted removals of 20% of social relations also resulted in an 80% reduction in interconnectedness. Targeted removals of two core ecological resources (29% of core resource layers) resulted in a 62% reduction in interconnectedness. And in Venetie, targeted removals of 20% of households resulted in an 80% reduction in interconnectedness, whereas targeted removals of 20% of social relations resulted in an 80% reduction in interconnectedness. Targeted removals of two core ecological resources (20% of core resource layers) resulted in a 54% reduction in interconnectedness.

Finally, targeted removal of species by resource category (Fig. 3) contrasts coastal communities' dependence on available marine and terrestrial species (where removals reduce interconnectedness substantially) with their relative lack of dependence on riverine resources (*SI Appendix*, Table 1). The large effect of marine removals is partly a function of the major role of social relations in whale distributions (crew shares, HH shares, captains shares, etc.) in coastal communities. In contrast, interconnectedness in Venetie is dependent on terrestrial and, secondarily, riverine species, but not on marine resources, as would be expected given its geographical location in Alaska's interior. Generally, interconnectedness decreases linearly for terrestrial, marine, and riverine species. The loss of one species in a category may not have drastic effects unless it potentially influences cultural ties related to cooperation and sharing (i.e., social relations loss scenario in Fig. 3).

To summarize, removals of different components of the multiplex networks allowed us to probe the robustness of social–ecological networks in mixed economies under plausible scenarios of change. Targeted removal results for households reinforce the 30:70 theory: Key households generate most of the food and contributions that are then shared among community households. Even the loss of very few of such households has a significant effect on the overall robustness of mixed-economy communities. Targeted removals of key households or key social relations reduced interconnectedness more than removals of resources (random and targeted), suggesting greater community vulnerabilities to household loss and social change. Specifically, (*i*) loss of key social relations had larger effects than loss of resources in all communities; (*ii*) loss of key social relations had the largest effect in two of three communities; (*iii*) loss of key households had nonhomogeneous effects across the three communities, with the smallest effect on Wainwright robustness, but a larger effect than the loss of key social relations in the other two communities analyzed here; and (*iv*) loss of different groups of core resources (marine, terrestrial, and riverine) had varied effects, depending on the geographic location of communities.

Conclusion

Significant changes are occurring in mixed subsistence–cash economies globally, yet predicting how these changes will manifest is complex. In this paper, we quantified the potential effects of plausible changes on three indigenous communities' social–ecological networks from a structural perspective, leveraging unique methodological advances for multiplex networks. We found that social–ecological interactions among humans and animal species remain a fundamental characteristic of these mixed economies and that communities' structural properties mediate the effects of changes on network interconnectedness. Changes in social relations precipitated steeper declines in network interconnectedness than changes in ecological resources. This result highlights potential social vulnerabilities for communities in mixed economies that rely on social capital ties.

Historically, these study communities have already experienced substantial ecological disruptions. Variability is a core feature of Arctic systems. Resources central to the Iñupiaq economy—bowhead whales and walrus—were decimated by Yankee whalers in the later 19th century (42, 43), yet Iñupiaq culture persisted while resource populations recovered. The Gwich'in were subject to similar disruptions: the fur trade, multiple gold rushes, and significant declines in salmon stocks (44). On the economic side, Iñupiaq have not just weathered but exploited the oil boom on the North Slope (45, 46) and Gwich'in households are strongly engaged in the cash economy.

Vulnerability science suggests that social and ecological changes often act cumulatively and iteratively, demanding ever greater flexibility from households in the face of change (14, 47). Significant patterns of agency and adaptation do characterize mixed livelihoods, such as livelihood diversification, social learning, and changes in social relations. Communities may be able to adapt to single stressors. There is evidence that, over time, individual households cycle in and out of the superhousehold role even as the role itself persists in Arctic communities (48). Nonetheless, households' abilities to cohere and adjust to emergent conditions are speculative and may involve significant tradeoffs, whereas community responses to multiple, interdependent changes remain unclear. Structural properties alone can only partially predict how plausible scenarios of change could affect communities relying on mixed economies, but can highlight existing vulnerabilities that set the stage for future adaptation.

A caveat is that the analysis of separate scenarios on multiplex networks' structural properties cannot fully predict the effects of iterative changes. Nonetheless, our results serve to highlight potential vulnerabilities that may influence future adaptations (36). Furthermore, there is a critical need for comparable, longitudinal, empirical data on social–ecological networks (49, 50). Longitudinal data would illustrate adaptive strategies, identify possible domino effects, and inform iterative scenario analyses. Future efforts in this area would be particularly relevant to societies where social relations support access to core resources, where community cohesion remains a core feature of livelihoods and well-being, and where perturbations are frequent and pressing.

The research protocol was approved by the University of Alaska Fairbanks Institutional Review Board (20090625) and reviewed by the Traditional Councils of the three communities. Interviews occurred with heads of household over 18 y of age and consent was obtained.

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