Upscaling the resilience assessment through comparative analysis

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Resilience is the capacity of any system to maintain its function, structure and identity despite disturbances. Assessing resilience has been elusive due to high levels of abstraction that are difficult to empirically test, or the lack of high quality data required once appropriate proxies are identified. Most resilience assessments are limited to specific situation arenas, making comparison one of the unresolved challenges. Here we show how leveraging comparative analysis can provide insights on how Arctic communities (N = 40) can best deal with social and environmental change. We found that the capacity to self-organize, and nurturing diversity are sufficient conditions for Arctic communities whose livelihoods have been resilient, or for communities whose livelihoods have been transformed. Our study provides an alternative perspective on how to assess resilience by leveraging comparison across cases. It also identifies governance pathways to support adaptations and transformations in the Arctic, a geography with some of the most dramatic social and natural challenges to come.

Introduction

Resilience is the capacity of any system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, feedbacks, and therefore identity.¹ There are over 70 definitions of resilience,² making it a hard concept to grasp, to operationalize, and empirically ground. How does one measure resilience remains a non-trivial challenge and a key frontier of active research.³⁻⁵

Seminal and foundational work on resilience emerged from reflections about ecological stability⁶ and the possibility that ecosystems can undergo regime shifts.⁷ Regime shifts are abrupt and persistent changes in the function and structure of systems.⁸ Thus if regime shifts relate to the possibility that a system can exist in multiple configurations, resilience is the ability to keep a system within a particular configuration. They are two complementary sides of the same coin. Not surprisingly, early theoretical work attempting to operationalize resilience measures focused on metrics such as the size of the basin of attraction, its depth, slope, or proximity to the boundary that separates different regimes.⁹ More recent endeavours of approximating resilience from that perspective suffer from the problem of finding sufficient observables,¹⁰ or high quality data to characterize the multidimensional configurations of social-ecological systems.¹¹

While resilience is often introduced in the context of ecological problems, its roots go beyond ecology. In fact, the use of the term in the social sciences precedes its use in ecology, and the ideas of multiple attractors would have not been possible without the development of bifurcation theory in mathematics almost a century and a half ago.¹² Bifurcations have found applications in the theories of poverty traps already in the 1950s,¹³ segregation in sociology by the 1970s,¹⁴ and over the last half century in fields that span medicine, climate science, linguistics, finance or physics,¹⁵ and of course social-ecological systems.^{8,16}

If these concepts are so widely used, why is it so hard to find good empirical proxies of resilience? One problem with the general applicability of these concepts is that applying it to different systems requires answering *a priori* the questions of resilience of what to what?¹⁷ Doing so reduces the ability of comparing

across systems. For example, one might successfully approximate the resilience of a cancer, but it does not mean one can use the same method or proxies to assess the resilience of climate, or not even a different type of cancer. Consequently, most resilience assessments have been centered around particular problems by particular actors (e.g. water management), and remain participatory consultations limited by the perceptions of participants. They are important exercises to generate shared knowledge of a management problem enabling communities to identify feedbacks, slow variables or potential leverage points for intervention.^{18–20} However, more generic, cross-system approaches are needed.^{5,21,22}

Time being a common dimension to any dynamical system lends itself for the development of generic proxies of resilience,⁵ in particular recovery time.⁷ Complex systems when close to regime shifts leave statistical signatures on time series that reveals resilience loss,^{5,21,23} in a nutshell it takes longer to recover after a small disturbances.^{5,11} These methods can fail when dynamics are driven by stochastic processes,^{24,25} and often require long time series to detect meaningful signals.¹¹ Time-based metrics offer no insight into two important evolutionary dimensions of resilience: adaptive and transformative capacities.¹

Here we propose a qualitative comparative method for upscaling resilience assessments. We study 40 communities in the Arctic facing environmental and social challenges related to potential regime shifts in Arctic ecosystems, or socio-economic and political pressures opened by recent pathways of development (Fig 2). We outline how leveraging the power of comparison enables extracting patterns that transcend individual case studies informing theory development, as well as potential management or governance arrangements. We hope our qualitative proposal complements current quantitative metrics that focus on recovery time by gaining insights about the ability to adapt and transform that define communities in the Arctic. But why the Arctic?

Figure 1: **Arctic case studies** 40 cases were analyzed across Arctic nations.

The Arctic is a region of the world where the resilience of communities is being tested at a extreme. Climate change alone is impacting Arctic ecosystems ~4 times faster than the rest of the globe.²⁶ Climate impact is greater than ice loss, fundamentally changing landscape and seascape connectivity, the flow of energy and nutrients, and structure and function of biological communities. The Arctic is also the scene of vast

socio-economic changes and challenges.²⁷ The reduction of Arctic sea ice is opening the possibility for mining exploration and new international shipping routes,^{28,29} increase in pollution^{30,31} or changing conditions for fisheries and aquaculture.³² Securing basic food, water and energy, as well as diversifying economies, remain key human development challenges for Arctic communities.³³

How can Arctic communities respond to these social and ecological challenges? Will they adapt and continue with their traditional livelihoods, or transform towards new social-ecological configurations?

Methods

To answer these questions we first revisited the literature on adaptive capacity and designed a coding scheme for capturing elements of resilience across case studies. We co-designed and co-developed a template to guide case study selection, literature reviews, and validation with experts. Then we applied qualitative comparative analysis to infer necessary and sufficient conditions for resilience, transformations or resilience loss in 40 communities across the Arctic. Below we describe in detail each of these steps.

Figure 2: **Descriptive statistics** 40 cases were analyzed across Arctic nations (A) covering a range of sectors (B) and responding to different types of drivers (C). The time span of our case studies depend on what is reported on literature reviews. While most concentrate on contemporary issues, some cases date back centuries (D). The category "other" in (A) refers to the case of the Bering Strait which lies in international waters between Russia and USA.

Measuring adaptive capacity: We draw inspiration from early conceptual developments on how to approximate adaptive capacity. Adaptability is related to the capacity to learn, combine experience and knowledge, innovate, and adjust responses and institutions to changing external drivers and internal processes.¹ Berkes et al³⁴ proposed a two-tier set of variables grouped around four key dimensions: i) learning to live with change and uncertainty (N), ii) nurturing diversity for reorganization and renewal (D), iii) combining different types of knowledge for learning (K), and iv) creating opportunities for self organization (S). We complemented the two-tier approach with a third-tier of variables (Fig 3) by combining recent developments on principles for building resilience³⁵ with expert knowledge elicitation. The refining of our third-tier of variables benefited from input and testing of preliminary case studies in the context of the Arctic Resilience Assessment.²⁷

Figure 3: **Adaptive capacity** We expanded the original proposition by Berkes et al to include a third tier variables that enable the identification of adaptive capacity features from literature reviews and expert elicitation. The variables were co-designed and tested with a broad range of stakeholders.

The Arctic Resilience Assessment was commissioned by the Arctic council under the Swedish Ministry of Environment chairmanship. The assessment was lead by the Stockholm Resilience Centre and the Stockholm Environmental Institute.²⁷ It builds on collaborations between the Arctic countries, Indigenous peoples in the region, and several observers that include NGOs and academic institutions. The research questions, methods development, and selection of cases were informed and shaped by representatives of member states and permanent participants representing Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, the Aleut International Association, the Arctic Athabaskan Council, the Gwich'in Council International, the Inuit Circumpolar Council, the Russian Association of Indigenous Peoples of the North, Siberia and Far East, and the Saami Council. We also received input from representatives of the Arctic Council working groups of the Arctic Contaminants Action Program, the Arctic Monitoring and Assessment Programme, Conservation of Arctic Flora and Fauna, Protection of the Arctic marine Environment, and the Sustainable Development working group of the Arctic Council. As Arctic Council observers, we counted with participants from the European Environmental Agency, the International Arctic Science Committee, the International Arctic Social Science Association, the Arctic Centre - University of Lapland, the University of the Arctic, the Resilience Alliance, the Stockholm Environmental Institute, and the WWF Global Arctic Programme.

Co-designing a case study template: We initially designed a template to capture social-ecological dynamics from literature reviews and expert elicitation inspired by the Regime Shifts database.³⁶ Our first template was however modified to incorporate the feedback, needs and priorities of the different actors involved. We modified and tested the gathering data tool through workshops and focus groups that took place in Washington, Tromsø, Bodø, and Stockholm (2015-16). The group also guided our selection of case studies to prioritize their most acute needs, and secure an heterogeneous selection of studies across problem issues and geographies.

The template was designed to capture key aspects of resilience and adaptive capacity based on literature reviews. The coder assigns whether the social-ecological system is resilient if the main livelihoods of the communities described are maintained over time, despite social and ecological disturbances. A case is coded as transformation if a community shifts their main source of livelihoods to a different set, but manages to continue developing within the same place. A case is coded as loss of resilience where the main livelihoods are lost, no new livelihoods are established, and symptoms of community collapse long last such as emigration, simplified local economies, high unemployment or high substance abuse (Fig 1). When possible, the templates were validated by experts in the topics who suggested new literature sources or improve our interpretation of the initial review. All templates collected are available in ([10.6084/m9.figshare.14779533](https://figshare.com/figures/data/10.6084/m9.figshare.14779533)) data repository. Table 1 presents a summary of the case studies.

Table 1: **Case studies.** Their outcome are coded as resilient [R], transformation [T], or loss of resilience [L].

Case name	Location	Key issue
Savoonga [R]	Alaska, USA	Maintaining traditional Yupik whaling practices
Dempster Highway [R]	Yukon and Northwest territories, Canada	Highway development and the Porcupine caribou herd
Näätämö River [R]	Finland	Skolt Sámi slamon fishing and river restoration
Kiruna [R]	Sweden	Relocation for mining activities
Porsángu and Varanger fjords [R]	Norway	Social-ecological change related to cod and kelp declines
Unjarga / Nesseby [R]	Norway	Adaptation of local sheep farming and reindeer herding to moth larvae outbreaks
Yamal-Nenets [R]	Yamal peninsula, Russia	Reindeer herding in the Yamal-Nenets autonomous Okrug
Bering Strait [R]	Bering strait, international waters	Arctic shipping development
Ikpiarjuk [R]	Nunavut, Canada	Ikpiarjuk technology and traditional knowledge to cope with the risk of climate change
Ulukhaktok [R]	Northwest Territories, Canada	Evolution of traditional knowledge and social networks to support traditional livelihoods
Pangnirtung [R]	Nunavut, Canada	Individual and collective adaptive strategies to face climate change
Khara Tumul [R]	Yakutia, Russia	Sharing networks evolution, connecting local to urban
Iqalut [R]	Nunavut, Canada	Inuit women facing climate change, vulnerabilities and adaptive capacity from a gender perspective, Iqaluit
Cape Dorset [T]	Nunavut, Canada	From nomadic hunters to international art sensations
Sisimiut [T]	Greenland	Cod to shrimp fishery transition
Barents [T]	Finland	Metal mining for northern communities
Húsavík [T]	Iceland	From fishing to whale-watching tourism
Upernavik [L]	Greenland	Aklavik, human-whale relation modification in environmental and social changes
Pacific Rim [T]	Canada	Revitalization of indigenous technologies and traditional management system to restore social ecological resilience
Utqiagvik Nuiqsut [T]	Alaska, USA	Emerging salmon subsistence fishery in Utqiagvik and Nuiqsut, Alaska.
Western Alaska [T]	Alaska, USA	Transforming knowledge system to adapt to climate change
Newfoundland [L]	Newfoundland, Canada	Seal industry in the Great Northern Peninsula

Case name	Location	Key issue
Finnmark [L]	Norway	Traditional reindeer herding and development
Vilhelmina [L]	Västerbotten, Sweden	Reinder herding husbandry
Teriberka [L]	Russia	Gas exploitation development and institutional drivers
Varnek [L]	Russia	Shipping in the Barents Sea
Kyallakh [L]	Russia	Flooding and relocation
Newtok [L]	Alaska, USA	Climate change-driven relocation of coastal indigenous communities
Cod collapse [L]	Newfoundland, Canada	Cod fishery collapse in the Great Northern Peninsula
Paamiut [L]	Greenland	Cod to shrimp fishery transition
Disko bay [L]	Greenland	The impact of sea ice reduction on resource dependent communities
Qaanaaq [L]	Greenland	From migratory fishers and hunters to relocated communities
Siglufjörður [L]	Iceland	Collapse of the herring fishery
Iglolik [L]	Nunavut, Canada	Food security in an Arctic Inuit community
Bulunsky [L]	Russia	Political transformation versus climate adaptation in Yukutia fishing communities
Uummannaq [L]	Greenland	Impact of sea ice reduction and rationalization policies
Hammerfest [L]	Norway	Fishing livelihoods decrease as oil company develops
Aklavik [L]	Northwest Territories, Canada	Human-whale relation in environmental and social changes
Kugluktuk [L]	Nunavut, Canada	Cultural and ecological dimension of food security constrained by climate change
Western Siberia [L]	Yamalo-Nenets Autonomous Okrug, Russia	Diet and lifestyle transformation on Siberian Arctic Indigenous People

Qualitative comparative analysis: Based on the templates, we coded a matrix of presence / absence of the third-tier variables used as proxies of adaptive capacity (Fig 3). A category is coded as -1 if the evidence in the literature or expert elicitation suggest that the case lacks that dimension, 1 if the evidence suggest presence of the category, or 0 if there is no evidence available. We aggregated the scores at the first-tier level by summing across the third-level categories. Qualitative comparative analysis was then used to investigate necessary and sufficient conditions for a case to be resilient, transformation, or loss of resilience.

Qualitative comparative analysis (QCA) is a method that leverage boolean algebra³⁷ and (fuzzy) set theory to investigate research questions with intermediate number of cases.³⁸ While its origins are rooted in political science and sociology,³⁹ the method has found application in several social-ecological systems problems.^{40–42} In our analysis, the four dimensions for adaptive capacity³⁴ were used as conditions, and the outputs were coded as resilience loss, transformation or resilience based on the templates. First, we calibrated thresholds for inclusion or exclusion using a logistic function where values lower than -2 were excluded, +2 included, and -0.5 was assumed to be maximum ambiguity. For example, if a case has a score >2 for variables under the category “*nurturing diversity for reorganization and renewal*”, the case is set to belong to the set **D**, which is a shorthand for diversity; if the score was <2, it does not belong to the set, which in QCA is denoted as **d**. Throughout the paper, capital letters are used to denote belonging to a set or presence of a feature, while small caps used for its absence or negation.

Next, we computed subsets of necessary and sufficient conditions for each possible output and its negation. We used the truth table of our case studies—a cross tabulation of the number of cases in our sample against all possible combinations of conditions and outputs—to perform boolean minimization and identify parsimonious, complex, and intermediate solutions. These solutions (or causal recipes in the literature) suggest a combination of conditions that leads to an output (being resilient) to be true or false. In other words, it helps us identify which features increase adaptive capacity, and hence resilience, in the Arctic communities in our

study. All the analysis was performed in R⁴³ using the QCA package.^{44,45} All the code used in our analysis is available at: https://github.com/juanrocha/Arctic_QCA

Results

Figure 4: **Calibrating adaptive capacity** Scores were calculated by adding all variables grouped by first-tier categories: i) learning to live with change and uncertainty (N), ii) nurturing diversity for reorganization and renewal (D), iii) combining different types of knowledge for learning (K), and iv) creating opportunities for self organization (S). Cases and adaptive capacity features are clustered around their scores, showing groups of resilient and transformation cases in the top, and resilience loss in the bottom (A). A logistic function was used to calibrate the raw data (B) for input into the qualitative comparative analysis. Fig A2 provides the raw values for the second-tier adaptive capacity features.

The 40 cases analysed showcase some of the challenges that Arctic communities are currently facing (Fig 2). The sectors most impacted across countries are fisheries and hunting, both for commercial and subsistence purposes. The most common challenges across our case studies are climate (35 cases), geopolitical conflicts (21), mining (15), and other socio-economic drivers (15). The country with most cases in our dataset is Canada (13), while Sweden, Finland and Iceland have only two cases each. While most of our case studies describe relatively recent phenomena, one of them focuses on the XIX and XX century, and another goes back to the 1600's. The time span reported in each case study depends on the literature reviewed.

We tested different approaches for calibrating the data and found that a logistic function best tailored our data needs (Fig. 4). Alternative approaches such as the empirical cumulative distribution function, or the totally fuzzy relative method, use the distribution features of the underlying variable to set thresholds for the inclusion or exclusion to a set.^{44,45} These data driven approaches are agnostic to the meaning of variable values. But in our case, the values zero have special meaning, it shows the adaptive capacity features for which there is maximum ambiguity (Fig 4). The logistic function allows us to incorporate that knowledge into the calibration of fuzzy sets⁴⁵ by setting thresholds for inclusion and exclusion as (2, -2) respectively, and maximum ambiguity at -0.5. The wider the inclusion / exclusion threshold ($> |2|$), the more fuzzy is the calibration. In the limit where the inclusion, exclusion, and ambiguity thresholds are the same, the data is not fuzzy anymore, but becomes crisp sets (only accepts values 0 or 1). The rest of our analysis is done

with fuzzy sets because it leverages the diversity of features to cover many of the possible combinations of cases. A crisp set analysis does not converge given poor coverage in the truth table.

Figure 5: **Truth tables** The truth tables show the distribution of cases across logical combinations. With 4 adaptive capacity features, there are 16 plausible combinations of which our cases only cover 7 of them (A). The sufficiency inclusion score (incl) indicates how much a logical combination is sufficient for an outcome (e.g. OUT Resilience = True), while the proportion of reduction in inconsistency (PRI) reveals potential contradictions with respect to all other combinations.

The truth table reveals that our 40 Arctic cases only capture 9 out of the 16 possible combinations of adaptive capacity features (Fig. 5). In qualitative comparative analysis, a case can only belong or not to a set. With the four features of adaptive capacity introduced,³⁴ there are 2^4 combinations. Despite having over twice as many cases as possible combinations, our coverage is less than half. This phenomena of limited diversity is common in the social sciences,^{38,45} and QCA leverages the unobserved combinations (logical reminders) to optimize different types of boolean minimization. For example, the logical combination **nDks** or **ndKS** reflect cases that could be classified simultaneously as belonging to the sets of resilient, transformations, or resilience loss (Fig 5B). However, the sufficiency inclusion score (incl) and the proportional reduction of inconsistency (PRI) suggest that such cases are more likely to belong to the loss of resilience set.

The analysis of necessity and sufficiency reveals that resilient and transformation cases are very similar. Both have the same sufficient conditions with relatively similar scores for inclusion and consistency reduction (Fig 6A.). While our cases have relatively low coverage for features describing the capacity to self-organize, the highest scores for inconsistency reduction is attributed to cases who rank high on self-organization, even in the absence of other attributes such as the ability to navigate uncertainty (N) or nurturing diversity (D). The analysis of necessity, however, show very similar results for all three possible outcomes (resilience, transformation, or loss of resilience): high scores in the ability to navigate change and uncertainty (N), nurturing diversity (D), or combining different types of knowledge (K) are necessary conditions for all the three outcomes.

We derived parsimonious solutions, or a minimum set of conditions, that make a case resilient, transform or erode resilience, by means of boolean minimization (Fig 7). We found again that the solutions for resilience and transformation cases are very similar, where the higher combination of features falls on cases with strong ability to self-organize (S). On average, a resilient case need to do well in at least 2 out of the 4 adaptive capacity features, and the strongest contributions are for cases whose causal recipe includes $d * K * S$ or $N * K$. Transformation cases follow a similar logic, where a successful case needs to score high in at least two out of the four adaptive capacity dimensions, and the most important seems to be self-organization (S),

Figure 6: **Necessary and sufficient conditions** The analysis of necessity and sufficiency compares observed combinations of features that can be relevant for an output. These combinations are additive (set union, logical OR) for necessity, and multiplicative (set intersection, logical AND) for sufficiency. The coverage and inclusion statistics help comparing the contribution of features to the outcome, while the proportional reduction of inconsistency (PRI) and relevance of necessity (RoN) weight the contribution to the solution with respect to others.

followed by a combination of knowledge (K) and the capacity to navigate uncertainty (N). Lastly, cases with resilience loss are observed especially where 3 out of the 4 features are missing ($n * k * s$), even in the presence of different types of knowledge and the capacity to self-organize.

Discussion

In summary, our results show that all features of adaptive capacity are important for resilience and transformation, but stresses the importance of the capacity to self-organize and nurturing diversity of social and ecological sources of memory. We observe that despite many communities can rank high in a few of these capacities, it is not enough with being strong in one or few aspects of adaptive capacity. Many of the communities studied are showing symptoms of resilience loss and no sign of transformations or shifting to alternative livelihoods ($N = 20$). Therefore, management and governance arrangements that help communities build their adaptive capacities are welcome in fora such as the Arctic council. Examples include strengthening the ability of communities to manage their territories, having the autonomy to craft their own rules, and getting support for long term monitoring or a legal framework that promotes autonomy. Another example is nurturing networks of knowledge exchange where people can share success and failure stories for tackling similar issues, from climate change impacts, to herd management, or dealing with novel economic activities that can be in conflict with traditional use of their territories.

Our study explores a deeper approach to comparing adaptive capacity features by developing a third-tier of variables that can be coded from literature reviews. These variables can be complemented in future studies or adapted to other social-ecological systems outside the Arctic. We developed these variables because we initially failed when attempting coding cases at the second-tier proposed by Berkes et al,³⁴ or the recently developed principles for building resilience.³⁵ These sources, while conceptually appealing, are too general to be able to code presence or absence of features at the case study level. These concepts are strongly rooted in the scholarly community of social-ecological systems and a fair amount of conceptual translation was required on our part to share the template and develop categories that were codable with and by other

Figure 7: **Parsimonious solutions** Minimal set of conditions (rows) that can lead to different types of outcomes (resilience, transformations or loss of resilience). Each term is a set of sufficient conditions that combined lead to a full minimal parsimonious solution. For example, the outcome resilience can be reached when a case $D*s + n*k*s + d*K*S + N*K \rightarrow R$. Multiplicative terms (*) means logical AND, and additive terms means logical OR. Inclusion and coverage for sufficiency (covS, inclS), the unique coverage (covU), and the proportional reduction in inconsistency (PRI) allow comparing the different contributions of each term to the solutions.

scholars, or validation with stakeholders during the process. We hope our study presents a first attempt at that translation, and that others can replicate and improve our codification to other social-ecological systems.

Qualitative comparative analysis as a method proved useful to analyze a relatively small sample size against an enormous combinatorial space of possibilities. If the analysis was run at the second-tier variables ($N = 13$), one would have $2^{13} = 8192$ combinations, and one would need a similar amount of cases. Our solution to simplify from the third-tier proposition ($N = 71$) to the four features of adaptive capacity was to add across each of them. The aggregation by summing has the implicit assumption that all categories have equal importance. That is, the researcher does not have an *a priori* information to decide which variables could be more relevant for adaptive capacity. As theory develops, one could relax such assumptions by using other (e.g. geometrically weighted) aggregation schemes or motivating a different calibration for the QCA. In the meantime, our analysis presents a first order approximation where no assumption of importance is made, nor bias is induced to particular features of adaptive capacity.

In the search for solutions, different boolean minimization techniques were tested, but only the parsimonious solution reported. We tried intermediate and complex solutions but they did not offer further minimization. Intermediate solutions are tested when the logical reminders (logical combinations for which we do not observe cases, Fig 5A) are assumed to be true. Since we have so many of such combinations that were not observed (7/16), such assumption does not offer further insights on the minimal solution. Complex solutions are computed by explicitly coding theoretically based expectations, for example that being strong on the four features of adaptive capacity would lead to a resilient outcome ($NDKS \rightarrow R$). However, the complex solution did not further minimize the parsimonious solution, in particular because many of the cases that are coded as resilient or transformation do actually lack at least one of the adaptive capacity features (Fig 5B).

Our study is largely based in literature reviews and expert elicitation, and as such it is limited by their focus and scope. For example, several of our cases come from ethnographic work with fishing and hunting communities which typically involve male informants. Thus, our cases might lack other analytic dimensions such as inequality or gender that the literature reviewed was not necessarily targeting. Another example is the role

of communication and knowledge networks. Many of the social and ecological challenges these communities face in the Arctic are common across countries. Our analysis does not take into consideration learning and knowledge exchange across different places. Further research might target these limitations by combining other sources of data such as communication through social media groups, national statistics, or remote sensing.

Conclusion

Resilience is a fundamental feature of complex social-ecological systems. Yet, approaches for measuring resilience, adaptive or transformative capacities remain confined to single case studies, limiting theory testing, hypothesis development, or simply comparison. Here we developed a qualitative approach for measuring resilience inspired by the adaptive capacity framework. Through a co-production process, we expanded the framework with a third tier variable, and used comparative analysis to distill features that increase resilience in Arctic communities. Communities with high capacities to self-organized, to combine multiple sources of knowledge, or who nurture diversity are more likely to maintain their livelihoods or transform towards new social-ecological configurations. We hope our methodological approach complement existing quantitative methods such as early warning signals to approximate resilience, and encourage the community to test and improve our coding approximation in other social-ecological systems.

Box 1. Case examples

Resilience: Pangnirtung- Nunavut Territory-Canada: Individual and collective adaptive strategies to face climate change

Located on Baffin Island, Pangnirtung is an Inuit fishing community that has developed collective and individual adaptive strategies to respond to ecological and social-economical disturbance. Sea-ice conditions, landscape, seascape, weather conditions are the main effect of climate change in the area. Meanwhile, socio-economic changes are related to change in Inuit fishing, lifestyle and the market. To cope with these social ecological changes, communities have mixed economies having commercial fisheries owned by Inuit people and subsistence fisheries as their traditional livelihoods. The coexistence of these livelihoods, among the introduction of technology, sharing networks, social learning, strong indigenous institutions and the integration of different knowledge systems has given the community the flexibility to deal with uncertainty under climate change and social-economic transformations.

Transformation: Húsavík in Skjálfandi Bay- Iceland: Fishing to whale watching tourism – Iceland

Iceland's industry has historically been dominated by fishing. However, over the last few decades, changes in international regulations affected the productivity of the fishing sector. Employment in fishing communities declined due to reduced cod quotas and the introduction of tradable quotas, which led to the fishing industry consolidating into a few larger companies. Fishing also decreased due to the international whaling moratorium, which also led to increases in whale populations. These changes stimulated a reorganization of Húsavík's fishing community to whale-watching tourism, based on a new application of existing knowledge and skills. Today, Húsavík is one of the main whale-watching hotspots in Iceland. Several other Icelandic fishing communities have made a similar transition.

Resilience loss: Aklavik- Northwest Territory-Canada: Human-whale relation in environmental and social changes.

Aklavik is a settlement from Northwest Territory, inhabited mainly by Inuvialuit people. Residents used to hunt beluga as the primary food source and as a key element of their cultural identity. There has been a decrease in these practices, risking losing the knowledge and cooperative value of shared food systems, collaborative hunting. Climate change has impacted the sea ice dynamics of the area and the weather

stability, decreasing the spots available to hunt whales and increase the hunting risk. The integration of Western values, technology, time in formal education, wage labor, external food supplies and climate effect has demotivated young people to hunt. Among these, the aging of elders is risking knowledge and skill transmission. However, communities identify as hunters and recognize the importance of protecting this practice to adapt

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References

1. Folke, C. Resilience (Republished). *Ecology and Society* **21**, art44 (2016).
2. Fisher, L. Disaster responses: More than 70 ways to show resilience. *Nature* **518**, 35–35 (2015).
3. Liu, X. *et al.* Network resilience. (2020).
4. Gao, J., Barzel, B. & Barabasi, A.-L. Universal resilience patterns in complex networks. *Nature* **530**, 307–312 (2016).
5. Scheffer, M. *et al.* Early-warning signals for critical transitions. *Nature* **461**, 53–59 (2009).
6. Lewontin, R. C. Meaning of Stability. *Brookhaven Sym Biol* 13–24 (1969).
7. Holling, C. S. Resilience and stability of ecological systems. *Annual review of ecology and systematics* **4**, 1–23 (1973).
8. Folke, C. *et al.* Regime shifts, resilience, and biodiversity in ecosystem management. *Annu Rev Ecol Evol S* **35**, 557–581 (2004).
9. Clark, W. C. Notes on Resilience Measures. (1975).
10. Liu, Y.-Y., Slotine, J.-J. & Barabasi, A.-L. Observability of complex systems. *P Natl Acad Sci Usa* **110**, 2460–2465 (2013).

11. Dakos, V., Carpenter, S. R., Nes, E. H. van & Scheffer, M. Resilience indicators: prospects and limitations for early warnings of regime shifts. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* **370**, 20130263–20130263 (2015).
12. Poincare, H. Sur l'équilibre d'une masse fluide animée d'un mouvement de rotation. *Acta Math.* **7**, 259–380 (1885).
13. Bowles, S., Durlauf, S. N. & Hoff, K. *Poverty Traps*. (Princeton University Press, 2006).
14. Schelling, T. Models of segregation. **59**, 488–493 (1969).
15. Solé, R. V. *Phase Transitions*. (Princeton University Press, 2011).
16. Scheffer, M. *Critical Transitions in Nature and Society*. (Princeton University Press, 2009).
17. Carpenter, S., Walker, B., Anderies, J. M. & Abel, N. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* **4**, 765–781 (2014).
18. Resilience Alliance. *Assessing Resilience in Social-Ecological Systems*. (2011).
19. Walker, B. & Salt, D. *Resilience Practice*. (Island Press, 2012).
20. Walker, B. & Salt, D. *Resilience Thinking*. (Island Press, 2012).
21. Scheffer, M. *et al.* Anticipating Critical Transitions. *Science* **338**, 344–348 (2012).
22. Scheffer, M. & Carpenter, S. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol Evol* **18**, 648–656 (2003).
23. Strogatz, S. H. *Nonlinear Dynamics and Chaos*. (Hachette UK, 2014).
24. Hastings, A. *et al.* Transient phenomena in ecology. *Science* **361**, eaat6412 (2018).
25. Hastings, A. & Wysham, D. B. Regime shifts in ecological systems can occur with no warning. *Ecol Lett* **13**, 464–472 (2010).
26. Ford, J. D., McDowell, G. & Pearce, T. The adaptation challenge in the Arctic. *Nature Climate Change* **5**, 1046–1053 (2015).
27. Carson, M. & Peterson, G. *Arctic Resilience Report*. (2016).
28. Barnhart, K. R., Miller, C. R., Overeem, I. & Kay, J. E. Mapping the future expansion of Arctic open water. *Nature Climate Change* (2015).
29. Huntington, H. P. *et al.* Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Marine Policy* **51**, 119–127 (2015).
30. Schröder, C., Reimer, N. & Jochmann, P. Environmental impact of exhaust emissions by Arctic shipping. *Ambio* **46**, 400–409 (2017).

31. Law, K. S. *et al.* Local Arctic air pollution: Sources and impacts. *Ambio* **46**, 453–463 (2017).
32. Troell, M., Eide, A., Isaksen, J., Hermansen, O. & Crépin, A.-S. Seafood from a changing Arctic. *Ambio* **46**, 368–386 (2017).
33. Larsen, J. N. & Fondahl, G. Arctic Human Development Report : Regional Processes and Global Linkages. (2015).
34. Berkes, F., Colding, J. & Folke, C. Navigating Social-Ecological Systems. (2003).
35. Biggs, R. *et al.* Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annu. Rev. Environ. Resour* **37**, 120810110322007 (2011).
36. Biggs, R., Peterson, G. & Rocha, J. The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems. *Ecology and Society* **23**, art9 (2018).
37. Boole, G. An investigation of the laws of thought: on which are founded the mathematical theories of logic and probabilities. (1854).
38. Ragin, C. C. *Redesigning Social Inquiry: Fuzzy Sets and Beyond*. (Univ. of Chicago Press, 2008).
39. Rihoux, B. & Marx, A. QCA, 25 Years after "The Comparative Method": Mapping, Challenges, and Innovations—Mini-Symposium. *Political Research Quarterly* **66**, 167–235 (2013).
40. Crona, B. I., Van Holt, T., Petersson, M., Daw, T. M. & Buchary, E. Using socialecological syndromes to understand impacts of international seafood trade on small-scale fisheries. *Global Environ Chang* **35**, 162–175 (2015).
41. Bodin, O. & Osterblom, H. International fisheries regime effectivenessActivities and resources of key actors in the Southern Ocean. *Global Environmental Change* **23**, 948–956 (2013).
42. Basurto, X. Global Environmental Change. *Global Environ Chang* **23**, 573–587 (2013).
43. R Core Team. R: A Language and Environment for Statistical Computing. (2017).
44. Thiem, A. & Dusa, A. *Qualitative Comparative Analysis with R*. (Springer, 2012).
45. Dusa, A. *QCA with R*. (Springer International Publishing, 2019).

Supplementary Material

Figure A1: **Correlogram** Matrix of correlations between features of adaptive capacity before calibration.