Supplementary Information for

Diverse pathways for climate resilience in marine fishery systems

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The Supplementary Information includes:

Appendix 1

Supplemental tables and figures.

Appendix 2

Case study rubric.

Appendix 3

Detailed narratives on climate resilience within each case study.

Appendix 1

Table S1. Working group leaders, members, external advisors, and additional case study co-authors.

Scientist	Primary affiliation	Country of residence
Leaders		
Kathy Mills	Gulf of Maine Research Institute	USA
Kristin Kleisner	Environmental Defense Fund	USA
Pat Sullivan	Cornell University	USA
Members		
Alba Aguion	University of Vigo	Spain
Anne Hollowed	University of Washington	USA
Christopher Free	University of California, Santa Barbara	USA
Christopher Golden	Harvard University	USA
Claudio Silva	Pontificia Universidad Católica de Valparaíso	Chile
Eddie Allison	WorldFish	Malaysia
Gaku Ishimura	Iwate University	Japan
George Freduah	University of the Sunshine Coast	Australia
Gretta Pecl	University of Tasmania	Australia
Jacob Eurich	Environmental Defense Fund	USA
Jacqueline Lau	WorldFish	Australia
Julia Mason	Environmental Defense Fund	USA
Kanae Tokunaga	Gulf of Maine Research Institute	USA
Lily Zhao	University of California, Santa Barbara	USA
Mark Dickey-Collas	International Council for the Exploration of the Sea	Denmark
Meghan Fletcher	The Nature Conservancy	USA
Merrick Burden	Pacific Fisheries Management Council	USA
Mireia Valle	Basque Research and Technology Alliance	Spain
Whitney Friedman	University of California, Santa Barbara	USA
Willow Battista	Environmental Defense Fund	USA
Advisors		
Vera Agostini	UN Food and Agricultural Organization	USA
Derek Armitage	University of Waterloo	Canada
Manuel Barange	UN Food and Agricultural Organization	UK
Lyall Bellquist	The Nature Conservancy	USA
William Cheung	University of British Columbia	Canada

Josh Cinner	James Cook University	Australia
Chris Costello	University of California, Santa Barbara	USA
Rod Fujita	Environmental Defense Fund	USA
Beth Fulton	Commonwealth Scientific and Industrial Research Organisation	Australia
Steve Gaines	University of California, Santa Barbara	USA
Roger Griffis	NOAA Fisheries	USA
Sangeeta Mangubhai	Wildlife Conservation Society, Talanoa Consulting	Fiji
Tim McClanahan	Wildlife Conservation Society	Kenya
Essam Mohammed	WorldFish	Malaysia
Henrik Österblom	Stockholm Resilience Centre	Sweden
Myron Peck	Royal Netherlands Institute for Sea Research	Netherlands
Andy Pershing	Climate Central	USA
Xiao Recio-Blanco	Environmental Law Institute	USA
Andy Rosenberg	Union of Concerned Scientists	USA
Jörn Schmidt	International Council for the Exploration of the Sea	Germany
Lynne Shannon	University of Cape Town	South Africa
Rich Stedman	Cornell University	USA
Rashid Sumaila	University of British Columbia	Canada
Eleuterio Yáñez	Pontificia Universidad Católica de Valparaíso	Chile
Rosa Zavala	Ministry of Production, Peru	Peru
Jono Wilson	The Nature Conservancy	USA
Additional case-study authors and external experts		
Katie Westfall	Environmental Defense Fund	USA
Yuga Kisara	Iwate University	Japan
Stephen Kasperski	National Marine Fisheries Service	USA
Erica Cunningham	Environmental Defense Fund	USA
Kendra Karr	Environmental Defense Fund	USA
Julio Chamorro	Juan Fernandez Island fisherman	Chile
Layla Osman	Environmental Defense Fund	Chile
Gonzalo Macho	Independent Fisheries Consultant	Seychelles
Martin Pastoors	Pelagic Freezer Association (PFA)	Netherlands
Andrea Dell'Apa	Independent International Consultant	USA

Table S2. Summary of case study characteristics that were apparent in the case studies. The country is noted in parentheses if the fishery or fisheries are specific to a province, autonomous community, state, prefecture, island, or island chain. For fishery location the following question was provided: "What is the physical context within which the fishery takes place? Check all that apply: A. Intertidal (e.g. beach, mangrove); B. Estuary; C. Coastal/nearshore (e.g. lagoon, fjord, coral reef, archipelago); D. Shelf; E. Deep sea (e.g. canyon); F. Pelagic; G. Island; H. Other (please specify)." For primary productivity contributors the following question was provided: "Which of the following contribute to primary productivity? Check all that apply: A. Upwelling; B. Fluvial inputs/plumes; C. Sea ice; D. Vegetated habitats (e.g. salt marsh, mangroves, seagrasses, kelp forests); E. Coral reefs; F. Other (please specify)." For climate stressor the following question was provided: "Which of the following climate disturbances are projected to alter the future of the fishery and surrounding ecosystem? Check all that apply: A. Ocean warming; B. Ocean acidification; C. Frequency and/or severity of coral bleaching; D. Frequency and/or severity of marine heatwaves; E. Frequency and/or severity of extreme El Nino-Southern Oscillation events; F. Frequency and/or severity of large storm events; G. Ocean cooling; H. Loss of sea ice; I. Sea level rise; J. Increase or decrease in upwelling; K. Changes in ocean current patterns; L. Other (please specify):"

Case Study	**Continent**	**Fishery scale**	**Fishery location**	**Primary productivity contributors**	**Climate stressor**
Galicia stalked barnacle fishery (Spain)	Europe	Small	Intertidal, Coastal or nearshore	Upwelling	Ocean warming, Increase or decrease in upwelling, Other (overfishing, oil spill, conflict with mussel seed harvesters)
United States West Coast Pacific sardine fishery	North America	Large	Coastal or nearshore, Shelf	Upwelling	Ocean warming, Frequency and/or severity of extreme El Nino-Southern Oscillation events, Other (overfishing)
Northeast Atlantic small pelagics fishery	Europe	Large	Pelagic shelf, Deep sea	Other (oceanic surface mixing, intrusions onto shelf)	Increase or decrease in upwelling
Kiribati giant clam fishery	Oceania	Small	Coastal or nearshore, Island	Coral reefs	Ocean acidification, Frequency and/or

					severity of marine heatwaves
California Dungeness crab fishery (United States	North America	Small	Coastal or nearshore	Upwelling, Vegetated habitats	Frequency and/or severity of marine heatwaves
Fiji nearshore fisheries	Oceania	Small	Coastal or nearshore, Intertidal, Island	Vegetated habitats, Coral reefs	Frequency and/or severity of marine heatwaves, Frequency and/or severity of large storm events, Sea level rise
Madagascar nearshore fisheries	Africa	Small	Intertidal, Estuary, Coastal or nearshore, Freshwater rivers, Rice paddies	Coral reefs	Ocean acidification, Frequency and/or severity of large storm events, Sea level rise, Other (changes in human nutrition)
United States Bering Sea groundfish fisheries	North America	Large	Shelf, Deep sea	Sea ice, Other (nutrient flux/stratification, wind patterns - inner-middle-outer fronts)	Frequency and/or severity of marine heatwaves, Loss of sea ice
Juan Fernandez Islands demersal fisheries (Chile)	South America	Small	Coastal or nearshore, Island	Vegetated habitats, Coral reefs	Frequency and/or severity of marine heatwaves, Other (invasive species, contamination)
Madang reef fish fishery (Papua New Guinea)	Oceania	Small	Coastal or nearshore, Island	Upwelling, Vegetated habitats, Coral reefs	Ocean acidification, Increase or decrease in upwelling
Iceland groundfish fisheries	Europe	Large	Shelf, Pelagic	Upwelling, Other (mixing of warm Atlantic and cold Polar currents, interactions with	Ocean warming

				submarine canyons and ridges)	
Maine American lobster fishery (United States)	North America	Small	Coastal or nearshore, Shelf	Other (currents, tidal mixing, seasonal turnover, wind patterns)	Ocean warming
Tasmania rock lobster fishery (Australia)	Oceania	Large	Coastal or nearshore, Shelf	Upwelling, Vegetated habitats, Other (rocky reeks, kelp forests, currents)	Ocean warming, Frequency and/or severity of marine heatwaves
Senegal small pelagics fishery	Africa	Small	Shelf	Upwelling, Fluvial inputs/plumes	Other (overfishing, shifting migratory patterns)
Mie spiny lobster fishery (Japan)	Asia	Small	Intertidal, Coastal or nearshore	Upwelling (Kuroshio Current)	Ocean warming
United States Atlantic and Gulf of Mexico highly migratory pelagic longline fishery	North America	Large	Coastal or nearshore, Shelf, Deep sea, Open ocean	Upwelling, Fluvial inputs/plumes, Vegetated habitats, Coral reefs	Other (overfishing)
Moorea reef fish fishery (French Polynesia)	Oceania	Small	Coastal or nearshore, Island	Coral reefs	Ocean acidification, Frequency and/or severity of marine heatwaves, Frequency and/or severity of large storm events, Sea level rise, Other (ocean pollution)
Hokkaido set-net fishery (Japan)	Asia	Small	Coastal or nearshore	Fluvial inputs/plumes	Other (shifting migratory patterns)

Figure S1. Spearman rank correlation plot between importance and score per attribute. Attributes are organized by dimension and are ordered by decreasing Spearman rank correlation coefficient. Attributes with moderate or strong correlations between importance and score are bolded (n = 11; $\rho \geq 0.5$; gray dashed line). No correlation ($\rho = 0$) is denoted by a gray dotted line. $\rho = 0.31$ when all attributes and case studies are considered together.

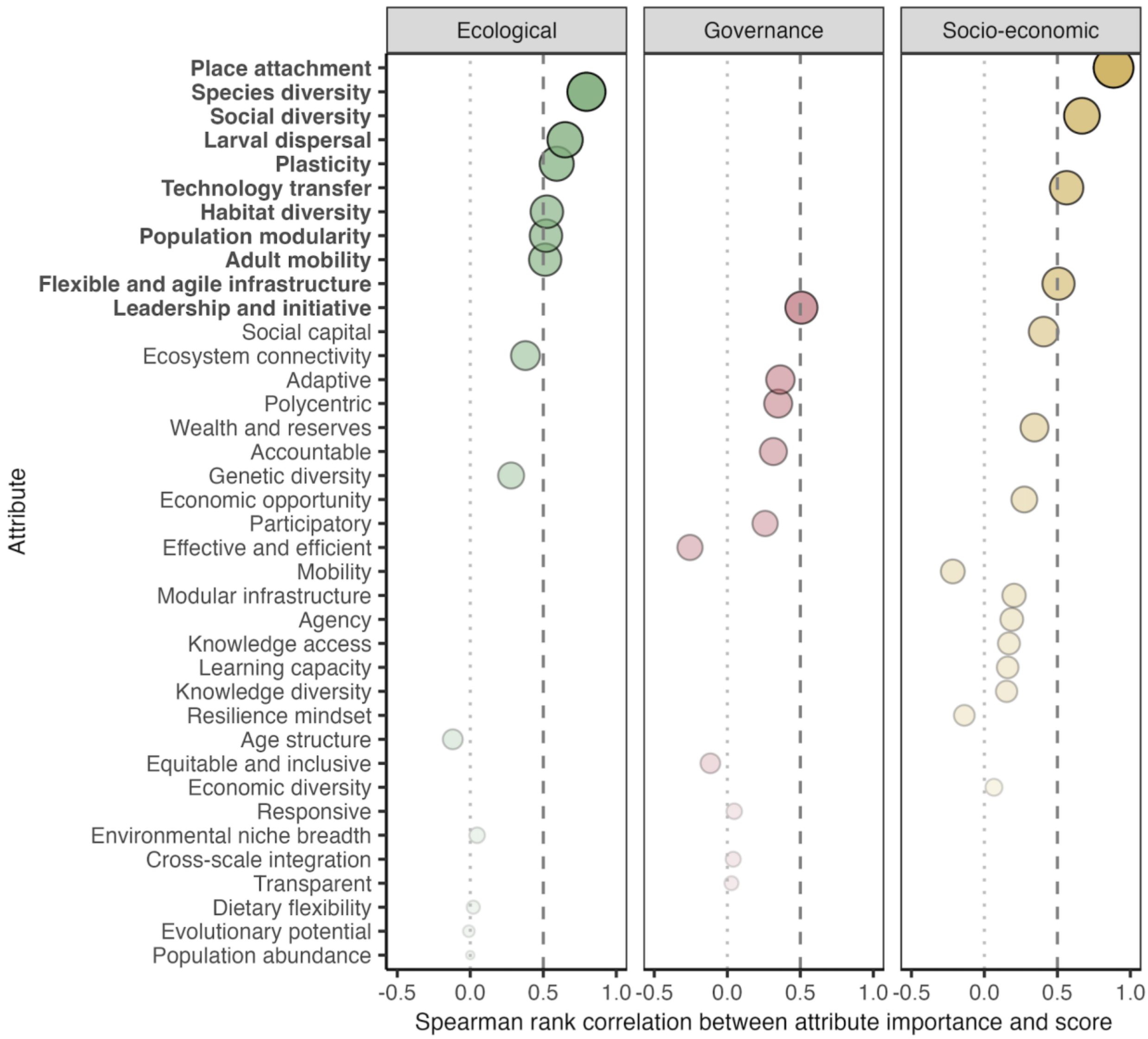


Figure S2. The quality of the data used to score attributes in the 18 evaluated case studies. Attributes are organized by dimension and are ordered by decreasing average data quality.

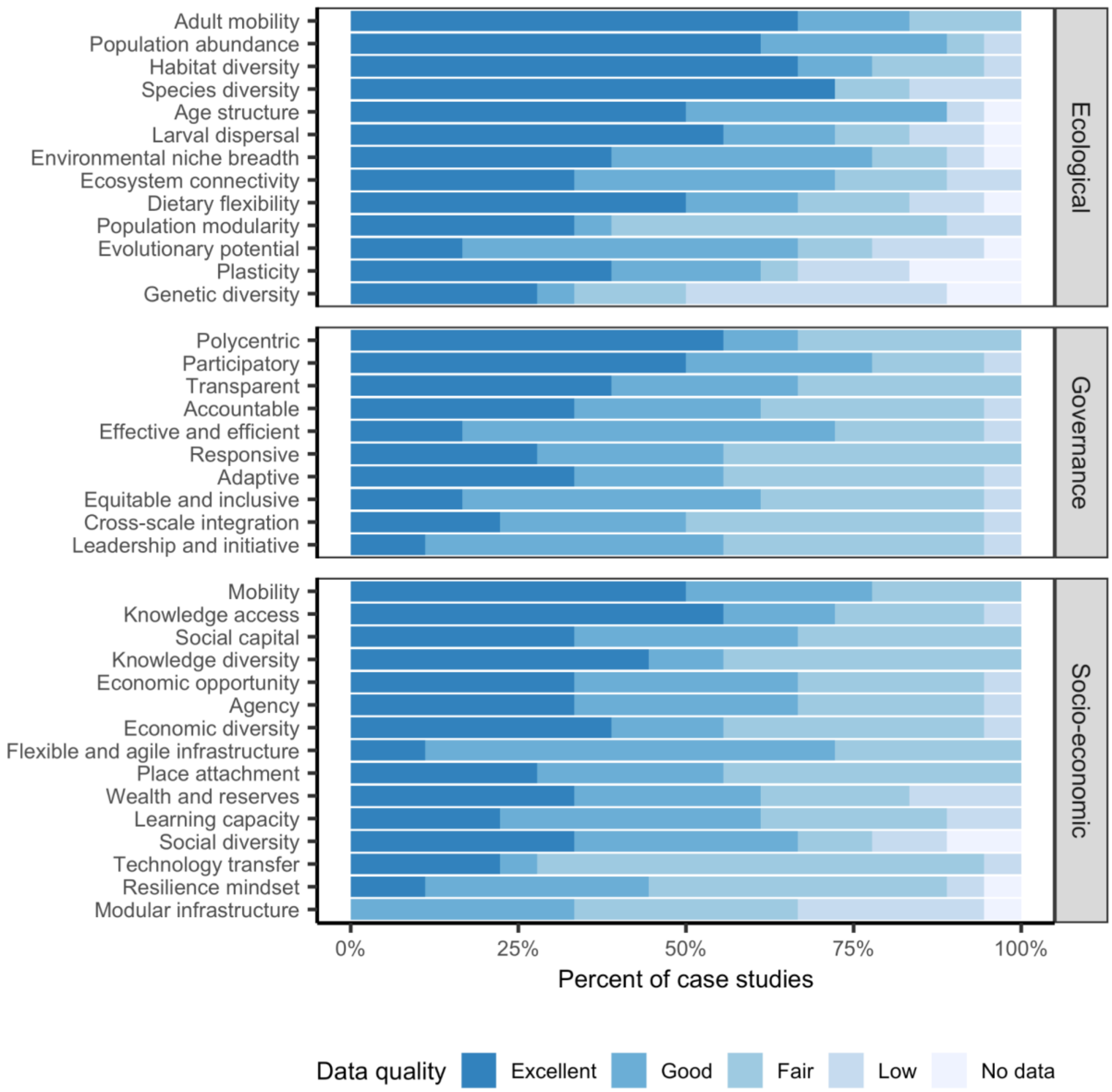
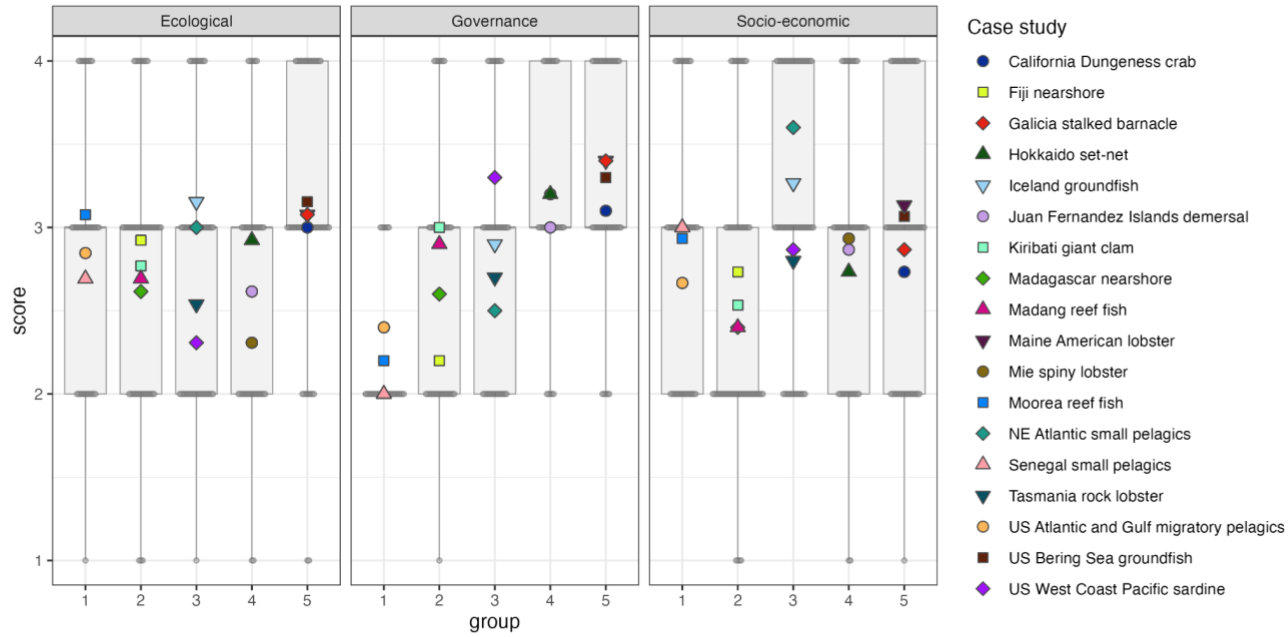


Figure S3. Mean attribute score by case study (colored shapes), cluster group (x-axis), and dimension (panels). Gray points and boxplots show the underlying distribution of all attribute scores from the cases within each group and dimension.



Appendix 2

Case study rubric.

Note: the below information was a pilot research project and was incorporated into the Climate-Resilient Fisheries Planning Tool, a product of the Science for Nature and People Partnership (SNAPP) working group on Climate-Resilient Fisheries.

For the pilot research project, case study authors were provided with the following instructions and questions:

Directions: Based on the information and evaluation of the fishery system provided in the preceding modules, please provide your assessment of capacities (and conversely, limitations) that will affect its ability to be resilient to the impacts of climate change. This assessment should reflect current capacities in the system. Questions are open-ended and responses should be in the form of short narrative statements. The "questions to consider" are intended to prompt thinking about potentially relevant topics, but are not meant to constrain responses to only those topics.

For each question:
1. Use the yellow cells to record your response & information quality [not shown here].
2. Indicate 'Don't know' or 'Not relevant' in the appropriate columns as needed. (Then select Option E or Option NA in the 'information quality' column.)
3. Record any additional information in the gray cells.

Information quality scoring: For each question, please use the 'information quality' column to indicate the quality of the answer provided by using the following metrics:
A - The answer provided is based on adequate and reliable data/information
B - The answer provided is based on limited data/information and expert judgment
C - The answer provided is based solely on expert judgment, and I am fairly confident that the answer provided reflects the true state of the system
D - The answer provided is based solely on expert judgment, but I am not confident that if the answer provided reflects the true state of the system
E - No data. I do not have sufficient information available to answer this question and no basis for providing an expert opinion.
NA - Not relevant in this system

Resilience attributes (Section 4):
For each resilience attribute, indicate the degree to which this attribute is present within the fishery system (Column G) and evaluate the information quality associated with that score (Column K). For each attribute, a mechanism for how it influences resilience is proposed in

Column L. In Column M, please indicate whether the mechanism works as described in the fishery system being studied. If 'yes', additional notes can be provided in Column O. If 'no', please explain why not or indicate an alternative mechanism relevant to this fishery case in column N. If the respondent doesn't have sufficient information to score an attribute, indicate 'don't know' (Column I). Then select option E in Column K and 'NA' in Column M. If the attribute is not relevant to the fishery system, indicate 'not relevant' (Column J). Then select option F in Column K and 'NA' in Column M. For each subset of resilience attributes, provide a brief description of those features and how they exist and are being maintained in the system.

Section 1 - Key Case Identifiers		
Sub-section	**Question ID**	**Question**
1.1.	1.1.1.	Name of fishery system
1.2.	1.2.1.	What species are fished? (If multi-species, please list all) *
1.3.	1.3.1.	Where does the fishery occur geographically? (LAT; LON) *
1.4. Spatial	1.4.1.	At what spatial scale are you considering the system? (km2) *
	1.4.2.	What are the lat/lon bounding coordinate of the system. *
1.5. Temporal	1.5.1.	At what temporal scale are you considering this system? (over how many past years)
	1.5.2.	At what temporal scale are you considering this system? (over how many future years)?
1.6.	1.6.1.	What is the scale of the fishery? A. Large-scale B. Small-scale C. Mixed
1.7.	1.7.1.	Who are the actors within the fishery system? A. Fishers B. Traders/dealers C. Processors D. Local community E. Scientists F. Resource Managers G. Others (please specify):
	1.7.2.	Of the actors listed above, which do you know enough about to consider in this case study? A. Fishers B. Traders/dealers

		C. Processors D. Local community E. Scientists F. Resource Managers G. Others (please specify):

Section 2 - Contextual Description		
Sub-section	**Question ID**	**Question**
2.1.1.	2.1.1.1.	What is the physical context within which the fishery takes place? Check all that apply: A. Intertidal (e.g. beach, mangrove) B. Estuary C. Coastal/nearshore (e.g. lagoon, fjord, coral reef, archipelago) D. Shelf E. Deep sea (e.g. canyon) F. Other (*please specify*):
2.1.2.	2.1.2.1.	Which of the following contribute to primary productivity? A. Upwelling B. Fluvial inputs/plumes C. Sea ice D. Vegetated habitats (e.g. salt marsh, mangroves, seagrasses, kelp forests) E. Coral reefs F. Other (*please specify*):
2.1.3. Species	2.1.3.1.	What is/are the focal species of the fishery? *Please describe*:
2.1.3. Species	2.1.3.2.	What are the recent population trends (at a time scale relevant to focal species lifespan)? (For a multispecies fishery, please generally describe types of population trends for groups of species in the "describe" column.) A. Increasing B. Stable C. Declining D. Threatened or vulnerable E. Insufficient data
2.1.4. Habitat	2.1.4.1.	What is the key habitat that supports species in this fishery? *Please*

		describe:
2.1.4. Habitat	2.1.4.2	What is the general status of the key habitat used by species in this fishery? (select one) A. Favorable B. Inadequate to unfavorable C. Unfavorable D. Collapsed E. Data deficient
2.1.4. Habitat	2.1.4.3.	Trend in key habitats: A. Improving B. Stable C. Deteriorating D. Data deficient
2.1.5. Stressors	2.1.5.1.	Is overfishing currently occuring on the stock/stocks in this fishery? (For a multispecies fishery, please *describe* which stocks (or groups of stocks) are overfished in the "describe" column. A. Yes - substantially B. Yes - moderately C. Yes - minimally D. No E. Data deficient
2.2.1. Social	2.2.1.1.	Are cultural, traditional, and historic practices observable? A. Yes, *please describe:* B. No
2.2.1. Social	2.2.1.2.	How dependent are harvesters on the fishery for food or nutrition compared to their dependence on other food options? Please indicate the general range if there is a high degree of variability among participants. A. High B. Moderate C. Low D. NA
2.2.1. Social	2.2.1.3.	How dependent are the communities on the fishery for food or nutrition compared to their dependence on other food options? Please indicate the general range if there is a high degree of variability among participants. A. High B. Moderate

		C. Low D. NA
2.2.1. Social	2.2.1.4.	Are any groups particularly dependent on this fishery for food or nutrition? A. Indigenous B. Women C. Rural D. Other (*please specify*):
2.2.2. Political governance quality	2.2.2.1.	What is the average of the following indicator in the World Bank's Governance Indicators, each scored [-2.5,2.5] ? Government Effectiveness
2.2.2. Political governance quality	2.2.2.2.	What is the average of the following indicator in the World Bank's Governance Indicators, each scored [-2.5,2.5] ? Regulatory Quality
2.2.2. Political governance quality	2.2.2.3.	What is the average of the following indicator in the World Bank's Governance Indicators, each scored [-2.5,2.5] ? Rule of Law
2.2.2. Political governance quality	2.2.2.4.	What is the average of the following indicator in the World Bank's Governance Indicators, each scored [-2.5,2.5] ? Control of Corruption
2.2.2. Political governance responsiveness	2.2.2.5.	What is the average of the following indicator in the World Bank's Governance Indicators, each scored [-2.5,2.5] ? Voice and Accountability
2.2.2. Political governance responsiveness	2.2.2.6.	What is the average of the following indicator in the World Bank's Governance Indicators, each scored [-2.5,2.5] ? Political Stability
2.2.3 Economic	2.2.3.1.	Which income category does(do) the harvesting country(ies) belong to (see definition by World Bank here)? A. High

		B. Upper-middle C. Lower-middle D. Low
2.2.3 Economic	2.2.3.2.	What kind of sectors operate in the fishery? A. Small operators B. Large operators C. Recreational D. Artisanal E. Indigenous F. Other (*please specify*):
2.2.3 Economic	2.2.3.3.	What is the current landed volume? *Please describe and indicate year represented:*
2.2.3 Economic	2.2.3.4.	What is the current landed value? *Please describe and indicate year represented:*
2.2.3 Economic	2.2.3.5.	What are the trends in landings over the past 10 years? (For a multispecies fishery, this response should represent the fishery as a whole, not individual stocks.) A. Increasing B. Declining C. Stable D. Variable with no clear trend E. Data deficient
2.2.3 Economic	2.2.3.6.	Approximately how many vessels participate? *Please describe and estimate of number or order of magnitude: tens, hundreds, thousands:*
2.2.3 Economic	2.2.3.7.	How dependent are harvesters on the fishery for jobs and income compared to their other livelihood options? Please indicate the general range if there is a high degree of variability among participants. A. High B. Moderate C. Low D. NA
2.2.3 Economic	2.2.3.8.	How dependent are shoreside businesses on the fishery for jobs and income compared to their other livelihood options? Please indicate the general range if there is a high degree of variability among participants. A. High B. Moderate C. Low

		D. NA
2.2.3 Economic	2.2.3.9.	How dependent are dealer/processors on the fishery for jobs and income compared to their other livelihood options? Please indicate the general range if there is a high degree of variability among participants. A. High B. Moderate C. Low D. NA
2.2.3 Economic	2.2.3.10.	How dependent is the community on the fishery for economic benefits compared to its other sources of revenue? A. High B. Moderate C. Low D. NA
2.2.3 Economic	2.2.3.11.	What is the primary purpose for utilization of the species harvested? A. Fresh consumption B. Processed (value-added) products (including both domestic and export-oriented) C. Export product D. Other (*please specify)*:
2.3.1.	2.3.1.1.	Within which jurisdiction(s) is the fishery contained? A. One domestic regional jurisdiction B. Multiple domestic regional jurisdictions C. One coastal state D. Multiple coastal states E. Areas Beyond National Jurisdiction (ABNJ) F. Other (*please specify*):
2.3.2.	2.3.2.1.	What laws, policies and practices exist concerning the fishery and are they upheld? (If you know them, or can easily look up, please list name of the statute and year in 'notes' column) A. International Treaty B. National C. Regional (State, Province, Prefecture, etc.) D. Municipal/Local E. Community (Including formal and informal rules and practices. implemented by local cooperatives, sectors, and other organizations) F. Other (*please specify*):

2.3.3.	2.3.3.1.	What is the nature of governance arrangements? A. Top-down B. Community-based (e.g. LMMA, TURF) C. Co-management D. Traditional/customary (e.g. ICCA) E. Other (*please specify*):
2.3.4.	2.3.4.1.	Who is involved in governance? A. Multinational fishery management body B. National government agencies C. Regional (State, Province, Prefecture, etc.) government agencies D. Municipal/local government agencies E. Individual harvesters or harvester associations F. Dealers, processors or their associations G. Shoreside businesses H. Environmental NGOs I. Community organizations J. Other (*please specify*):
2.3.5.	2.3.5.1.	Do <u>Financial Resources</u> confer or limit the capacity to effectively participate in the governance system? *Please describe; note whether your selection pertain to particular groups selected above* A. Confers B. Limits C. Neither confers or limits D. Both confers and limits
2.3.5.	2.3.5.2.	Do Human Resources confer or limit the capacity to effectively participate in the governance system? Please describe; note whether your selection pertain to particular groups selected above A. Confers B. Limits C. Neither confers or limits D. Both confers and limits
2.3.5.	2.3.5.3.	Do Social Factors (trust, social networks) confer or limit the capacity to effectively participate in the governance system? Please describe; note whether your selection pertain to particular groups selected above A. Confers B. Limits C. Neither confers or limits D. Both confers and limits

2.3.5.	2.3.5.4.	Does Scientific Competency confer or limit the capacity to effectively participate in the governance system? Please describe; note whether your selection pertain to particular groups selected above A. Confers B. Limits C. Neither confers or limits D. Both confers and limits
2.3.5.	2.3.5.5.	Do Other factors (please specify) confer or limit the capacity to effectively participate in the governance system? Please describe; note whether your selection pertain to particular groups selected above A. Confers B. Limits C. Neither confers or limits D. Both confers and limits
2.3.6.	2.3.6.1.	Is power in the governance system related to religion, gender, ethnic origin, political party, language, race or sexual orientation? A. Yes, *please describe*: B. No
2.3.7.	2.3.7.1.	Do power relations cause tension within the fishery? A. Yes, *please describe*: B. No
2.4.1.	2.4.1.1.	Does a management plan exist for this fishery? A. Yes, *please describe*: B. No
2.4.2.	2.4.2.1	Who is involved in the management process? A. Multinational fishery management body B. National government agencies C. Regional government agencies (State, Province, Prefecture, etc.) D. Municipal/local government agencies E. Individual harvesters or harvester associations F. Dealers, processors or their associations G. Shoreside businesses H. Environmental NGOs I. Community organizations J. Other (*please specify*):
2.4.3.	2.4.3.0.	Who plays the following roles in the fishery management process? Each may include multiple actors (2.4.3.1 - 2.4.3.5). (*Please write response in 'describe' column.*)

2.4.3.	2.4.3.1.	Determining access and harvest rights
2.4.3.	2.4.3.2.	Determining harvest procedures and rules
2.4.3.	2.4.3.3.	Enforcing rules
2.4.3.	2.4.3.4.	Monitoring fishery activity (e.g., catch)
2.4.3.	2.4.3.5.	Providing scientific information
2.4.3.	2.4.3.6.	Please add any other roles important to fisheries management in your case and indicate which actors play that role.
2.4.4.	2.4.4.1.	What are the tools used to control catch? (please check all that apply) A. None specific to this fishery B. Total allowable catch limit C. Individual catch limit D. Total allowable effort limit E. Individual effort limit F. Size limits G. Spatial restrictions on fishing H. Temporal restrictions on fishing I. Gear restrictions J. Species restrictions K. Other (*please specify*):
2.4.5.	2.4.5.1.	What measures are taken to conserve habitats? A. None specific to this fishery B. Gear restrictions C. Season closure D. Year-round no-take zones E. Seasonal no-take zones F. Other (*please specify*):
2.4.6.	2.4.6.1.	Are management enforced, and if so, how? A. Not routinely enforced B. Fines and penalty fees C. Revocation of access and harvest rights D. Social ostracism E. Other (*please specify*):
2.4.7.	2.4.7.1.	What fishery dependent data are collected to support management? A. Landed volume B. Discard volume C. Landed value D. Size

		E. Other (*please specify*):
2.4.7.	2.4.7.2.	Who collects and reports the fishery dependent data? A. National government agencies B. Regional (State, Province, Prefecture, etc.) government agencies C. Municipal/local government agencies D. Individual harvesters or harvester associations E. Dealers, processors or their associations F. Environmental NGOs G. Community organizations H. Other (*please specify*):
2.4.7.	2.4.7.3.	Are fishery-independent data (e.g., trawl survey) collected to support management? A. Yes B. No
2.4.7.	2.4.7.4.	Who collects fishery-independent data? A. National government agencies B. Regional (State, Province, Prefecture, etc.) government agencies C. Municipal/local government agencies D. Individual harvesters or harvester associations E. Dealers, processors or their associations F. Environmental NGOs G. Community organizations H. Universities and/or other scientific organizations I. Other (*please specify*):
2.4.7.	2.4.7.5.	How often are fishery-independent data collected? A. Seasonal (2 ~ 4 times a year) B. Annual C. Every 2 ~ 5 years D. Undermined frequency E. Other (*please specify*):
2.4.7.	2.4.7.6.	Are environmental data collected to support management? A. No B. Yes, in situ samples C. Yes, from buoys D. Yes, from remote sensing E. Yes, other (*please specify*):
2.4.7.	2.4.7.7.	Who collects and manages environmental data? A. National government agencies

		B. Municipal/local government agencies C. Individual harvesters or harvester associations D. Dealers, processors or their associations E. Environmental NGOs F. Community Regional (State, Province, Prefectures, etc.) G. Universities and/or other scientific organizations H. Other (*please specify*):
2.4.8.	2.4.8.1.	What are the general types of information sources used to manage the fishery? A. Local knowledge B. Scientific observation C. Stock assessment process D. Other (*please specify*):
2.4.9.	2.4.9.1.	How is stock size tracked? *Please describe.*
2.4.9.	2.4.9.2.	If stock assessments are in place, what types are used and who conducts them? *Please describe.*
2.4.9.	2.4.9.3.	If stock assessments are not in place, are data synthesized in any manner to track stock size trends or status? If so, who conducts the synthesis? *Please describe.*
2.5.1.	2.5.1.1.	Has the system experienced any major shocks in the last 20 years (detrimental or beneficial)? A. No shocks B. Environmental shocks (e.g. coral bleaching event, marine heatwave, king tide flooding or sea level rise, predator or invasive species outbreaks, disease events, typhoon/hurricane/cyclones, earthquake/tsunami, volcano, pollution, oil spills, nuclear disaster) C. Governance/management shocks (e.g. change in political/ruling party, change in fishery management structure, change in management approach) D. Socio-economic shocks (e.g. military conflicts, public health crises, recessions, major supply chain disruptions) E. Other (*please specify*):
2.5.2.	2.5.2.1.	Please identify the most important shocks (of any type) experienced in the system that have shaped its current structure, status, and capacities. *Describe briefly.*
2.5.3.	2.5.3.1.	What were the major impacts on natural (e.g., biological, oceanographic, coastal landscapes, habitat), human (e.g., economic, social, governmental), and coupled systems caused by the shock or

		shocks mentioned above? *If multiple shocks occurred, please describe and be specific about which shocks caused which effects to the fishery or stock(s).*
2.5.4.	2.5.4.1.	What actions were taken to alleviate such impacts, and who took (or contributed to) these actions? *If multiple shocks occurred, please describe and be specific about which actions are associated with which shock.*
2.5.5.	2.5.5.1.	Subsequently what happened to the natural, human, or coupled system? A. Full recovery to the pre-shock state B. Recovering towards the pre-shock state C. Transformed to a different state but still providing valuable services D. Transformed to different state but losing a majority of services E. System still responding, outcome not yet known
2.5.6.	2.5.6.1.	What kind of changes do we observe in the natural, human, or coupled systems if we compare pre-shock state to post-shock state? *Describe briefly*.
2.5.7.	2.5.7.1.	Did experiences during this shock lead to changes that will enhance resilience to future shocks? *Please describe.*
2.6.1.	2.6.1.1.	What types of climate change projections are available for the system? A. Global climate models only B. Downscaled regional projects C. Other (*please specify*):
2.6.2.	2.6.2.1.	What time frame is most relevant to this case study, for which projections are available within your consideration? A. Projections to 2050 B. Projections to 2100 C. Interdecadal variability D. Interannual variability E. Other (*please specify*):
2.6.3.	2.6.3.1.	What are the key limitations of available climate projections in the context of this case study? *Please describe.*
2.6.4.	2.6.4.1.	Which of the following climate disturbances are projected to alter the future of the fishery and surrounding ecosystem? A. Ocean warming B. Ocean acidification C. Frequency and/or severity of coral bleaching

		D. Frequency and/or severity of marine heatwaves E. Frequency and/or severity of extreme El Nino-Southern Oscillation events F. Frequency and/or severity of large storm events G. Ocean cooling H. Loss of sea ice I. Sea level rise J. Increase or decrease in upwelling K. Changes in ocean current patterns L. Other (*please specify*):
2.6.5.	2.6.5.1.	How is climate change expected to affect physical conditions (e.g. water chemistry, habitat availability or quality, primary productivity) in the system? *Describe briefly*.
2.6.6.	2.6.6.1.	How is climate change expected to affect the species that are the focus of this fishery case (e.g. abundance, distribution, phenology)? *Describe briefly*.
2.6.7.	2.6.7.1.	How is climate change expected to affect fishing opportunities and the fishery (e.g. yield, variability, effort)? *Describe briefly*.
2.6.8.	2.6.8.1.	How is climate change expected to affect social and economic conditions of individuals and communities (e.g. overall profit, profit distribution, trade mechanisms, societal effects (e.g. markets, migration, labor, consumption), harvest safety, infrastructure, or other livelihood opportunities)? *Describe briefly*.
2.6.9.	2.6.9.1.	Will climate change and fishing interact in ways that could create negative or positive feedback loops for the natural, human, or coupled system? If so, how would these dimensions interact and in what direction? *Describe briefly*.
2.6.10.	2.6.10.1.	Are there any perverse incentives created by climate change? *Describe briefly*.

Section 3 - Climate-Resilient Actions			
Topic	**Sub-section**	**Question ID**	**Question**
General resilience	3.1.1.	3.1.1.1.	What types of measures have been adopted to foster <u>general resilience</u> in the ecological dimension of the fishery system?

General resilience		3.1.1.2	What types of measures have been adopted to foster general resilience in the social dimension of the fishery system?
General resilience		3.1.1.3	What types of measures have been adopted to foster general resilience in the economic dimension of the fishery system?
General resilience		3.1.1.4	What types of measures have been adopted to foster general resilience in governance and management of the fishery system?
Specific resilience short-term	3.2.1.	3.2.1.1.	What actions have been taken to support climate resilience in response to short-term uncertainties and shocks that occur unexpectedly (e.g., heatwave, disease event, storms)? Consider the ecological, social, economic, governance and management dimensions of the system.
Specific resilience short-term		3.2.1.2.	Were these measures designed to “resist”, “recover” from, or “adapt” to climate effects?
Specific resilience short-term		3.2.1.3.	How were these measures put in place? (What features of and mechanisms in the system enabled them to be enacted?)
Specific resilience short-term		3.2.1.4.	Were there any specific resilience attributes present in the system that enabled or prompted these action(s)?
Specific resilience long-term	3.2.2.	3.2.2.1.	What actions have been taken to support long-term climate resilience to plan and prepare for expected future changes (e.g., planning/preparedness, conservation measures, rights/entitlements, adaptive institutional or management processes)?
Specific resilience long-term		3.2.2.2.	Were these measures designed to “resist”, “recover” from, or “adapt” to climate effects?
Specific resilience long-term		3.2.2.3.	How were these measures put in place? (What features of and mechanisms in the system enabled them to be enacted?)
Specific resilience		3.2.2.4.	Were there any specific resilience attributes present in the system that enabled or prompted these action(s)?

long-term			
Climate resilience actions	3.2.3.	3.2.3.1.	Are short- or long-term climate resilience actions directed mainly towards one dimension of the system (e.g., ecological, social, economic, governance), or will they preferentially benefit one dimension of the system? How?
Climate resilience actions	3.3.1.	3.3.1.1.	Are there any clear steps that should be taken, but are not currently in place, to enhance climate resilience in the fishery? What types of benefits would be expected from these actions?

Section 4 - Resilience Attributes					
Dimensions	**New Domain**	**Question ID**	**Resilience attribute**	**Definition**	**Options**
Ecological	Assets		Population abundance	The abundance or biomass of a species present in a defined geographic range.	1 - Very low abundance (Critical) 2 - Low abundance (Overfished) 3 - Moderate abundance 4 - High abundance
Ecological	Assets	4.1.3.5	Age structure	The age distribution of individuals within a population.	1 - Highly disturbed (e.g age-truncated, skewed) 2 - Moderately disturbed 3 - Mildly disturbed 4 - Undisturbed/in-tact
Ecological	Assets	4.1.3.3	Genetic diversity	The diversity or variability of genetic traits within a population.	1 - No diversity 2 - Limited diversity 3 - Moderate diversity 4 - High diversity
Ecological	Assets	4.1.3.2	Species diversity	The diversity of species within a	1 - No diversity 2 - Limited

				community.	diversity 3 - Moderate diversity 4 - High diversity
Ecological	Assets	*Please describe the role of* ***<u>ecological assets</u>*** *in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Ecological	Flexibility	4.1.2.5	Adult mobility	The mobility of a population's mature adults.	1 - Movement is completely restricted 2 - Movement is somewhat restricted 3 - Movement is minimally restricted 4 - Movement is unrestricted
Ecological	Flexibility	4.1.2.4	Larval dispersal	The degree to which eggs or larvae spread from a spawning site to a settlement location (benthic species) or until yolk sac re-adsorption (pelagic species).	1 - No capacity 2 - Weak capacity 3 - Moderate capacity 4 - Strong capacity
Ecological	Flexibility	4.1.1.1	Environmental niche breadth	The degree and extent to which a species can tolerate or acclimate to changes in environmental conditions.	1 - No capacity 2 - Weak capacity 3 - Moderate capacity 4 - Strong capacity
Ecological	Flexibility		Dietary flexibility	The range of prey items that a population can exploit or the diversity of feeding strategies available.	1 - No diversity 2 - Limited diversity 3 - Moderate diversity

					4 - High diversity
Ecological	Flexibility	4.1.3.1	Habitat diversity	The range of suitable, adjacent, and available habitats that a population can exploit.	1 - No diversity 2 - Limited diversity 3 - Moderate diversity 4 - High diversity
Ecological	Flexibility	4.1.1.2	Plasticity	The capacity for one genotype to yield more than one phenotype in response to environmental cues.	1 - No capacity 2 - Weak capacity 3 - Moderate capacity 4 - Strong capacity
Ecological	Flexibility	4.1.1.3	Evolutionary potential	The capacity of a population to evolve in response to environmental change.	1 - No capacity 2 - Weak capacity 3 - Moderate capacity 4 - Strong capacity
Ecological	Flexibility	*Please describe the role of* ***ecological flexibility*** *in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Ecological	Organization	4.1.2.2	Ecosystem connectivity	The degree to which an ecosystem facilitates the structural and physical connection among suitable, adjacent, and/or available ecosystem functions and components.	1 - Fully disconnected 2 - Weakly connected 3 - Moderately connected 4 - Strongly connected
Ecological	Organization	4.1.2.3	Population modularity	Modularity, the opposite of connectivity, refers to the compartmentalization of populations in space	1 - Fully connected 2 - Weakly modular 3 - Moderately modular 4 - Strongly modular

				and time.	
Ecological	Organization	*Please describe the role of* ***<u>ecological organization</u>*** *in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Socio-economic	Assets	4.2.3.2	Wealth and reserves	The aggregate value of assets available to individuals, organizations, and communities that contribute to human well-being.	1 - Fully connected 2 - Weakly modular 3 - Moderately modular 4 - Strongly modular
Socio-economic	Assets	4.2.1.2	Economic diversity	The variety of income earning activities that an individual, household, or community can partake in.	1 - Highly concentrated (no diversity) 2 - More concentrated than distributed 3 - More distributed than concentrated 4 - Highly distributed
Socio-economic	Assets	4.2.1.1	Social diversity	The variety of social characteristics that shape the preferences, attitudes, values, and norms in a particular population.	1 - No diversity 2 - Limited diversity 3 - Moderate diversity 4 - High diversity
Socio-economic	Assets	*Please describe the role of* ***<u>socio-economic assets</u>*** *in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Socio-economic	Flexibility		Flexible and agile	The ability of built structures and facilities	1 - No flexibility 2 - Limited

			infrastructure	to provide needed services under a wide range of conditions and to quickly respond to predictable and unpredictable changes.	flexibility 3 - Moderate flexibility 4 - High flexibility
Socio-economic	Flexibility	4.2.2.1	Mobility	An individual's and/or community's ability to move freely and easily, either temporarily or permanently.	1 - No mobility 2 - Limited mobility 3 - Moderate mobility 4 - High mobility
Socio-economic	Flexibility	4.2.2.3	Economic opportunity	Physical (e.g., transportation network) and non-physical (e.g., social relations) means and processes that enable individuals and communities to benefit from new or alternative income-earning or subsistence activities.	1 - Not accessible 2 - Limited accessibility 3 - Moderate accessibility 4 - High accessibility
Socio-economic	Flexibility	4.2.5.1	Resilience mindset	The degree to which individuals accept "resilience thinking" from a perspective that recognizes characteristics of complexity, uncertainty, nonlinearity, thresholds, feedbacks, irreversibility, and multi-scale and multi-level interactions in a changing world.	1 - No capacity 2 - Limited capacity 3 - Moderate capacity 4 - High capacity
Socio-economic	Flexibility	4.2.2.5	Place attachment	The extent to which individuals and	1 - No attachment 2 - Limited

				communities feel tied to the geographical location in which they live and operate, affecting their response to risk, including willingness to move homes, fishing grounds, or processing location in the face of adverse conditions.	attachment 3 - Moderate attachment 4 - High attachment
Socio-economic	Flexibility	*Please describe the role of **socio-economic flexibil**ity in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Socio-economic	Organization	4.2.2.2	Social capital	The strength of networks of relationships among people and organizations who live and work in a particular community.	1 - No social capital 2 - Limited social capital 3 - Moderate social capital 4 - High social capital
Socio-economic	Organization	4.2.4.3	Technology transfer	The level and capacity of individuals and communities to develop and acquire new technologies and methods as well as the ease with which these technologies and methods are transferred between and among actors in the system.	1 - No capacity 2 - Limited capacity 3 - Moderate capacity 4 - High capacity
Socio-economic	Organization	4.2.3.1	Modular infrastructur	The degree of compartmentalization	1 - No ability 2 - Limited ability

			e	within and across built structures and facilities and the ease with which diffusion can proceed.	3 - Moderate ability 4 - High ability
Socio-economic	Organization	*Please describe the role of* ***socio-economic organization*** *in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Socio-economic	Learning	4.2.1.3	Knowledge diversity	The variety of types and origins of knowledge that are available to individuals and members of the community.	1 - No diversity 2 - Limited diversity 3 - Moderate diversity 4 - High diversity
Socio-economic	Learning	4.2.4.1	Knowledge access	The ability of individuals and communities to obtain and derive benefit from existing knowledge about the system.	1 - Not accessible 2 - Limited accessibility 3 - Moderate accessibility 4 - High accessibility
Socio-economic	Learning	4.2.4.2	Learning capacity	The degree to which individuals and communities are able to perceive risk, learn from experience, synthesize information, and grow their own knowledge.	1 - No capacity 2 - Limited capacity 3 - Moderate capacity 4 - High capacity
Socio-economic	Learning	*Please describe the role of* ***learning*** *in the socio-economic dimension of the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)

Socio-economic	Agency	4.2.2.4	Agency	The capacity of individuals and communities to negotiate, make decisions, and act on their own free will.	1 - No capacity 2 - Limited capacity 3 - Moderate capacity 4 - High capacity
Socio-economic	Agency	*Please describe the role of **social and economic agency** in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Governance	Flexibility	4.3.3.2	Responsive	The sensitivity, readiness, speed, and accuracy with which a governance system handles, resolves, and follows up on a management-relevant change to meet stakeholders' needs (Sheng, 2009).	1 - Not responsive 2 - Limited 3 - Moderately responsive 4 - Highly responsive
Governance	Flexibility	*Please describe the role of **governance flexibility** in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Governance	Organization	4.3.2.1	Participatory	The degree to which an institution empowers participants to influence and share control in processes of public decision-making, ranging from intermittent consultation opportunities to ongoing self-	1 - Not participatory 2 - Limited participation 3 - Moderate participation 4 - High participation

				mobilization (Coghlan & Brydon-Miller, 2014; Leite & Pita, 2016).	
Governance	Organization	4.3.1.3	Equitable and inclusive	The degree to which the governance system is fair in the distribution of benefits and burdens (risks), participatory in rule and decision-making for relevant actors, and engaged and inclusive of marginalized and disadvantaged groups (Bennett et al., 2020).	1 - Not equitable 2 - Limited equitability 3 - Moderate equitability 4 - High equitability
Governance	Organization	4.3.1.1	Accountable	The degree to which decisions and decision makers can be held culpable to both the individuals and communities that they govern as well as to higher-level mandates, commitments, goals, and objectives they serve (Battista et al., 2019; Lebel et al., 2006; Ostrom, 1990).	1 - No accountability 2 - Limited accountability 3 - Moderate accountability 4 - High accountability
Governance	Organization	4.3.2.2	Transparent	The openness and accessibility of timely information, decision-making rules and procedures, and outcomes to members of the public or stakeholders affected by management actions (Clark et al.,	1 - Not transparent 2 - Limited transparency 3 - Moderate transparency 4 - High transparency

				2015; Davis & Hanich, 2020).	
Governance	Organization	4.3.1.2	Effective and efficient	The degree to which the governance system produces outcomes that achieve societal and/or fishery objectives while efficiently using available resources.	1 - Not effective or efficient 2 - Limited effectiveness or efficiency 3 - Moderate effectiveness or efficiency 4 - High effectiveness or efficiency
Governance	Organization	4.3.2.3	Polycentric	The degree to which multiple bodies at different levels of the governance system overlap and interact to make and enforce rules within a specific policy arena or location (Ostrom, 2005; Folke et al., 2005).	1 - Not polycentric 2 - Limited 3 - Moderately polycentric 4 - Highly polycentric
Governance	Organization	4.3.2.4	Cross-scale integration	The degree to which actors and/or organizations acknowledge, work with, and attempt to understand the relevance and transition of scale and the interlinkages between various other organizations, institutions, and management structures.	1 - No integration 2 - Limited integration 3 - Moderate integration 4 - High integration
Governance	Organization	*Please describe the role of **governance organization** in the fishery case you are*			(Please use yellow cell to describe)

		examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).			
Governance	Learning	4.3.3.1	Adaptive	The capacity to implement a structured, iterative process of continual innovation, testing, learning, and adjustment that facilitates robust, flexible decision-making and action in the face of uncertainty and complexity.	1 - Not adaptive 2 - Limited 3 - Moderately adaptive 4 - Highly adaptive
Governance	Learning	*Please describe the role of* ***governance learning*** *in the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*			(Please use yellow cell to describe)
Governance	Agency	4.3.4.2	Leadership and initiative	A system that legitimizes and supports the development of leaders who are guided by collective interests, who mobilize and direct responses to disruptions (Kerner & Thomas 2014, pp 682), and who take responsibility and act when necessary (Bodin & Crona, 2008; Gutierrez et al., 2011, Crona et al., 2017).	1 - No leadership 2 - Limited leadership 3 - Moderate leadership 4 - Strong leadership

Governance	Agency	*Please describe the role of **agency** in governance of the fishery case you are examining. If this is a critical domain, please indicate details of how its associated attributes exist and are maintained in the system (i.e., how it has been operationalized).*	(Please use yellow cell to describe)

Section 5 - Capacity of Systems to Improve Climate resilience		
Question ID	**Question**	**Questions to Consider**
5.1.	Is the scientific system able to document and forecast climate-related changes in the fishery?	Do data collection systems document changes at appropriate scales (spatial and temporal)? How have these been received and used? Are future projections available for the fishery? How have these been received and used?
5.2.	Is the harvesting system itself adaptive to climate change?	Do participants know about and anticipate climate-driven changes as they make decisions? Are participants adjusting operations or tactics to respond to change or prepare for future changes?
5.3.	Is the social dimension of the fishery system adaptive in the face of climate change?	Do people consider ongoing and future change in the fishery system as they make decisions? Are there opportunities to learn and innovate to respond as changes occur? Are there resources available to support desired changes?
5.4.	Is the economic dimension of the fishery system adaptive in the face of climate change?	Are markets adapting to climate-driven changes in species availability? Does the fishery have influence in the market such that market-driven solutions could support climate adaptation? Are economic incentives or penalties being used to influence responses to climate change? Are there economic resources (e.g., loans, insurances) available to assist adaptation to climate change?
5.5.	Are the governance dimensions of the fishery system set up to anticipate responses needed for climate trends or events?	Is it highly centralized, or is there a balance between the central and local authorities? Are there powerful vested interests that resist change, or powerful actors that innovate and promote change?

5.6.	Are the management dimensions of the fishery system capable of designing and implementing measures for additional resilience, and doing so in a timely fashion?	Are there policies in place that either facilitate or limit responses to change? In what ways is management adjusting tactics to respond to change or prepare for future changes?

Appendix 3

Case study executive summary narratives ordered by cluster groupings.

Note: the below information was a pilot research project and was incorporated into the Climate-Resilient Fisheries Planning Tool, a product of the Science for Nature and People Partnership (SNAPP) working group on Climate-Resilient Fisheries.

For the pilot research project, case study authors were provided with the following instructions:

We will document case studies of a diverse set of fishery systems to identify:
1) What resilience (the ability of a system to recover, adapt, or transform) looks like in practice across a range of fishery systems, scales, and dimensions (i.e., ecological, social, economic, governance/management)
2) Why and how specific resilience attributes (or collection of attributes) play an important role and/or have been operationalized in particular fishery systems.
3) How those attributes may support (or constrain) climate resilience

Approach:
The semi-structured template questions will be used to develop a synthetic narrative focused on resilience of the case study fishery system to climate change. Responses to the template questions and the narratives will be used to support cross-case analyses, comparisons, and synthesis.

Outline instructions:
1) An "abstract" key findings paragraph – including the key resilient statement (of what, to what, for whom), an impact sentence, and key attributes operationalized, 2) a brief background of the fishery including key themes (scale and other descriptors), 3) the climate impact, 4) discussion of the resilience story/caveats – explicitly noting resilience attributes (italicized) and how they confer/constrain resilience, key linkages, missing attributes, characters (including missing actors as well), 5) concluding paragraph 6) references cited, and 7) acknowledgements (if applicable).

<u>Senegalese small-scale fisheries targeting small pelagic fish</u>

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Abstract

The Senegalese small-scale fisheries on small pelagic fish face challenges in terms of overexploitation of the resource, both by artisanal fisheries and by an industrial, large-scale fishery, as well as increasing effects of climate change. Ecologically, the target species show high resilience to climate change through *adult mobility, habitat diversity* and *ecosystem connectivity*. Overexploitation and social and economic changes challenge the fishing communities, but they show resilience through high *social diversity, mobility* and *social capital*. However, resilience is constrained by certain socio-economic conditions, including limited *wealth and reserves, resilience mindsets, knowledge access,* and capacity for *technology transfer*. In addition, weak governance attributes—particularly *effective and efficient, polycentric,* and *cross-scale* governance arrangements—may reduce resilience of these small-scale fisheries.

Fishery background

Senegalese small-scale fisheries target two Sardinella species (*Sardinella aurita* (Round Sardinella) and *Sardinella maderensis* (Flat or Madeiran Sardinella)), as well as *Ethmalosa fimbriata* (Bonga Shad). Both Sardinella species perform a migration along the West-African coast, and they are harvested by small-scale fisheries in nearshore coastal waters as well as a small industrial local fleet and industrial foreign vessels (Ter Hofstede & Dickey-Collas, 2006). The fishery on both Sardinella species became important in Senegal with the development of artisanal purse seine fishing in the 1970s, following an FAO project to promote different forms of fishing (Ba et al., 2017). This fishery contributes to both food security and employment, with more than 25% of artisanal fishers (16,000 fishers) targeting these two species and providing about 70% of the consumption of fisheries products in Senegal (Ba et al., 2019).

Catch is dominated by *S. aurita*. Its share in total purse seine landings is above 80% for all regions but Thiès Sud (57%) (Ba et al., 2017). This fishery is mostly artisanal and open access. The production is mainly used for human consumption locally and more importantly on the regional markets (including landlocked countries like Mali and Burkina-Faso) (Lancker et al., 2019). However, the establishment of fishmeal plants increases the demand and thus increases the fishing pressure and may lead to a reduction in the supply for local markets in the mid- to long-term (Ba et al., 2017).

In general, Senegalese fishers are mobile, both in terms of extending the range of fishing operations as well as migrating either temporarily or permanently along the West-African coast.

Senegalese fishers are active in neighboring countries, mainly Mauritania, as the workforce in fisheries is low there and the development of fish meal plants increased the demand in Mauritania (Binet et al., 2012). Mobility of the fleet confers resilience to expand fishing opportunities, which is important given that the possibility of diversification of income is limited depending on the local context. Some communities can include agriculture production as alternative income sources (e.g., Kayar). Others, for example in the Sine Saloum, adapt to changing conditions such as declines in fishing opportunities and the loss of arable land by expanding salt harvest as the main source of income.

Climate impacts

The abundance of both species is generally determined by strong seasonal patterns, with *S. aurita* peaks in spring and autumn and *S. maderensis* in summer. Interannual fluctuations are linked to the precocity and duration of the upwelling season (Thiaw et al., 2017).

Climate change has an impact on the migration and the general distribution of the species harvested in this fishery. *S. aurita* is a climate sensitive species. Its abundance has been linked to changes in sea surface temperature (SST). Diankha et al. (2015) find an optimal temperature of 22.7°C, and a generally high abundance between 20°C and 24°C for Senegalese waters. SST in Senegalese waters fluctuates between 18.85 and 28.6°C. Recruitment is linked to upwelling and the availability of zooplankton (Baldé et al., 2019). Fewer studies exist of *S. maderensis*, but those that are available indicate that it is less sensitive to environmental conditions than *S. aurita* but also may have less adaptive capacity by virtue of more limited migration (Diankha et al., 2018; Ba et al., 2016).

Climate change is also projected to weaken upwelling, which will reduce productivity of the marine ecosystem off Senegal. In addition, sea level rise is projected to flood low-lying coastal areas, and in some locations, to mobilize nutrients and toxic pollutants in soils. Sea level rise as well as more intense and frequent storms threaten infrastructure that supports fisheries in Senegal (Government of Senegal 2016).

Resilience attributes and linkages

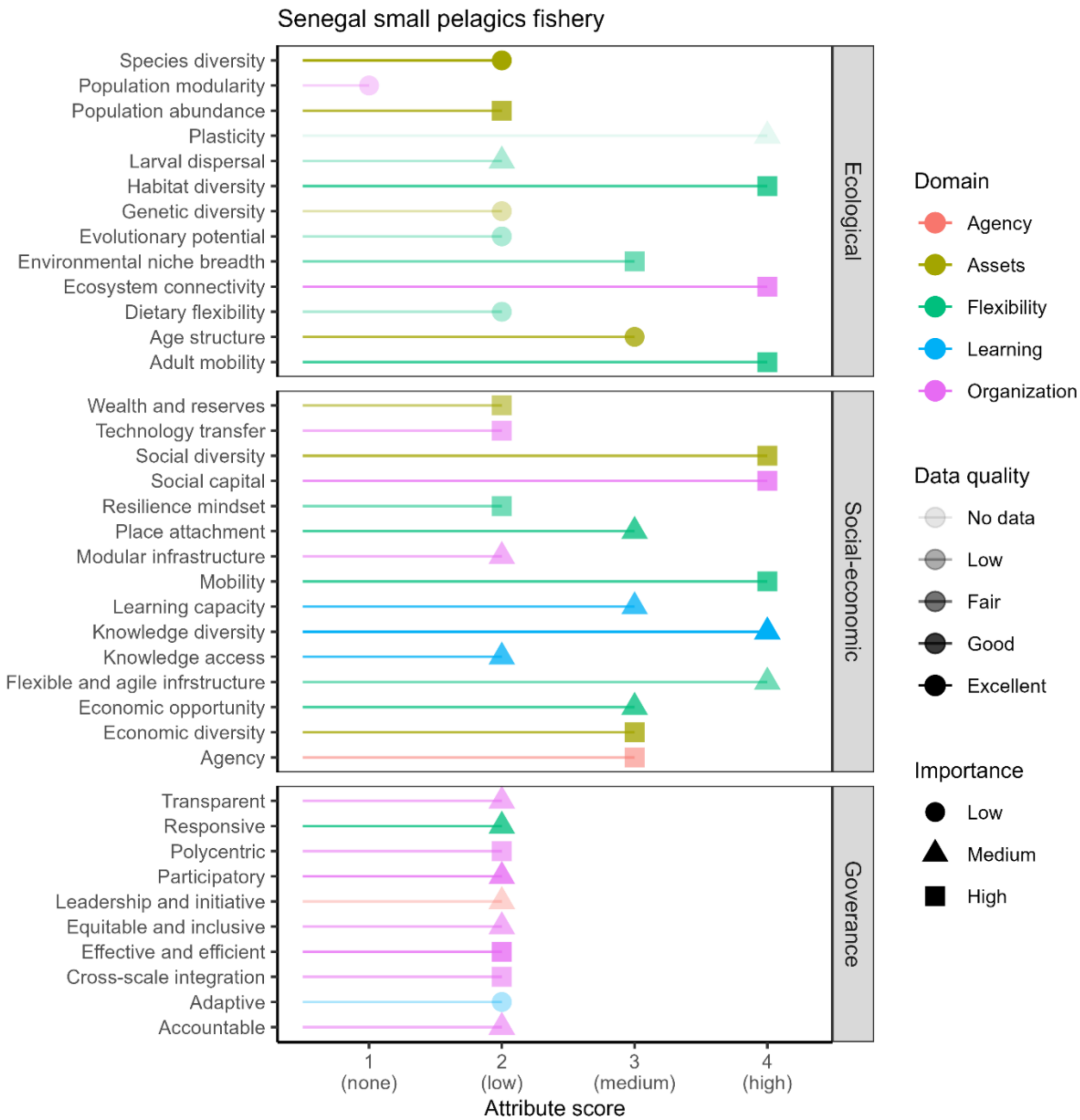
Climate resilience in Senegal's small-scale fisheries for small pelagics is currently supported by adaptive capacities of the target species (e.g., *adult mobility, habitat diversity, ecosystem connectivity*) and *mobility* of the fishing fleet. *Social capital*, which includes bonding, bridging and linking social capital, and *social diversity* forms the basis for collective action and enables the communities to function effectively. However, though *social diversity and social capital* are present in the fleet, groups don't necessarily coordinate together.

Resilience to ongoing and increasing impacts of climate change may require building additional socio-economic and governance attributes and prioritizing *social diversity and social capital* within the fishing community and connecting traditional and new knowledge (Mbaye et al., 2020). Subsidies might amplify climate effects through catch potential increasing with climate change, induced by stock distribution changes (Lancker et al., 2019).

The anticipated climate impacts on this fishery are substantial, yet there is limited funding (i.e., *wealth and reserves*) for fisheries management and of climate change programming (Government of Senegal 2016). In addition, there is limited scientific and institutional capacity for climate-fisheries modeling and adaptation planning in the region, which constrains *knowledge access* in decision-making processes (Badjeck et al., 2010). Finally, *polycentric* and *cross-scale* governance mechanisms will be needed to address climate issues at national and regional scales (Badjeck et al., 2010).

Conclusion

Climate change is already impacting Senegal's small-scale fisheries for small pelagics and will continue to do so at an increasing rate. The migratory pattern and productivity of the target species (*Sardinella aurita* and *Sardinella mderensis*) are linked to the precocity and duration of the upwelling season, which climate change will weaken. In addition, overexploitation by both small-scale and large-scale fisheries exert extra pressure on the resource. The high mobility of the adult stock as well as habitat diversity and ecosystem connectivity support ecological resilience. By continuing to build the resilience capacity of the existing management regimes and fishing communities the small pelagics fishery will be able to adapt to these impacts. Investment in climate change programming and increasing scientific capacity to monitor climate impacts, at national and regional scales, will be key to overcoming climate-related impacts and increase long-term resilience. In summary, overexploitation and social and economic changes challenge the fishing communities, but they show resilience through high *social diversity*, *mobility*, and *social capital*.



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Moorea reef fish fishery (French Polynesia)

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Abstract

This case study examines the resilience of Moorea nearshore coral reef fisheries to increased intensity of cyclones, increased frequency and intensity of marine heatwaves in the context of increasing development. In Moorea high *ecosystem connectivity* and *species diversity* have previously buffered to some degree low just governance attributes. However low just governance attributes, (those that measure procedural equity) impede ecological resilience. Moreover, climate change stressors in the context of increasing coastal development are further reducing the ability of strong intrinsic ecological assets to be sustainability converted into socio-economic assets. Increasing tourism and coastal development have led to increasing tension over management of lagoon space in relation to fishing access. Additionally, explanations for the underlying tensions between community members and scientists center on unfair broader contexts and past inequities. Colonialism and its effect on *agency* and bridging *social capital* have impeded resilience. After past losses of trust, trust-building between diverse stakeholders is a slow process.

System overview

More than 40 genera are fished including soldierfish (*Myripristis* spp.), parrotfish (*Scarus* spp., *Chlorurus* spp.), and unicornfish (*Naso* spp.). Offshore fisheries and tourist preferences limit tourist consumption of reef fish and prevent intense overfishing of reef fish species. Moreover, with steep ravines, porous bedrock and numerous inlets, the land and sea of Moorea are intimately connected. Moorea's population has doubled since the 1980s and the island is a top destination for travelers in Polynesia. In Moorea coastal development, lack of wastewater infrastructure, increasing tourism and changes in agriculture have degraded buffer zones between land and sea and increased nutrient pollution and sedimentation. These stressors can interact synergistically with climate change hazards to reduce coral health, ultimately impacting the reef fishery and culture of Moorea. Many local associations exist for preserving the culture and environment of the island.

Climate impacts

Scientists perceive acute disturbances (such as crown-of-thorns starfish outbreak, cyclones and bleaching events) as greater risks than Moorea's residents who have longer temporal perspectives of the reef and recovery (Lauer et al., 2022). Moorea residents note the diminishing size of many reef fish caught as compared to their parent's generation and often perceived localized chronic stressors to be greater risks to the lagoon. However, the impacts of climate change on the lagoon do seem to be of increasing concern. For example, residents consider the ability of corals to recover from bleaching a priority topic for research. Moorea's coastlines, where over 80% of the population reside, remain highly vulnerable to climate risks (Calandra et al., 2022). Global environmental change has also led to the increasing use of Moorea as a base for foreign scientists to study the impacts of climate change on coral reefs.

Resilience attributes and linkages

Resilience of Moorea's coral reef fishery is a composite of the three interconnected resilience dimensions. Ecological attributes represent the capacity of Moorea's lagoon to resist a disturbance and the speed at which it recovers in terms of coral cover and fish abundance, such that the ecosystem maintains its essential function and structure and continues to provide ecosystem services for Moorea's population. Social-economic attributes represent the capacity of each of Moorea's residents to cope with and adapt to stressors and disturbances including marine heatwaves while maintaining the capacity to alter personal livelihoods, asset configurations and social relations and derive benefit from ecosystem services. The governance attributes represent the capacity of the marine resource governance systems to manage the relationship between the lagoon and Moorea's residents such that the lagoon continue to provide ecological services for all of Moorea's population and future generations in the face of social and environmental stressors and that both the institutions and processes can adapt, learn, and maintain the ability to transform in both response and anticipation of change.

Ecological resilience

The Moorea multi-species reef fishery in French Polynesia shows resilience in the ecological dimension to marine heatwaves and ocean acidification where *ecosystem connectivity*, and *larval dispersal*. Simultaneously colonial legacy and contextual equity is to be a major constraint to the resilience of coral reefs in Moorea. Bridging *social capital* can be built through attempts to build trust and outline pathways towards reconciliation for groups with multiple perspectives. Additionally, there is high *species diversity* within the fishery (multi-species), which provides increased flexibility (including differences in depth and spatial ranges, life history traits, and spawning seasons). However, local chronic stressors including nutrient pollution and sedimentation threaten the ability of coral reefs.

Socio-economic resilience

Social diversity without bridging and linking *social capital* reduces resilience of Moorea's fisheries to climate change due to evidence of lack of trust between some managers, fishers, other sectors and scientists. Social diversity also leads to diversity of priorities with regards to climate change research. Western researchers are more interested in studying topics related to global climate change while residents are more likely to consider local chronic stressors in addition to climate change as important issues to focus attention on. Extensive fishing and traditional knowledge combined with extensive Western scientific monitoring has been conducted by the two research stations on the island meaning that there is high knowledge diversity in the fishery system. However, a lack of incorporation of *diversity of knowledge* sources in marine spatial planning and low *access to knowledge* in terms of dissemination of marine research related findings also affect the ability of the current management system to be effective.

Governance resilience

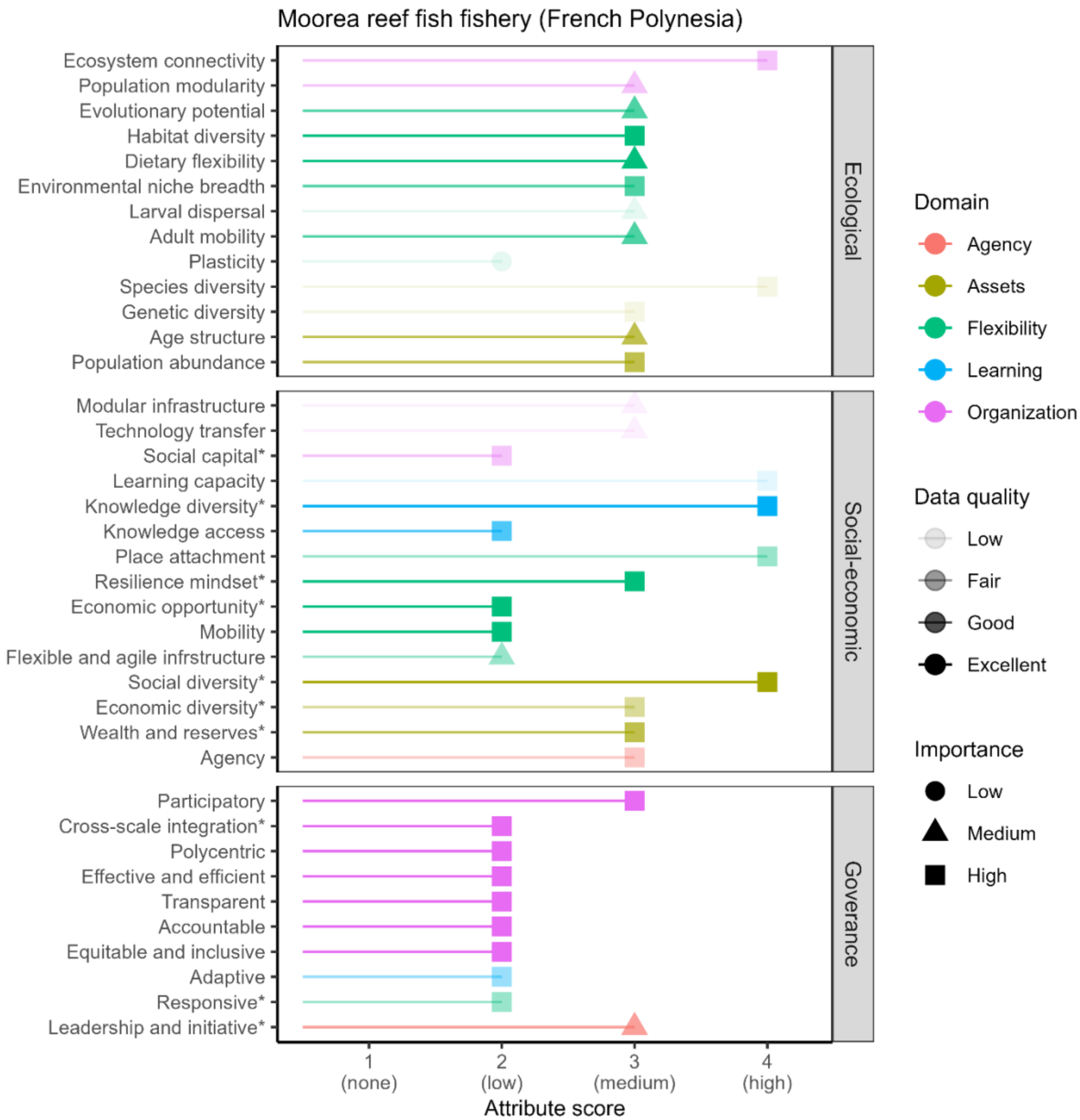
The way in which people experience marine management plays a crucial role in whether they follow the management plan. In Moorea perceptions of unjust resource governance and distribution (including low *equitable and inclusive governance, accountability* and *transparency*) led to low compliance with spatial regulations and diminished the ability of the marine protected area network to promote population abundance (Thiault et al., 2019; Wencélius et al., 2022). Some fishers also perceive that the locations of the marine protected areas were designated to benefit local tourism causing tension between sectors. Low compliance (i.e., less *effective and efficient governance)* can reduce ecological assets including fish *population abundance*. In this manner low just governance attributes in Moorea have impacted ecological resilience as well as linking and bridging *social capital* through reduced trust in other actors. However, this case highlights a pathway from perceived inequity to management reform (Hunter et al., 2018; Wencélius et al., 2022). Most recently, growing intolerance of inequity is sparking self-organization and the social capital for collective action towards a more socially accepted (and thereby likely resilient) fishery management regime. However, very low perceptions of governance can lead to a more *social capital* through the need for collective action and unifying around a goal of fair resource management.

Although marine management has been *participatory* (e.g., people were surveyed regarding marine spatial planning): lack of legitimacy based on perceived lack of *transparency* in how marine protected areas are designated, as well as perceptions of hypocrisy regarding the research institution associated with marine management means that marine protected area regulations were not followed. However, increasing communication and participation on its own is not a cure-all. If these engagement practices are perceived as unfair processes, it can lead to reduced trust. A lack of perceived legitimacy by fishers and municipal level managers ultimately stems from the legacy of a historical lack of broader *equitable and inclusive* governance. There is also limited *polycentric governance* and some confusion regarding which levels of governance can make marine spatial planning policies relating to unharmonized laws.

Management leads to socially differentiated access to socio-economic attributes

Non-compliance can also be associated with perceived inequity in the distribution of specific socio-economic attributes related to the management regime, wealth and reserves, mobility, and place attachment (Hunter et al., 2018). The implementation of permanent protected areas, as opposed to rotating ones, led to reduced mobility and could exacerbate challenges for those already facing mobility limitations (Walker & Robinson, 2009). The location and overall framework of the management scheme also unevenly affected place attachment, as its design contributed to the displacement of the Polynesian conception of land-sea continuity (Gaspar & Bambridge, 2008).

The resilience of the fishery moving forward will depend on the success of the governance system. Namely the extent to which participatory processes are perceived as *equitable and inclusive* and *effective* and final decision-making processes are *transparent* is exceedingly important in this fishery.



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United States Atlantic and Gulf of Mexico highly migratory pelagic longline fishery

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Abstract

When accounting for the impacts of climate change, the U.S. Atlantic and Gulf of Mexico pelagic longline (PLL) fishery that target Highly Migratory Species (HMS) has key challenges to overcome in terms of economic viability and sustainability, which hinder resilience in the face of climate change. Fortunately, many of the solutions that can help build climate resilience will also address existing issues in the fishery. Many HMS have key attributes that provide ecological resilience, such as dietary flexibility and high mobility, though other

characteristics (e.g., slow growth rate and late maturity) make some HMS incredibly vulnerable. A governance structure encompassing international and domestic domains and regulatory systems add complexity to the HMS fishery management, which can be inadequate and ineffective at the international level. Improved international management and cooperation to manage target stocks and bycatch more sustainably will improve overall population and ecosystem health. Domestically, the United States has adopted a strong legal mandates and several effective bycatch mitigation measures that promote sustainable fisheries, thus fostering resilience. The PLL fishery has a history of gear innovation, learning, and implementation of cutting-edge technologies (e.g., collection of real-time information through electronic technologies) that can help achieve more optimal fishing (higher rates of target species and less bycatch). However, the domestic fishery management is characterized by a top-down decision-making process, and some fishery regulations have not been co-developed with the industry. Every year, the PLL fishery registers a reduction in fishermen numbers, as many leave the fishery due to an inability to maintain profitability while complying with management measures and competing with import products that undercut prices. Given the difficult economic situation of many PLL fishermen, efforts to build resilience must be done collaboratively and inclusively with all affected fishing communities to ensure these measures are effective, practical, and achieve fishery sustainability goals.

Systems overview

This PLL fishery operates from ports stretching from New England, south along the Atlantic seaboard, into the Caribbean Sea (CS) and the Gulf of Mexico (GOM), targeting primarily North Atlantic swordfish, bigeye tuna, and yellowfin tuna. Secondary target species include mahi mahi (dolphinfish) and wahoo, and certain sharks that are retained and commercialized (e.g., shortfin mako sharks and common thresher sharks). Today, a U.S.-flagged fleet fishes for HMS in the Atlantic Ocean, CS, and the GOM, in the U.S. EEZ and beyond (NMFS, 2021). One of the major challenges in the PLL fishery is bycatch of marine life including sea turtles, sea birds, billfishes, marine mammals, and coastal and pelagic sharks (Garrison, 2007; Mandelman et al., 2008; Klaer, 2012; Stokes et al., 2012; NMFS, 2021). Gear adaptations in materials, lengths, and deployment methods can greatly affect the selectivity of longline fishing (Watson & Kerstetter, 2006; Gilman et al., 2020; Poisson et al., 2022).

Climate impacts to HMS and the PLL fishery

The effects of climate change on HMS will differ depending on the species, life stage, and the region. Projections indicate that many HMS will shift their ranges poleward, and some will experience changes to their abundances in equatorial areas (decreases for swordfish and increases for yellowfin and skipjack tuna) (Dueri et al., 2014; Muhling et al. 2015; Monllor-Hurtado et al., 2017; Erauskin-Extramiana et al., 2019; 2020). HMS are particularly sensitive to low oxygen levels (Brill, 1994; Bernal et al., 2009; 2012; Leung et al., 2019), and oxygen-depleted waters due to ocean warming will potentially make survival more difficult for many

HMS after being released alive from fishing gear (Gallagher et al., 2014; Musyl et al., 2015; Dell'Apa et al., 2018). In some global coastal and marine regions oxygen-rich layers will become shallower, driving some species to the surface where they will become more vulnerable to fishing gear (Prince & Goodyear, 2006; Prince et al., 2010; Stramma et al., 2012; Vedor et al., 2021). In addition, the timing and location of spawning is projected to shift for Atlantic bluefin tuna in the northern GOM (Muhling et al., 2011), and certain populations of sharks (e.g., sandbar sharks) will likely lose important nursery habitat (Crear et al., 2019; 2020).

Resilience attributes

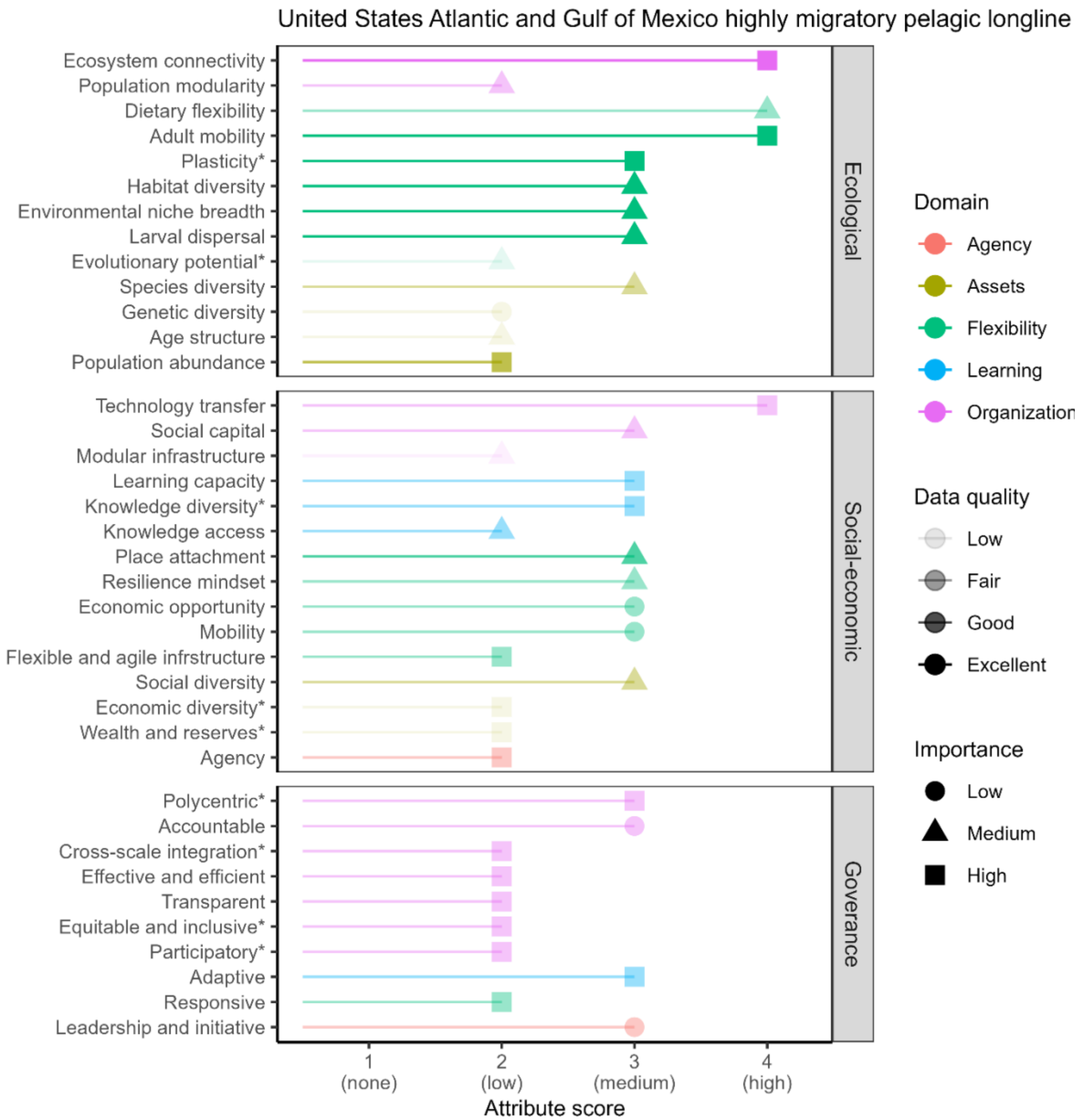
Key attributes (Mason et al., 2022) contributing to HMS ecological resilience include: 1) *spatial flexibility* due to wide *adult mobility* and *environmental niche breadth* and 2) *behavioral* and *dietary flexibility*. But other attributes may reduce ecological resilience, mainly *evolutionary flexibility* due to slow growth rate, late age of maturity, production of few offspring, and the fact that many HMS have specific thermal ranges and oxygen requirements. Also, several HMS have low *population abundance* due to overfishing and high bycatch levels contributing to reduced *age structure* in some HMS populations.

The current domestic governance structure of the PLL fishery result in a fishery system's *agency* characterized by a top-down management process, which, at times, can be perceived by the fishing community as being less *participatory* and *transparent*, though recognizing elements of a strong management foundation resulting in higher levels of *accountability* as compared to other PLL fisheries. For many HMS populations, the resilience level conferred by governance attributes of the domestic regulatory system may be reduced by lower levels of compliance for the international management and the lack of responsive harvest strategies for target species and effective bycatch regulations for most of the non-target species (e.g., large pelagic sharks) across the Atlantic Ocean. Hence, the international fishery management process can be perceived as less *responsive, accountable, transparent,* and *efficient and effective* than the corresponding domestic governance structure. The fishery system is also characterized by a moderate *flexibility* due to a somewhat contentious HMS management with conflicting interests across stakeholder groups making policy change slow and less *responsive*, and HMS fishing mortality not being *effectively integrated across scales and sectors*. On the bright side, resilience to the governance system can be fostered by the presence of good opportunities for *learning* and experimentation through *adaptive* decision-making process and innovations in fishing technology and practices.

Resilience in the socioeconomic domain of the PLL fishery system is constrained by reduced *wealth and reserves* among the fishing community, coupled with the fact that this community is prone to low *economic diversity* because of high dependency on the specificity of the fishery, markets, and target species composition. Also, though some *resilience mindset* and *social diversity* are present in the fleet, groups don't necessarily coordinate together. On the other hand, the high degree of *flexibility* due to high *mobility* through access to various fishing grounds and some presence of *flexible and agile infrastructures* that allow the fishery system to respond to unpredictable conditions and disruptions can help confer resilience in the face of climate change.

Conclusion

Climate change is already impacting HMS in the U.S. Atlantic and GOM and will continue to do so at an increasing rate. By continuing to build the resilience capacity of the existing management regimes and fishing communities, both nationally and internationally, the PLL fishery will be able to adapt to these impacts. Approaches that incentivize continued advancements in bycatch avoidance, while providing spatiotemporal flexibility in the fishery and facilitating adaptation to changing ocean conditions, could help to maximize the responsible and sustainable catch of target species and minimize bycatch of vulnerable species. Correspondingly, the international management of HMS needs the establishment of, and higher compliance to, sustainable harvest strategies for all target species and a more active and responsive management of bycatch species (e.g., reference points). Domestically, the transition to more adaptive, dynamic management approaches (e.g., deploying existing electronic technologies that can be used to develop real-time information systems to help fishermen optimize fishing) could enhance the fishery's climate readiness, while improving conservation and economic outcomes. To be successful, these approaches will require effective collaboration between managers, fishing communities, industry, environmental organizations, technology providers, scientists, and others through cooperative research and throughout the policy-making process, both domestically and internationally. Ultimately, such a management scheme could result in a triple win by improving conservation, profitability, and resilience in the fishery.



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Kiribati giant clam fishery – *see published manuscript at https://doi.org/10.1071/PC22050*

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Abstract

The Kiribati giant clam multi-species subsistence fishery in the Gilbert Islands shows resilience in the ecological and socio-economic dimensions to marine heatwaves and ocean acidification where adaptive customary management was successfully implemented despite limited capacity from the national government. Ecologically, the species fished are generally resilient to climate change due to high *plasticity*, *evolutionary potential*, *ecosystem connectivity*, and *larval dispersal*. Additionally, there is high *species diversity* within the fishery (multi-species), which provides increased flexibility (e.g., differences in depth and spatial ranges, life history traits, and spawning seasons). However, overfishing, eutrophication, and pollution have pushed this fishery past the threshold of ecological resilience in the urbanized island of South Tarawa where the governance and socio-economic dimension have failed. Conversely, on remote outer islands, where the socio-economic dimension has shown promise in combating these anthropogenic influences, ecological resilience has been enhanced and the fishery has persisted despite the frequency and severity of climate-related impacts increasing. Thus, the resilience of the fishery moving forward will depend on the socio-economic dimension and all accountable actors. Specifically, maintaining and fostering the *resilience mindset*, *learning capacity*, *place attachment*, and *agency* while maintaining *social capital*. Wide-scale habitat degradation from coral bleaching coupled with the unknown physiological stressors of changes in sea surface temperature and ocean acidification has, and will continue to, impact the fishery. However,

customary adaptive management through engaged local agents (Island Council; i.e., not national agents) has shown to be critical in the resilience of the fishery moving forward.

System overview

Four species of giant clam occur and are heavily targeted and fished for subsistence in the Gilbert Islands (by body size, large to small): *Tridacna gigas*, *Hippopus hippopus*, *T. maxima*, and *T. squamosa*. While *T. gigas*, the most endangered clam and largest living bivalve mollusk, is commonly known as the 'giant clam' all four species are giant clam species. The clams' primary habitat is on structured coral reefs and back reefs in both the fore-reef and lagoon reef habitats. Giant clams represent a key function within the coral reef community. Their tissues are food for a wide array of predators and scavengers, while their discharges of live zooxanthellae, feces, and gametes are eaten by opportunistic feeders. They increase the topographical heterogeneity of the reef, act as reservoirs of zooxanthellae (*Symbiodinium* spp.), and also potentially counteract eutrophication via water filtering. The shells also provide substrate for commensal and ectoparasitic organisms (Neo et al., 2015). Despite this, limited monitoring has been conducted by the Kiribati Fisheries Division from the Ministry of Fisheries and Marine Resources Development (MFMRD).

Parallel to the functional role on coral reefs, giant clams represent a traditionally and culturally important food source for Kiribati. This contextual consideration is particularly for remote outer islands. The clams are used in traditional dances, served for special occasions, and play a critical role in food security as they are dried, salted, stored, and eaten if the household is unable to obtain seafood for other reasons (e.g., weather, boat issues). Thus, all species are heavily fished by free divers year-round, resulting in a general understanding that the fishery has been in decline since 2004 (Delisle et al., 2016). Further, in 2008 *T. gigas* was thought to be nearly locally extinct from the urbanized and overpopulated island of South Tarawa and the neighboring islands of North Tarawa and Abaiang (Awira et al., 2008; Preston 2008a, 2008b). Across all islands species body size has similarly declined. While small operators, aquaculture, and artisanal based fisheries operate (very short value chains), the majority of fishing pressure comes from subsistence fishers (Preston 2008a).

Resilience attributes and linkages

The response from the government's national fishery branch, MFMRD, was the preparation of the Kiribati National Giant Clam Fishery Management Plan (FMP) in 2013, which followed the 2010 Fisheries Act and a large-scale coral bleaching event. The primary purpose of the giant clam FMP was to establish an effective and enforceable management structure for the Kiribati giant clam fishery. The main objective was to ensure the sustainable development, conservation, and management of the giant clam fishery and harvesting of giant clams. The 2013 FMP proposed *T. gigas* be banned from fishing, harvest restrictions for other giant clam species enacted, and increased reporting with an ongoing program for monitoring catch data and more scientific information. However, despite tangible action items for sustainable harvest, no national steps were made. Further, in South Tarawa, where governance operates at the island level due to not having distinct communities associated with a particular village, which has resulted in limited *place attachment* and *agency* paired with low *accountability* and *social capital*, the fishery continued to decline.

Island Councils (IC) represent the local level of governance on the remote outer Gilbert Islands in Kiribati. They act at the scale of a single village, allowing the IC to make *adaptive* decisions quickly. There is strong *leadership and initiative* through village elders, who have an interest in continuing the tradition of customary adaptive management, and ensuring a balance of ecological and social outcomes from the fishery (Campbell & Hanich, 2014). On outer islands where IC's operate, decision-making is the result of a *participatory*, *equitable and inclusive*, and bottom-up approach. However, the high *resilience mindset*, *learning capacity*, *place attachment*, and *agency* from the fishers and general public on outer islands has resulted in the implementation and success of community-based fisheries management. Across different outer islands IC's have independently implemented giant clam fishing quotas, permanent or rotational no take areas, and even banned the take of *T. gigas*.

Both South Tarawa and the outer Gilbert Islands have experienced system-wide shocks. Particularly, climate change has caused wide-scale habitat degradation following large-scale coral bleaching events. Severe coral bleaching can result in a high loss of coral cover, reduced structural complexity following coral mortality (a key habitat component of giant clams), and large-scale settlement of algae if a phase shift occurs (turf and macroalgae), which directly or indirectly, depending on severity, leads to reduced giant clam settlement and future recruitment if the *population abundance* is not stable. Coupled with the physiological stress from changes in sea surface temperature (symbiotic associations with photobionts) and ocean acidification (calcareous growth), threats to giant clams will continue to increase through the Anthropocene. However, recent studies have shown that giant clams, without additional anthropogenic pressure (overfishing, eutrophication, and pollution) are quite resilient to climate change through *plastic* and *evolutionary* responses associated with intact *ecosystem connectivity* and well-distributed *larval dispersal* when the *population abundance* and *age structure* is stable (Campbell & Hanich, 2014). For example, Morishima et al. (2019) found that under elevating temperature heat-resistant zooxanthella grew in clams and were passed to adjacent juveniles through photosynthetically active fecal pellets. However, overfishing, eutrophication, and pollution have pushed the giant clam fishery at South Tarawa past the threshold of ecological resilience.

Conclusion

Overfishing on remote outer islands has been mediated by customary closures, quotas, and species-specific regulations, which have acted as a buffer. On islands where the socio-economic dimension has shown promise in combating the aforementioned anthropogenic influences, ecological resilience has been enhanced and the fishery has persisted despite the frequency and severity of climate-related impacts increasing. Thus, while adaptive customary management is capable of implementing measures for resilience across all Gilbert Islands, maintaining and fostering the *resilience mindset*, *learning capacity*, *place attachment*, and *agency* at the local scale of each village has been the primary driver of resilience. Abaiang, despite giant clams nearly becoming locally extinct in 2008, stands as a flagship of resilience for the fishery. Through community-based fisheries management, specifically fisher-driven no take marine protected areas, Abiang today has a stable giant clam population and associated fishery despite the proximity to South Tarawa. Thus, maintaining the connections within the socio-ecological system will be key to overcoming climate-related impacts and increasing long-term resilience for other islands in the future. In summary, customary adaptive management through local actors, despite limited capacity from the national government, has enhanced the ecological resilience of the giant clam fishery in Kiribati.

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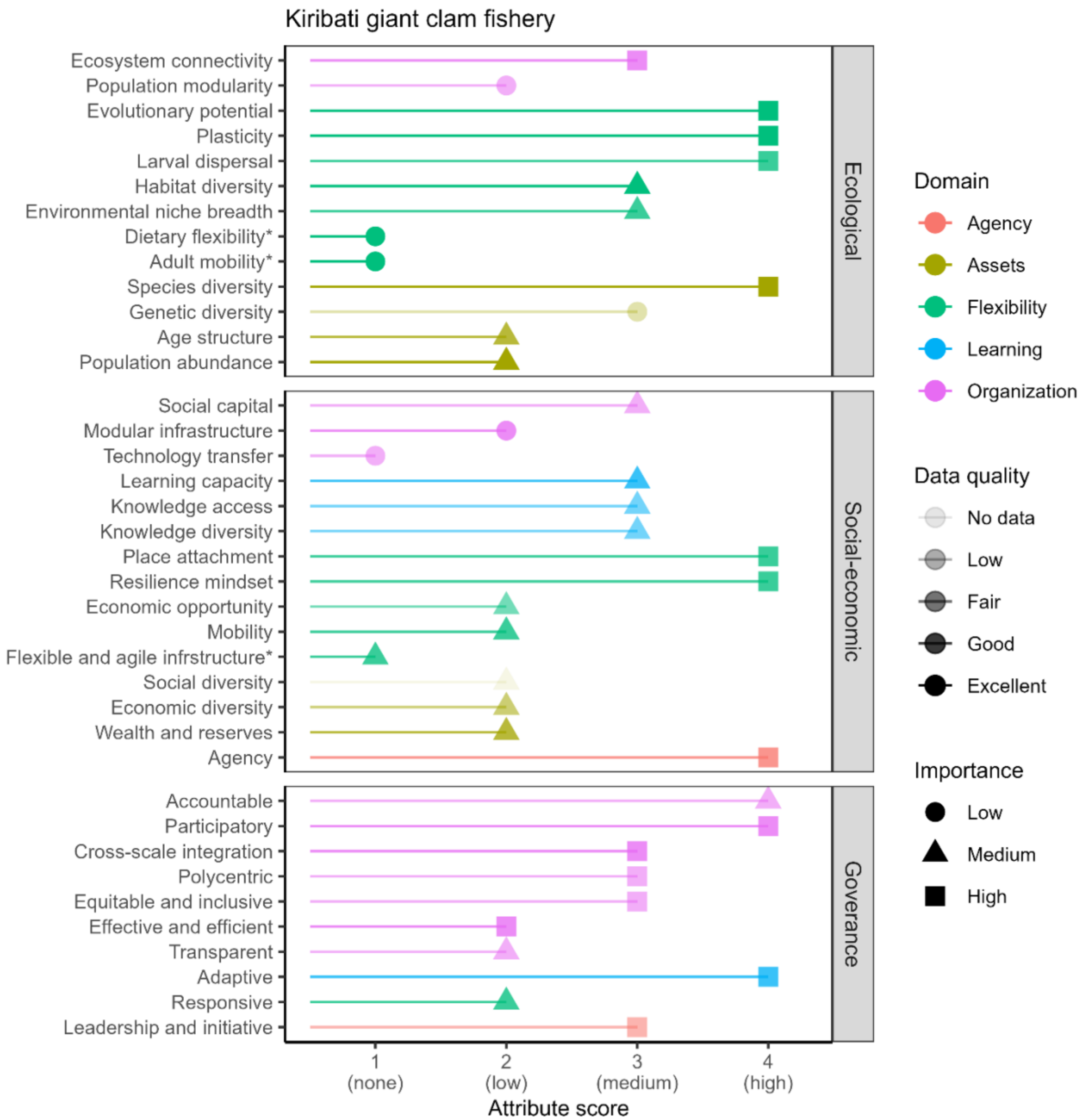

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Madagascar nearshore fisheries

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Abstract

Local Malagasy in the Bay of Antongil are heavily reliant on seafood for nutrition, and any disruptions to the seafood supply could prove very detrimental to overall nutritional status and threaten nutritional resilience. Climate change associated increases in the frequency and intensity of cyclones (World Bank 2018) have led to detrimental impacts on coral reef fisheries productivity for two primary reasons: 1) coral reef damage that led to reduced habitat availability and perceived reductions in fish availability; and 2) reduced water quality and dangerous wave conditions making it more difficult to fish. These coral reef damages can lead to long-term consequences on the quality of the fishery, and the ocean conditions lead to acute circumstances of food shocks that can last for more than one month. Socio-economic diversity, connection to place, ecosystem modularity, and indigenous knowledge seem to be the key resilience attributes that influence the system. In sum, the nutritional resilience of the local Malagasy people in the

Bay of Antongil in northeastern Madagascar is threatened by the increasing frequency and intensity of cyclonic damage to coastal ecosystems.

Background

The Malagasy multi-species subsistence fishery in Antongil Bay provides critical nutritional support to the local Betsimisaraka people who harvest a vast diversity of approximately 120 species for food. Many local Betsimisaraka have a vulnerable nutritional status in this region, and are dependent on an autarchic food production system which is driven by seasonal cycles of natural resource and agricultural production (Golden et al., 2019). The fishery is entirely small-scale subsistence and artisanal fishers, with key gear used being fishing nets, hook and line, and harpoon guns in addition to gleaning by hand.

Climate impact

There are a variety of environmental shocks affecting the fishery in this region including coral bleaching; sea temperature rise; increased cyclonic activity; deforestation and erosion leading to sedimentation into the reef; and harmful algal blooms. The focus of this case study is on increased cyclonic activity, and the northeastern region has a long history of being the locus of greatest burden in Madagascar (Nash et al., 2015).

Resilience story

Local Malagasy in this region have low *socio-economic diversity*, but high agricultural diversity that lends itself to supporting nutritional resilience. Sourcing foods/harvests from multiple sources is essential for nutritional resilience and thus this local cultural norm is a protective behavior in this context. Inter-generational *indigenous knowledge* transfer regarding fishing, food production, and nutrition is essential in building nutritional resilience. Receiving knowledge from fellow community members flows freely but *scientific knowledge* in shaping risk perception is scarce. Knowing how and where to fish, and when to give up certain areas, are lessons learned across generations. Sharing fishing times, productive locations, efficient gears and technologies, and other forms of intellectual collaboration enable resiliency in this system.

Ecosystem modularity and strong cultural *connection to place* may both inhibit nutritional resilience. Viewing nutritional resilience at a seascape level, there is significant variation in the quality of marine habitats and reefs along the Antongil Bay coast, and these micro-ecosystems appear to be fairly disconnected from each other. This high modularity of ecosystems and the relatively narrow fishing grounds by village would lead to targeted issues of nutrient supply shocks in some communities where ecological conditions are disturbed. Higher connectivity would enable nutrient supplies to flow more freely across villages and increase seascape-level nutritional resilience.

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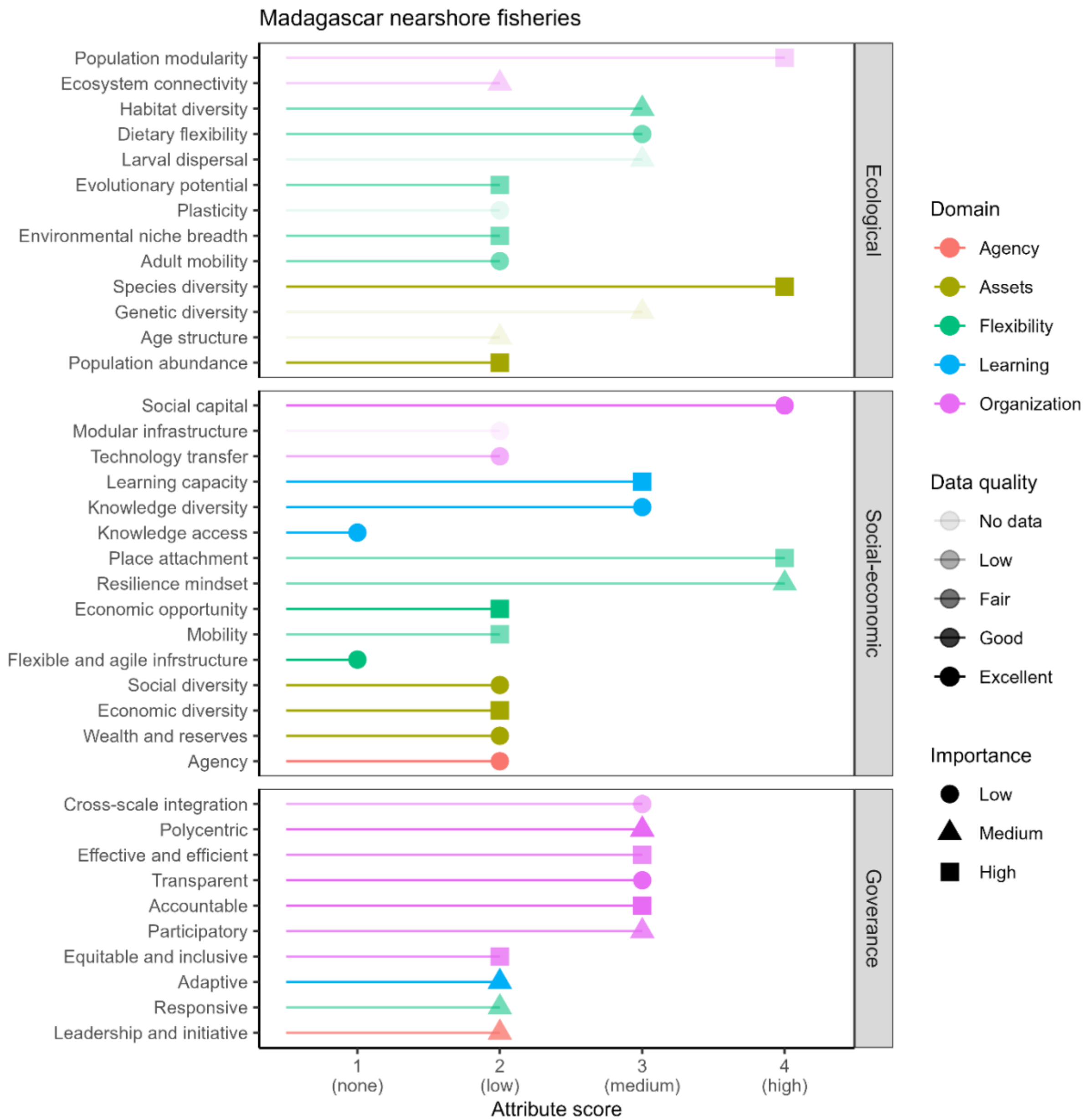

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Fiji nearshore fisheries

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Abstract

Fiji's rich marine biodiversity is central to food security, livelihoods, and culture. Fijian nearshore fisheries have, thus far, shown resilience to marine heatwaves and increased intensity of tropical cyclones due to a combination of strong ecological and social factors. Fijian reefs have high biodiversity, biomass, and connectivity; these features have likely contributed to the observed recovery and resilience of its fisheries to climate-induced disturbances. Indigenous communities have strong ties and relationships, traditional ecological knowledge of marine species and habitats that contribute to their resilience to different types of disturbances.

System overview

The primary participants in these fisheries are Indigenous (*iTaukei*) and non-Indigenous (e.g., Indo-Fijians) groups; however, access to fisheries resources and management rights differ widely between the two groups (Nand et al., 2021; Mangubhai et al., 2021). *iTaukei* communities have access rights to traditional fishing grounds that extend from the highwater mark to the edge of the reef (Mangubhai et al., 2019). At least 165 reef-associated fish species have been identified through fish market surveys with 29 species making up 90% of locally caught reef fish sold at markets (Prince et al., 2018, 2019). Marine and freshwater invertebrates are commonly harvested, with over 50 species identified in fish markets. Women and men both participate in nearshore fisheries, but generally access different habitats and in some cases, target different species. Women's fishing activities contribute substantially to household food security in *iTaukei* communities; as women tend to fish for subsistence, and sell catch to supplement household incomes (Thomas et al., 2021). Further, the diversity of species targeted by women likely contributes to more stable sources of nutrition when compared to the patchier and weather-limited access to offshore fish.

Resilience attributes and linkages

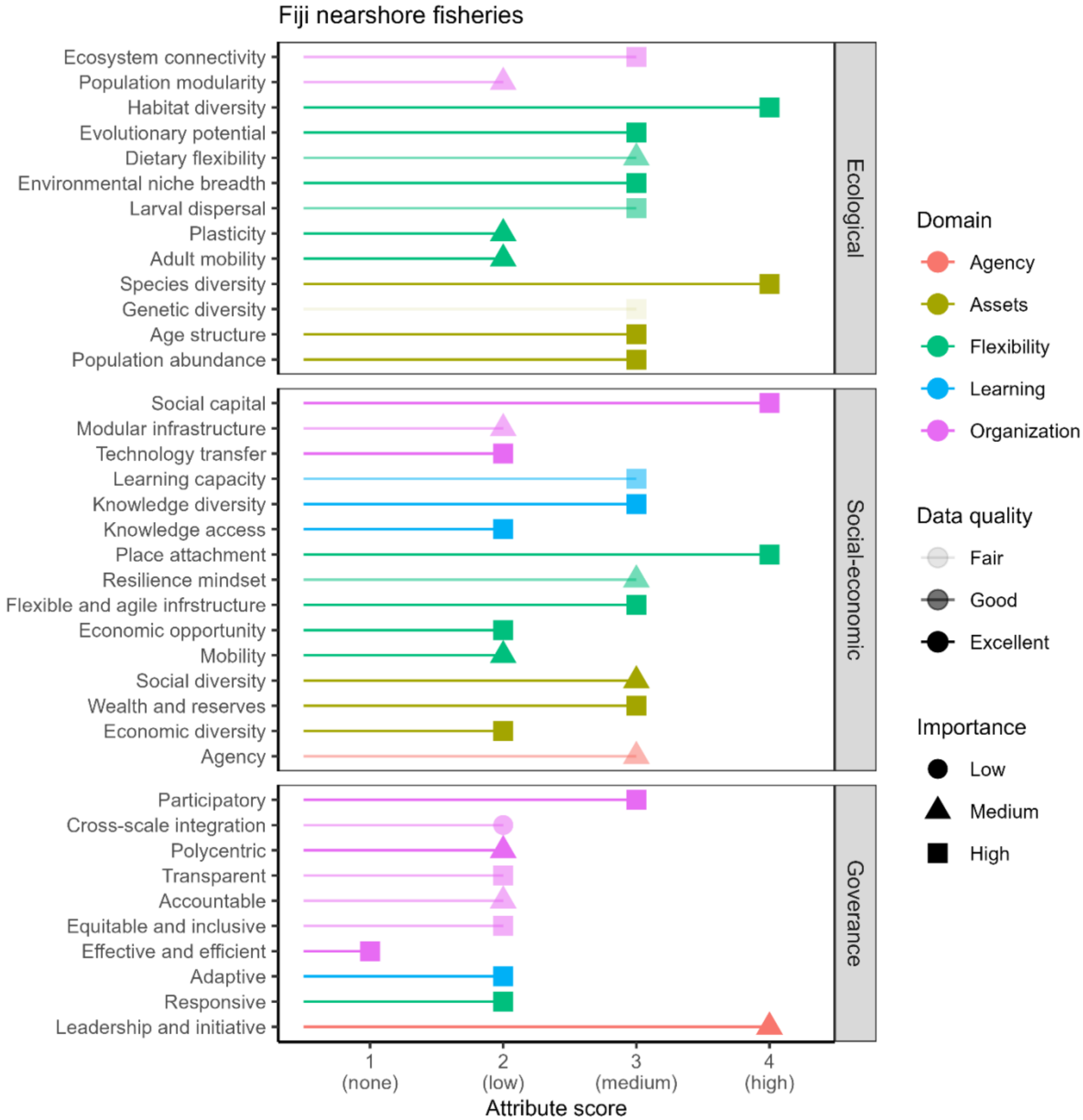
Despite the devastating damage to both ecological assets and community infrastructure caused by severe tropical cyclones, strong community relationships and traditions (social capital), traditional ecological knowledge, past experiences, and resilience mindset enabled *iTaukei* communities to work together to rebuild local infrastructure, harvest traditional forest foods (that are more cyclone resilient), increased investment in subsistence farming and fisheries, and gain support through food sharing networks; collectively, these helped buffer against nutritional shortages (Dacks et al., 2020; Thomas et al., 2021; Ferguson et al., 2022). The return to fishing was less costly (and faster) for fishers (largely women), that relied on bamboo (*bilibili*) rafts and low-technology fishing gear, compared to those who had invested in boats and engines (largely men), with limited wealth and reserves to repair or replace boats and fishing gear (Chaston Radway et al., 2016). In contrast, Indo-Fijians in the small-scale fisheries sector had little social capital, including safety nets and networks, making them vulnerable to disasters (Mangubhai et al., 2021).

Sustained high sea-surface temperatures during the 2000 La Niña resulted in widespread coral bleaching with 40-80% loss of scleractinian corals throughout Fijian reefs (Lovell and Sykes, 2007). Despite this widespread loss, the majority of reefs recovered to pre-bleaching levels within 5 to 11 years; "suggesting that Fiji's reefs are fairly resistant and resilient to these thermal stress events" (Mangubhai et al., 2019).

Category 5 Cyclone Winston caused mechanical damage to coral reefs up to 20-30m below sea surface; although the damage was patchy and highly variable between reefs (Mangubhai, 2016). Twelve months after the cyclone some reefs in the path remained denuded of coral, while others were showing new settlement and regrowth. Although there were no major changes to fish community composition, obligate corallivores including butterflyfish (*Chaetodon baronessa*) and tubelip wrasse (*Labrichthys unilineatus*) showed significant declines, most likely due to declines in coral cover; herbivore abundance increased immediately after the cyclone (Price et al., 2021). Five years post-Winston, some reefs and fish populations have recovered, faster-than expected, to pre-cyclone levels (Vierus 2021).

Conclusion

While fishing communities and ecosystems have withstood, rebuilt, temporarily transformed, and eventually recovered from several prior cyclones, it is not clear whether they will continue to be able to do so in the context of cumulative effects of multiple stressors increasing in frequency, intensity and overlap, as well as the differences in resilience among fishing communities. The evidence to date suggests that factors that limit resilience in this fishery include: cumulative effects of multiple stressors (e.g., cyclones, heatwaves, disease), overfishing, increases in land-based sources of pollution and sedimentation, and differences in access for different social groups.



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Madang reef fish fishery (Papua New Guinea)

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Abstract

This case study demonstrates how adaptive customary management confers resilience to key habitats, stock and social benefits in the face of fishing pressure (Cinner et al., 2006; Cinner 2007) and (hypothetically) climatic shocks through learning, agency, and flexibility. However, biomass is declining (Cinner et al., 2019) and previously successful adaptive management alone may not confer long-term resilience in the face of combined climate change effects and increased fishing pressure.

Fishery background

The fishery encompasses two neighboring coastal communities on Karkar Island in Madang Province, Papua New Guinea. Both communities pursue mixed-livelihoods, including fishing and cash crop and subsistence farming (Cinner 2007). Beside each community is a coral reef on a steep slope, which supports a mixed species coral reef fishery. The fishery is governed at a local level, allowing the communities to make quick adaptive decisions (Cinner et al., 2006). Clan leaders provide strong leadership in the fishery (Cinner et al., 2019). They lead the communities in continuing traditional rotational closures and ensuring a balance of ecological and social outcomes from the fishery (Cinner et al., 2006, 2019). Decisions are made through a combination of participation from the community and top-down from clan leadership (Lau et al., 2019).

The fishery is small and local. Most fish are for subsistence, though some are sold locally. The fishery itself has very little influence on broader markets, and there are no economic incentives or penalties related to climate change. There are also very limited economic resources available to assist with adaptation.

Climate change and resilience

There are few granular and long-term projected climate shocks for this case study, but more broadly, PNG is expected to experience sea-level rise, increased air and sea-surface temperatures (which will induce coral bleaching that directly threatens the coral reef fishery), and ocean acidification. The fishery has not experienced any distinct shocks over the past 20 years. Key resilience features of the fishery include:

1) strong, legitimate and effective local governance;
2) strong social capital;
3) well-defined boundaries based on clan sea-tenure;
4) a strong historical system of adaptive management and iterative learning;
5) a degree of socio-economic diversity in the fishery, with cash and subsistence crops also important for livelihoods and
6) moderate ecological connectivity, modularity and diversity.

These features, and especially the adaptive strategies based on local-environmental knowledge, their legitimacy—based on strong leadership, participation governance, and strong social capital—and the moderate ecological diversity of the fishery, are well placed to continue to confer some resilience in the face of climatic shocks.

To date, the customary management system has conferred resilience to local fishing pressure. It is well placed to navigate trade-offs between the social and ecological dimensions of resilience through processes for translating local environmental knowledge and local monitoring into socially-accepted management measures (Lau et al., 2021). Overfishing is mediated by customary periodic closures, which act as buffers (Cinner et al. 2006, 2019). However, there’s a broad trend of biomass decline suggesting that although these closures provide an effective boost of biomass, the baseline from which this boost is happening is eroding (Cinner et al., 2019). In sum, combined changes to the broader socio-ecological system (i.e., combined climate change impacts on the fishery, alongside subsistence and cash crops) may prove a challenge for existing resilience attributes to continue to confer long-term resilience.

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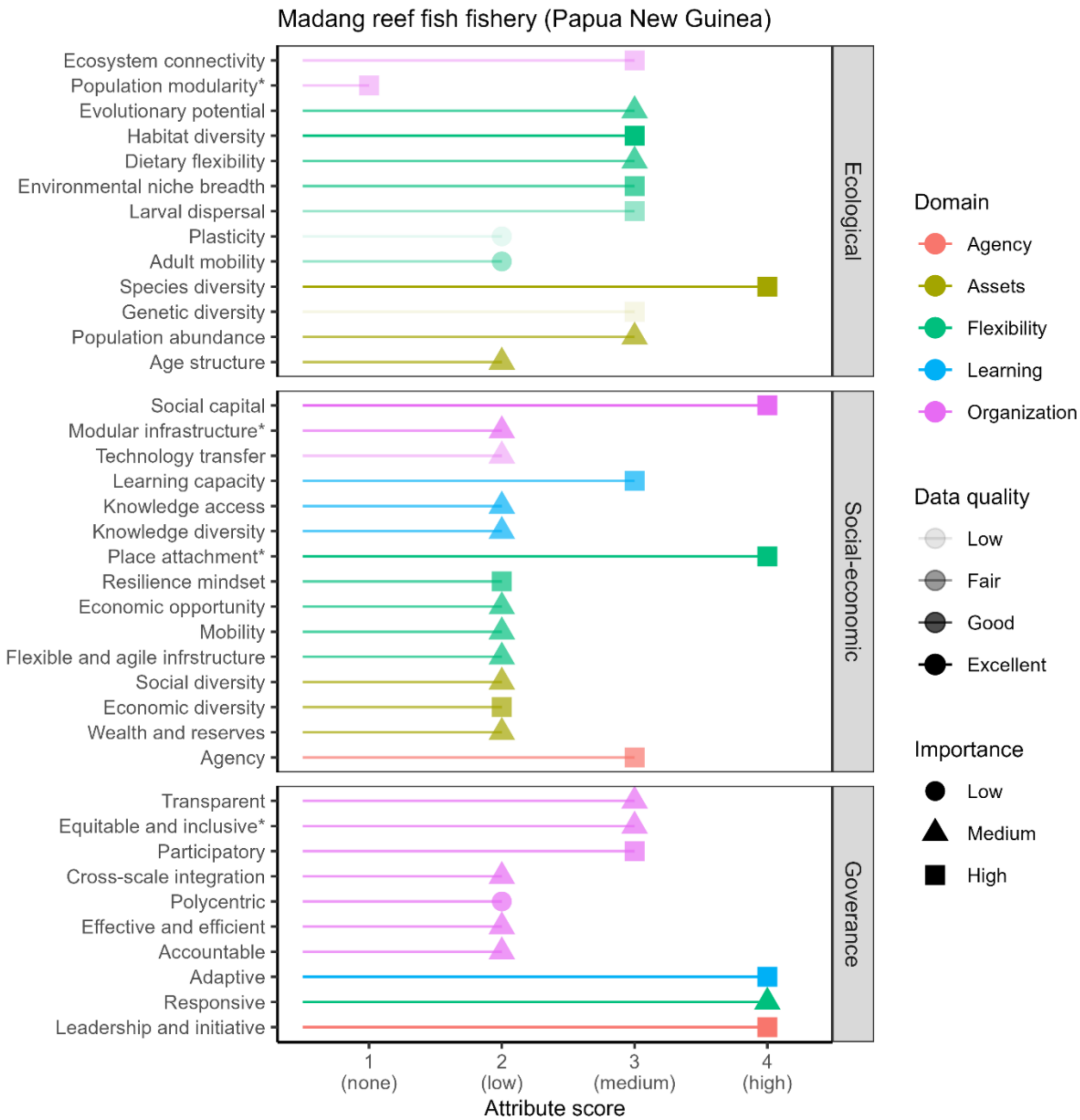

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Tasmania rock lobster fishery (Australia)

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Abstract

The commercial southern rock lobster (*Jasus edwardsii*) fishery is the second largest wild catch fishery in Tasmania, Australia, primarily exported to high-value Asian markets. The fishery occurs within one the fastest warming regions in the southern hemisphere. The climate-driven intrusion of the long-spined sea urchin (*Centrostephanus rodgersii*) has decimated key kelp forest lobster habitat as urchins overgraze the forests leaving 'urchin barrens'. However, royalties from an abalone *(Haliotis* spp.) fishery in the same kelp habitat subsidise dedicated commercial fishing of *C. rodgersii*, which has helped control the urchin population. Community support and alternative markets also helped the lobster fishery respond to supply chain and trade policy disruptions associated with the COVID-19 pandemic, but cumulative ecological impacts of climate change, overfishing, and a lack of climate leadership continues to threaten resilience.

Climate change and the rock lobster fishery

Waters off the east coast of Tasmania are warming almost 4 times the global average (Hobday & Pecl, 2014), however, Tasmanian southern rock lobsters not only face ocean warming but also enhanced interactions with potential competitors like the range-shifting eastern rock lobster, the world’s largest spiny lobster (Robinson et al., 2015; Gervais et al., 2021). Nonetheless, the resident southern rock lobster is not only more dominant in direct food competition than the range-shifting eastern rock lobster but also sustains competitive dominance beyond its physiological thermal optimum under predicted future ocean warming and heatwave scenarios (Twiname et al., 2021). This, however, may come at a high energetic cost, which may impair the resident southern rock lobsters’ resilience to other stressors such as moulting, disease or other novel invasive species (Oellermann et al., 2022).

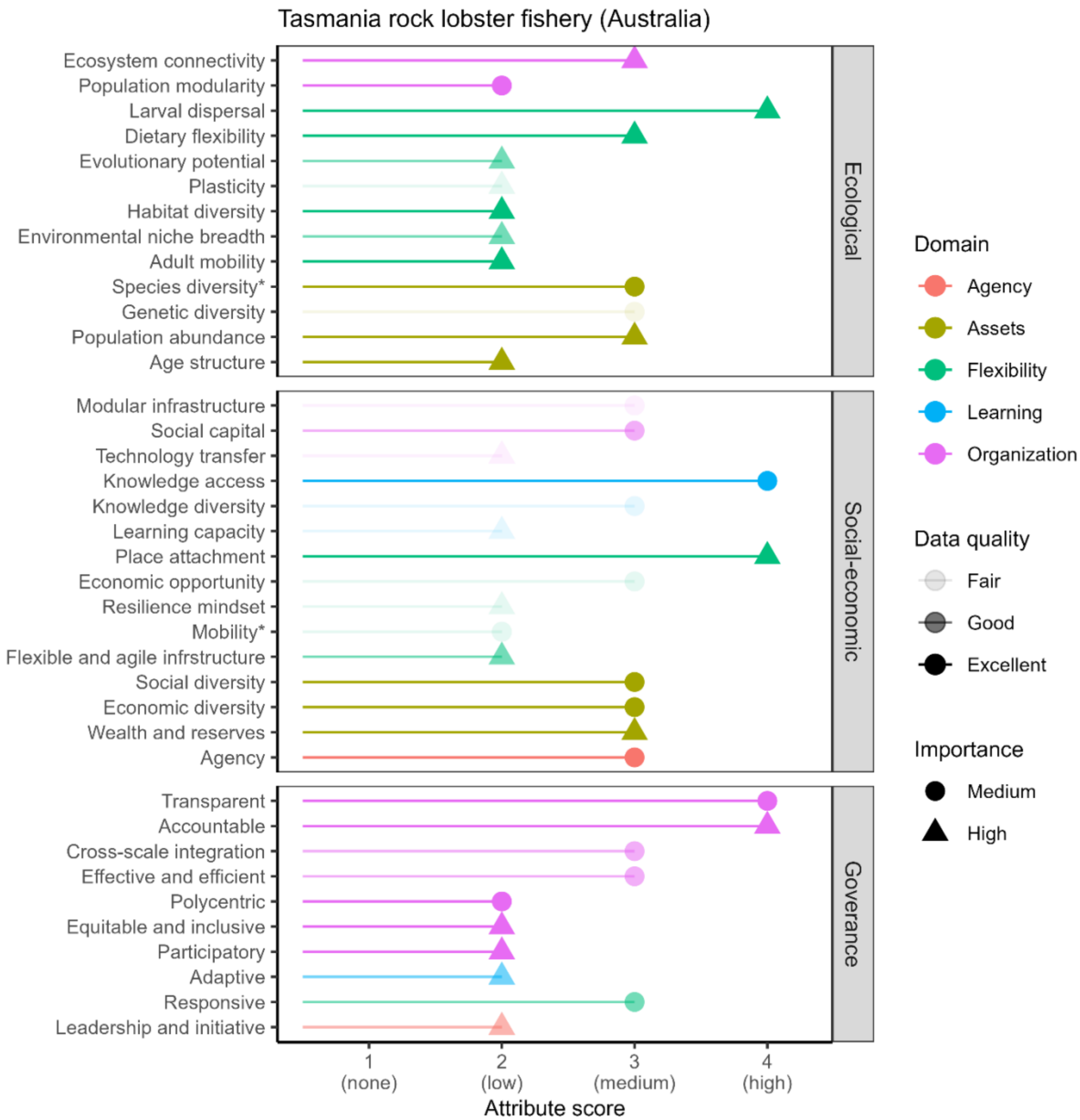
While historical overfishing has lowered lobster *population abundance*, the stock status is considered sustainable due to intact *age structure*. Kelp forest loss due to urchin barrens and warming have eroded suitable *habitat* for lobsters. Although the high-value fishery provides *wealth and reserves* contributing to well-being, there is limited management capacity to address issues beyond day-to-day fishing responsibilities.

Lobster *adult mobility* is low and although *larval dispersal* is high, and there is no suitable poleward habitat available, past Tasmania. *Access to economic opportunity* via domestic markets facilitated adaptation to pandemic disruption. However, for climate stressors, high *place attachment*, low occupational *mobility* in the predominantly older workforce and the lack of climate-aware *resilience mindsets* largely prevent adaptation. Many management restrictions limit fishery flexibility (e.g., zoned fishing regions, stock rebuilding zones, catch limits, size limits, transiting closed areas), although the industry is engaging in some autonomous adaptations to the stressors of climate change (Pecl et al., 2019). For example, in response to large mortalities of lobsters held in processor tanks, associated with warm water from the Tasman Sea 2015 heatwave (Oliver et al., 2017a, b), many operators have changed their landing practices so that they are unloading their (live) catch in areas with cooler waters (Pecl et al., 2019).

Limited connectivity, since Tasmania is the last coastal habitat before Antarctica, prevents lobster redistribution. Strong *social capital* supported fishers' transition to alternative markets, for example, during COVID. *Participatory* and *transparent* management arrangements could facilitate climate responses, if resources were made available. Moderate *integration across scales and sectors* facilitates collaboration and engagement between managers, industry and researchers.

A robust scientific system provides high *access to knowledge* and moderate *learning capacity*, which are key for evidence-based co-management. However, some denial of climate change within the industry and limited *adaptive governance mechanisms* may erode resilience. Prior to the extreme heatwaves of 2015/2016, acceptance of climate change was very low despite lobster fisher's observations of changes in the marine environment being almost entirely consistent with climate change (Nursey-Bray et al., 2012).

In the co-management structure, fishers have strong *agency* and *leadership* but there is also a disconnect between quota owners and fishery operators in terms of industry goals and agency. The fishery is in need of a *leadership* champion to push forward climate adaptation.



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United States West Coast Pacific sardine fishery

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Abstract

The Pacific sardine fishery has historically been a productive and lucrative industry along the West Coast of North America. However, climate change and increased fishing pressure have brought turmoil to this fishery resulting in its collapse first in the 1950s and later in 2015. Although the three Pacific sardine populations have oscillated across decades, recent booms have been far less productive and busts all the more devastating. The fishing community has been able to remain profitable by adaptively targeting different species and maintaining high levels of fishing skill within the community. However, the aforementioned impacts have pushed the fishery beyond its natural limits. This case study examines the effectiveness of the existing harvest control rule in light of climate variation, and its likely effectiveness in the face of climate change. Several contextual factors have made the existing harvest control rule – which sets the harvest rate based on the population size and the sea surface temperature, and which includes a

biomass threshold – possible, including a high capacity governance system, a science-based and participatory management system, and a broad understanding by stakeholders of the highly variable nature of the stock.

Fishery background

The Pacific sardine (*Sardinops sagax*) fishery has historically been one of the most abundant fisheries within the California Current Ecosystem (CCE), despite its boom-and-bust cyclical trends (McClatchie et al. 2017). There are three subpopulations of Pacific sardines which can range from Baja California, Mexico, to British Columbia, Canada (Smith et al. 2021). The natural boom and bust cycles of these populations occur on a timeline of 50-60 years and have been linked with trends in the Pacific Decadal Oscillation for hundreds of years (Kvamsdal et al. 2016). Unfortunately, the natural high and low biomass cycles of this fishery have been largely disrupted and influenced by both overfishing and climate change. The fishery first experienced increased fishing pressure in the early 1900s largely driven by the demand for a diversity of new food sources that resulted during World War I (Pacific Fishery Management Council, 2021). As a result, the Pacific sardine fishery became the largest fishery in the western hemisphere. By 1930-1940, Pacific sardines accounted for nearly 25% of the total fish biomass landed in the United States. However, their populations began to decline towards 1940 due to natural oceanic changes and overfishing (Pacific Fishery Management Council, 2021).

Followed by this decline, the fishery experienced a collapse in the 1950s which resulted in strict regulations implemented on the catch of the species. California, which had jurisdiction over the sardine fishery at the time, implemented a moratorium on commercial sardine harvest from 1967-1986 to aid in the recovery of the fishery. Additionally, fishing efforts shifted to focus on anchovies which had since increased in abundance. As a result, the Pacific sardine fishery began to recover during the 1980s-1990s when the Pacific Fishery Management Council (PFMC) assumed management responsibility for the sardine fisheries off California, Oregon, and Washington. Despite this improvement in stock abundance, a series of low recruitment years led to further abundance declines during the 2000's, resulting in the 2015 fishery closure (Sustainable Fisheries, 2016).

Currently, Pacific sardines are fully managed under the Coastal Pelagic Species Fishery Management Plan (CPSFMP) and are regulated by harvest control rules (HCRs) set on the fishery each year, which determine how much fishing can take place. These HCRs are based on ocean conditions, such as sea surface temperature, and previous stock assessment to determine annual catch limits that attempt to reduce the decline in sardine biomass (Kvamsdal et al. 2016). Various regulatory measures, including a biomass threshold for fishing, catch and seasonal limits, permitting, gear restrictions, and monitoring plans have also been put into place to promote recovery in the fishery and protect the fishery and its stakeholders from another collapse and closure as occurred in 2015 (NOAA Fisheries, 2020). These rules are intended to better conserve and manage the Pacific sardine stock off the U.S. West Coast.

Resilience to climate and fishing impacts

While much of the blame for Pacific sardine demise had been placed on the commercial fishing industry, climatic variation including marine heatwaves (MHW) appear to be impacting the distribution of the species. For example, the 1992 El Nino pushed populations farther north than had been recorded in over 40 years, indicating the clear connection climate-related heating events can have on this fishery (Sustainable Fisheries, 2016). Further research suggests that as the Pacific Ocean warms, some species will move farther north to compensate for the temperature increase in their original regions. Lastly, a recent study predicts that the northern Pacific sardine subpopulation is expected to be driven northward as a result of this warming – reducing the estimated northern sardine stock landings by approximately 20-50% in the next 60 years (Smith et al. 2021).

Despite this shift, researchers suggest that the southern subpopulation may move northward, thus mitigating the impacts of a reduced northern sardine stock in the region (Smith et al. 2021). Additionally, the Pacific sardine fishery has an inherent capacity to withstand ecological change, as evidenced by its survival in the face of El Nino events, changes in the Pacific Decadal Oscillation, variations in upwelling, and more. The existing harvest control rule implemented by the PFMC maps onto this inherent resilience by ensuring there is a reserve population large enough to survive during years when oceanographic conditions are not favorable and to recover when they are, via the biomass threshold provision. However, because this stock is transboundary, the lack of coordinated management (especially between the U.S. and Mexico) is a threat.

Ecological

Many attributes within the ecological dimension help confer resilience within the Pacific sardine fishery. These attributes include high *population abundance* during boom (productive) years, intact *age structure* with a low age at maturity (1-2 years) and long lifespan (up to 15 years), semelparous spawning, and *ecosystem connectivity*. Conversely, ecological features like high dependence on ocean productivity and environmental forcing and high levels of natural mortality might act to reduce resilience in the fishery. Fishing pressure has also reduced resilience by dramatically decreasing baseline biomass levels from historical unfished and fished levels, removing very young fish (1-3 years), truncating age structure, and likely reducing overall population fecundity.

Socio-economic

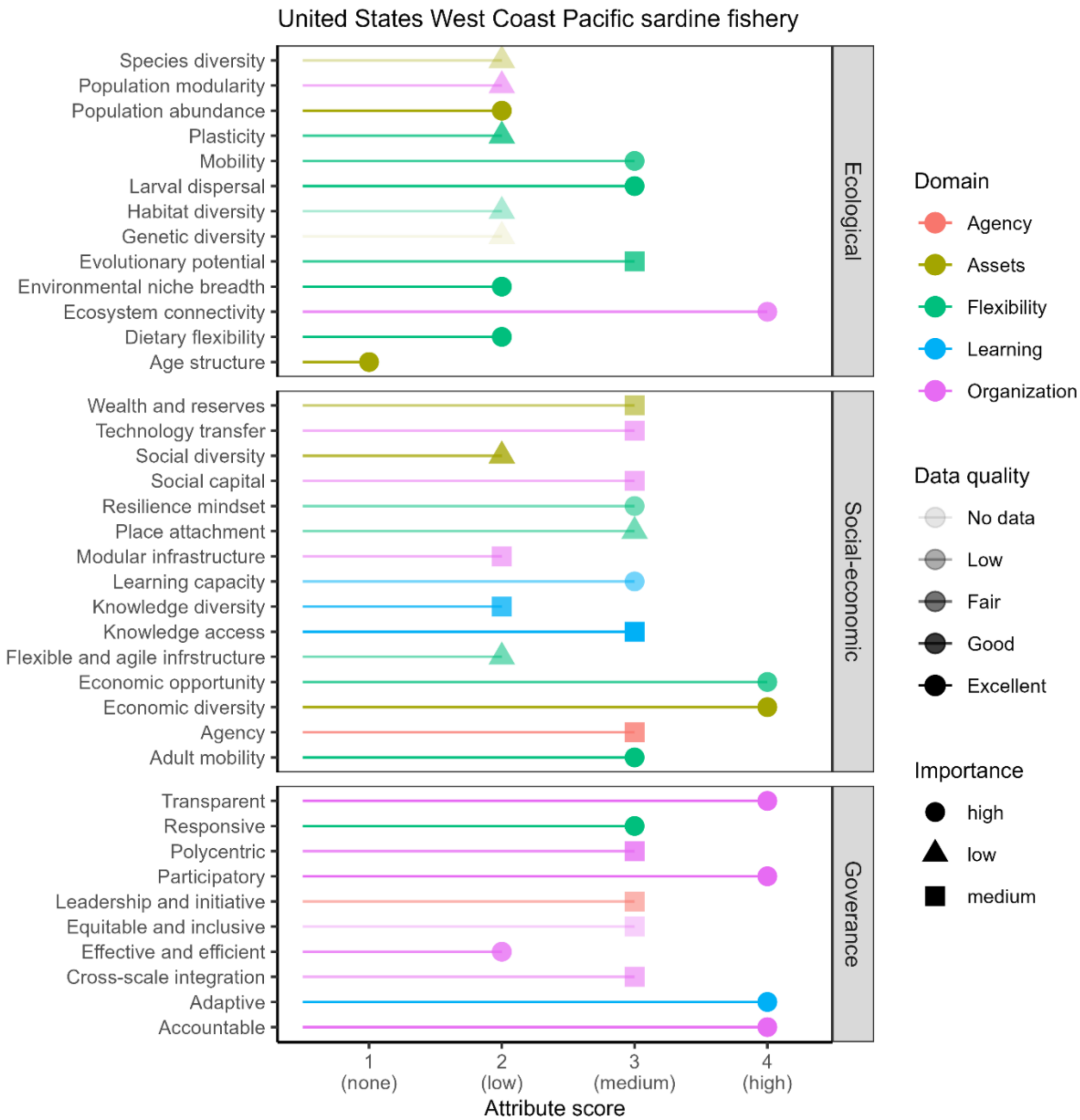
As mentioned, the Pacific sardine fishery has remained a critical fishery not only along the West Coast, but has made up a large portion of total U.S. catch in previous years. This has impacted the social and economic dimensions of this fishery. From a socio-economic perspective, high levels of fishing skill and *learning capacity* in the region and the adaptive ability to fish other species in the region or move with the species, has historically improved resilience in this fishery. The adaptive behavior and *knowledge diversity* of fishermen paired with the *species diversity* in the region has allowed fishermen to switch targets away from Pacific sardines when necessary without needing to make dramatic changes in vessels or gear, saving time and money in the process. However, low *social diversity* amongst fishermen, low levels of government *transparency* and *accountability*, and low *wealth and reserves* pose serious threats to the system and will ultimately reduce resilience. The low market power of fishermen relative to buyers places many fishermen at an economic disadvantage. Furthermore, limited trust in the government and high competition between competing fishermen lead to the failure of the fishing community to adopt an ITQ system which could have ultimately benefited the system as a whole if implemented successfully.

Governance

Participatory, consensus-driven governance has conferred resilience on this fishery. The fishery currently includes a voting mechanism to make decisions with good *leadership and initiative*, planning capacity, high scientific capacity, forward looking scientists, harvest control rules with biomass threshold and temperature-sensitive considerations, and the flexibility to shift to other species due to management under a single Coastal Pelagics FMP with no gear endorsements. Although participatory governance can confer resilience, it also retains drawbacks that cause it to limit resilience in the system largely due to the length of time it can take for decision-making to occur under this system and overall *responsiveness*. Additionally, misalignment between the scale of good management measures and distribution of the stock (i.e., the lack of good fishery governance throughout the stock's range) can result in overfishing within the fishery.

Conclusion

Although the trajectory of this fishery remains uncertain, it is clear that climate change promises to create future conditions that differ from past oceanographic conditions. Whether the inherent resilience of the Pacific sardine fishery will enable it to survive and thrive enough to allow for the sizable commercial harvests that periodically occur in the face of this change remains unknown. Similarly, whether the existing harvest control rule will provide a sufficient level of protection and harvest opportunity in the face of climate change also remains unknown. A management strategy evaluation, or similar exercise, would help shed light on these questions. However, evidence suggests that if fisheries respect and accept the importance of HCRs in enhancing future fishing opportunities within their systems, then they may be more willing to abide by formalized regulations and provide critical information to management to develop the health and success of the fishery. In order for this type of compliance and trust between fishers and management to prove successful, increasing the inclusion of fishers in these critical conversations and making sure they have a seat at the governance table will likely be critical (Kvasdal et al. 2016).



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Iceland groundfish fisheries – *see published manuscript at https://doi.org/10.1007/s13280-023-01859-8*

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Abstract

Iceland's Individual Transferrable Quota (ITQ) commercial fisheries demonstrate how flexible and responsive management, centralized organization that promotes learning, ample assets, and resilience mindsets interact to confer resilience of sustainable and profitable stock management to climate-driven changes in species abundance and distribution. However, the strong reinforcing feedbacks among attributes that stabilize the system may entrench economic inequalities and preclude adaptation to broader change.

System overview

The highly productive convergence of warm Atlantic and cold Arctic currents in Iceland's waters supports rich fisheries: Iceland consistently ranks among the top 20 marine capture nations globally, with around 1600 vessels landing around 1.5 million tonnes annually at 1.3 billion USD value (ICES 2019; FAO 2020). The commercial fishing sector is core to the economy, contributing around 40% of Iceland's total export value (Gunnlaugsson et al. 2020). Cod is the most important economic species; fishers also target diverse demersal species including haddock, saithe (pollock), and flatfishes as well as pelagic capelin, herring, blue whiting, and mackerel.

Fisheries management in Iceland is tightly controlled and centralized, with over 98% of catch and more than 30 species managed under the ITQ system. All commercial fishing requires a permit, no foreign vessels may own quota, and all landings are monitored, with data shared with fishers in real time. Annual catch limits are set based on scientific advice and, increasingly, precautionary harvest control rules (Gunnlaugsson and Valtysson 2022). The ITQ system's alignment of ecological and economic goals—firms are profitable and once-collapsing stocks have stabilized such that 99.98% of domestic catch is from sustainably-managed stocks (Gunnlaugsson and Valtysson 2022)—has built trust between industry and management and enabled more precautionary management. Iceland's fishing industry is dominated by vertically integrated firms selling high-value products for export, with a growing value-add and innovation sector focused on quality and sustainability (Sigfusson 2020). Meanwhile, smaller communities lost fishing access and thus employment opportunities in the wake of the ITQ system, and the industry is considered prohibitive to enter as a newcomer (Chambers and Carothers 2017).

The interactions between warm and cold currents that make Iceland's waters so productive also create dynamic conditions that influence species productivity and distribution on interannual to multidecadal scales (Astthorsson, Gislason, and Jonsson 2007). A prolonged warm anomaly from the mid-1990s-2010s drove northern range expansions of warmer-water species including a novel incursion of Atlantic mackerel, while other commercial species like capelin temporarily disappeared (Valtýsson and Jónsson 2018). Iceland's fleet rapidly capitalized on the mackerel opportunity, establishing a lucrative fishery but sparking international conflict over fishing rights (Spijkers and Boonstra 2017). Looking ahead, researchers project that local variability will dominate the global climate signal through mid-century, but Iceland could expect increased productivity and range expansions of some species consistent with a general pattern of poleward shifts (Campana et al. 2020; Mason et al. 2021; Mullon et al. 2016).

Resilience attributes and linkages

As demonstrated by rapid responses to mackerel and other species changes over the past 30 years, Iceland's fisheries appear resilient to climate-related changes in species abundance and distribution. Management is *responsive* to species changes through setting annual catch limits, authority to set immediate temporary closed areas to protect spawning areas, and incorporation of new species into the quota system based on catch history. High *learning capacity* via the strong scientific system enables this responsiveness. Regulatory measures also promote fisher flexibility to adjust to catch fluctuations through mechanisms to bank or borrow quota allotments and convert quota among species. *Fisher mobility* is unrestricted under the quota system.

High connectivity in management and supply chain organization structures including real-time data sharing, centralized national fish auctions, and vertical integration promote *transparency* and *access to knowledge*, facilitating rapid responses to environmental and market signals. Stable and transparent supply chains generate *access to economic opportunitie*s such as specializing in underutilized species. A growing "innovation cluster" model increases connectivity and *access to knowledge* across the value chain and may help *diversify knowledge sources*. Strong *social capital* in Iceland's society with a shared understanding of the fishing industry's economic and cultural importance fosters trust and collaboration within industry and among industry, government, and scientists.

The industry's access to natural and material assets underpins other resilience attributes. The combination of a productive environment and *effective* management supports commercial stock *population abundance*, healthy *age structure*, and relatively high *species diversity* for the latitude that have helped maintain stable catches despite environmental fluctuations. Profitable, vertically integrated firms have ample *wealth and reserves* that expand adaptive options such as buying high-capacity trawlers to increase mobility, purchasing more quota to diversity portfolios, and relying on reserve wealth and insurance to cope with species losses. However, these feedbacks reinforce economic inequalities, where the wealthiest firms are most poised to benefit from new economic opportunities or withstand losses; these wealthier actors also accrue political power and have strong incentives to maintain the system status quo. Increasing wealth accumulation and perceived inequality has been a source of social critique and political movements to reform or overturn the ITQ system.

Finally, a history of variable and uncertain environmental conditions, market competition, and the security of the Nordic welfare system may contribute to *resilience mindsets* of comfort with uncertainty and confidence in the industry's ability to adapt. Among communities and smaller firms, government innovation funding and little cultural stigmatization of failure provide individual leaders with *agency* to experiment and flourish with transformative ideas. While Iceland's industry has reason to be confident, an overall emphasis on reactivity seems to detract from planning and longer-term adaptation. Scholars and industry members have expressed concern about a lack of study and preparation for broader climate impacts such as ocean acidification and invasive species.

Conclusion

Iceland's overall high capacities—economic, scientific, management, social, ecological—and experience with a variable marine environment have contributed to strong and reinforcing climate resilience dynamics. Tightly controlled and effective ecological management paired connected markets and supply chains that promote information exchange allow fishers and firms to rapidly respond to ecological changes, and resilience mindsets backed by abundant assets enable them to translate those ecological changes into economic opportunities. Iceland's fisheries are in a strong position to react to climate change, but confidence in their responsiveness and vested interests in maintaining the status quo could impede proactive planning and entrench inequalities. Iceland's successful adaptation to species shifts may also incur tradeoffs at the international level without greater governance *integration across scales*. A key first step for Iceland may be greater prioritization and integration of broader ecosystem dynamics and climate forecasts in fisheries science. Protecting smaller processors, perhaps through enhanced access to assets, will be important for maintaining competition, diversification, and innovation in response to ecological change. Finally, without greater attention to social equity and better communication of how fisheries contribute to society, the ITQ system runs long term risks of reactionary political reform destabilizing its strong ecological and economic structures. Exploring how to build resilience to climate change may present an opportunity to reconsider equity, distribution of benefits, and the ongoing role of fish and fishing in Icelandic society.

Acknowledgements

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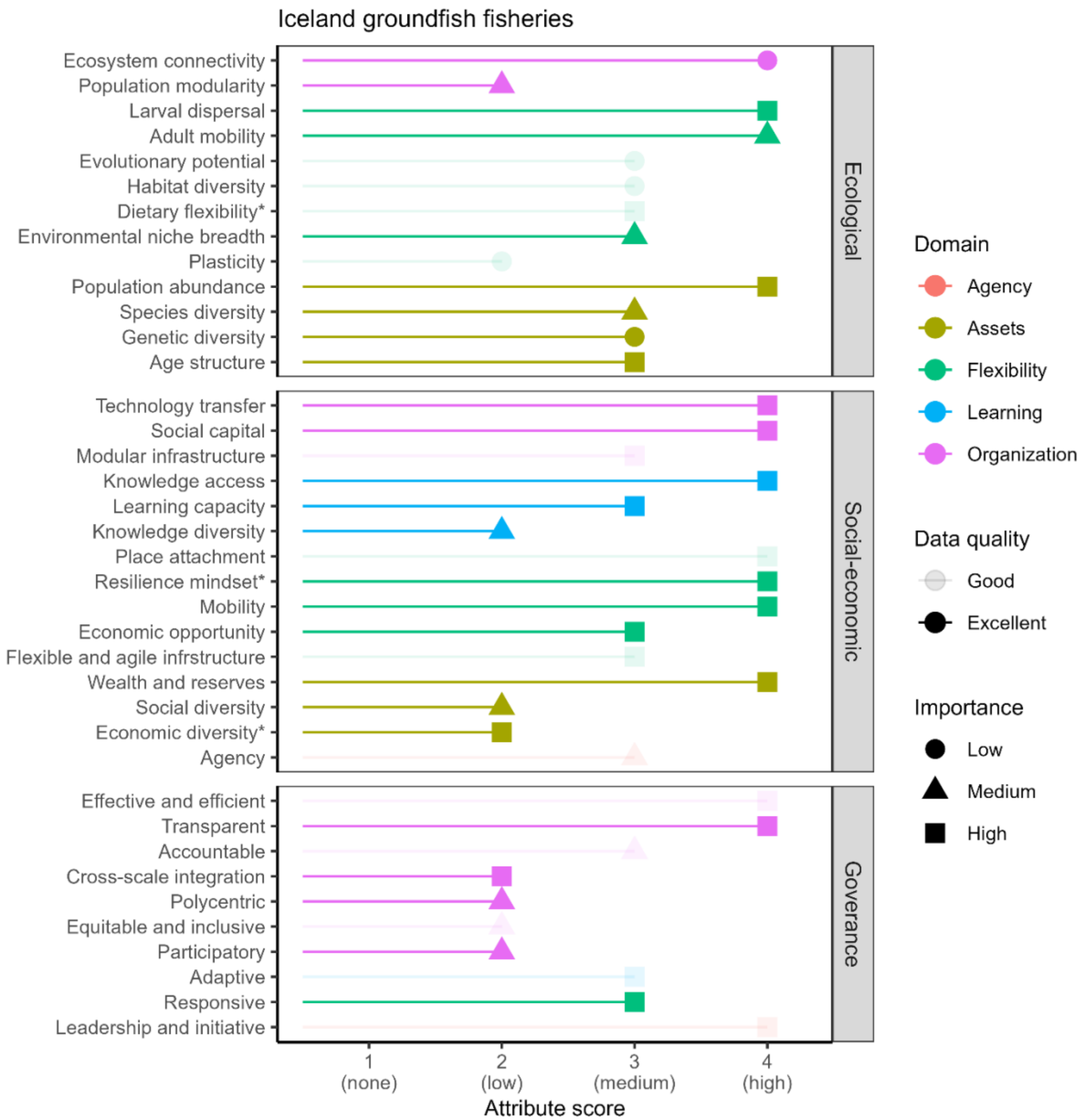

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<u>Northeast Atlantic small pelagic fishery</u>

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Abstract

This case study is about a fishery operating out of the Netherlands, UK, Denmark & Germany that targets pelagic fish using vessels greater than 40m in length. The case study focuses on the resilience of the fisheries and the fisheries system in which they operate, to the perturbations caused by climate change. The fisheries are considered the stakeholders (individuals/companies) that own the vessels/businesses. The fisheries were shocked in the 1970s by a collapse in their targeted fish stocks caused by overfishing. Those fishers that survived this shock responded by accessing capital to reinvest and change their business model. Climate change is currently impacting the distribution of the stocks (an ecological asset). Resilience is provided by the portfolio fishing method (seasonal sequential mixed fishery), flexibility attributes of *mobility* and *responsiveness*, together with the socio-economic assets of *wealth and reserves*, capital, and learning and *agency*. The major risk is the inflexibility in the governance dimension, with entrenched actors protective of their influence and opportunities. A failure to adapt the organization of the fisheries management is the greatest risk posed by climate change that threatens the resilience currently in the asset and agency domains.

Background of the fishery

The case study is the fishery operating out of the Netherlands, UK, Denmark & Germany that targets pelagic fish using vessels greater than 40m length. Although operating from different countries, and using 2 types of vessel (refrigerated sea water, RSW, or freezer trawlers, which store, process and freeze onboard), the fishery of approximately 50 vessels seasonally, sequentially targets mackerel, herring, blue whiting and horse mackerel, with additional species supplementary species (e.g. greater silver smelt, sandeel, redfish etc.). Their total annual catch is approximately 850,000 tonnes per year with a first sale value of approximately €350,000,000 usually for human consumption. The fishery operates in the North East Atlantic on and off the continental shelf, in national jurisdictions and in the areas beyond national jurisdiction. Thus they are managed through national, coastal states and regional fisheries management organizations. The owners and crews are predominantly European. The main management tool is the setting of total allowable catches, based on scientific advice. Separate coastal state negotiations occur for each of the stocks fished. There are a number of agreed and proposed management plans for some of the fisheries, which are also evaluated by scientists against precautionary and MSY criteria.

Climate impact

Climate change is likely already impacting the distribution and productivity of the fish stocks, and also the management of the fisheries as the stock shift into different jurisdictions. Two European horizon projects have invested the current impacts and potential future consequences of climate change (CERES, Peck et al., 2020, and CLIMEFISH, https://climefish.eu/). Projections suggest small changes in the availability of fish with a small increase in both mackerel and blue whiting spawning stock biomass, but reduction for some herring stocks. Further changes in the distribution of stocks are extremely likely, increasing the complexity in the negotiations on fishing rights allocations and access. In the social and economic dimension the risks posed by climate change are low. The two EU projects suggest that the pelagic industry in northern Europe has a low climate risk, with larger fishing vessels and those which fish with pelagic nets exhibiting the lowest climate vulnerability risk compared to other fleet metiers in Europe.

Discussion

The fishery is considered resilient across ecological, socio-economic, and governance dimensions. The mixed seasonal fishery provides a portfolio effect to changes in the availability of specific stocks, and the ability to fish further from home ports, across a wider range of sea and ocean to ensure fishing opportunities. The fishers are organized, well resourced, *adaptive* to opportunities and challenges, utilize a *diverse range of knowledge* and swiftly *incorporate new technology*. They operate effectively, generally to their advantage across the governance system with visible *leadership*, despite their *polycentric* organization. They have great control over their supply chain and marketing and the doors to the top level of fisheries politics are open to them. The attributes of resilience are apparent across all five resilience domains of assets, flexibility, organization, learning, and agency. Some could argue that these fishers have a high degree of organization and learning, leading to great agency, power and self-determination.

The fishery could be considered to show negative traits for the attributes of *transparency* and *participation*, with the owners of the fisheries potentially being seen forming closed clubs. There is little *social diversity* and there are observable distinctions between the roles, and prominence interests of the owners, organizational representatives, vessel officers and crew. There is little formal integration with other sectors in the siloed governance system (their power and influence is in the fisheries management governance system), and reducing their influence beyond their own arena of operation (the failure to address issues of conservation concern (e.g. bycatch and fishing in MPAs) and the loss of influence compared to offshore renewable energy production as an examples).

The fishers (owners of the vessels) are adept at changing fishing practices, incorporating new technology, *and diversifying target fish stocks*. They appreciate the value and respond to the evidence from *diverse knowledge sources*. The status of the fish stocks and opportunities for the fisheries are well known and supported by a very sophisticated fisheries science system. The fishers/companies have wealth and reserves with access to further capital. Their agency and ability to influence their direct milieu is high.

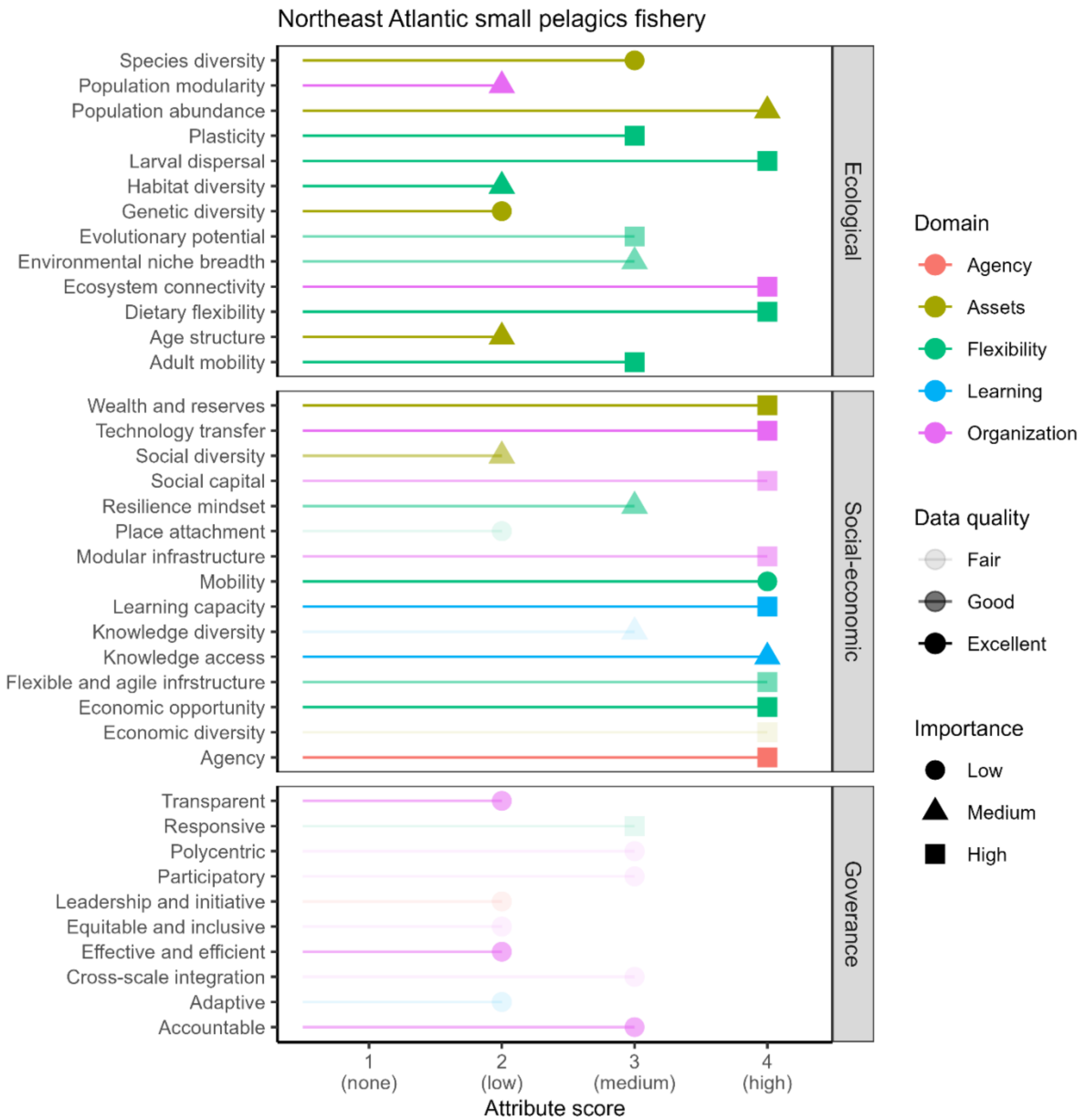
However, there is a risk in the governance dimension. Here poor performance in the domains of flexibility and organization are likely to increase risk. The complex fisheries management system and roles and power of multiple actors constitutes a major constraint on governance. The current management system is not able to adapt to the changes in the distribution across jurisdictions. Unless this is resolved, further complications should be expected in the quota and access negotiations in both Coastal states and Northeast Atlantic Fisheries Commission (NEAFC). This has already led to loss of sustainability accreditation and may lead to further loss of markets in the developed world. There are no apparent champions for change, or visible leaders coming forward to resolve the growing impasse. The complication of the UK leaving the EU and becoming an independent coastal state has further disrupted the dynamics of the management system. This inflexibility restricts the variety of applicable adaptation/mitigation governance measures and their effectiveness.

Conclusion

The attributes of the fishery that provide resilience to climate change are many, including an ecological asset that maintains opportunities for exploitation in the face of climate change and positive socio-economic attributes across assets (wealth, reserves, capital), learning and agency. The major risk is the inflexibility in the governance dimension, with entrenched actors protective of their influence and opportunities. A failure to adapt the organization of the fisheries management is the greatest risk posed by climate change that threatens the resilience currently in the asset and agency domains. The domains are interdependent.

Acknowledgements

Kathy Mills, Julia Mason and Martin Pastoors are thanked for the critical review of the case study.



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Hokkaido set-net fishery (Japan)

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Abstract

Through vertical integration with local industries, the large-scale set-net fishery in Todohokke, Hokkaido, which is a multispecies fishery (supported by high species diversity), has demonstrated the ability to adapt to changes in fish species composition that climate change has induced in fish landings. This fishery catches both groundfish and migratory fish at the confluence of multiple ocean currents with a fixed net at the designated fishing ground. This fishery has a passive nature and is immobile, which makes it difficult to adapt to changes in catch species over time and space, such as by adopting altered fishing strategies and fishing locations (high place attachments, immobility). Changes in sea surface temperatures and ocean heat wave effects, which are thought to be caused by climate change effects, have significantly altered the species composition of landing and changed the main landing species. Throughout its history, the local seafood industry and the landings of this fishery have shaped vertical integration. With the transition of the main landing species, the local fishing industry is able to create economic value in the fish market for new main landing species (flexible/agile infrastructure, resilience mindset). Therefore, the fishery was evaluated as being resilient to the change in fish species caused by climate change, not through the fishery alone, but by vertically integrating the fishery with the local seafood industries that require this fishery's landing for their economic activities.

Executive summary

The Japanese coasts are dominated by multispecies fisheries due to the significant influence that the local marine environment has on the abundance and species composition of fish available. Four distinct seasons and multiple large-scale ocean currents characterize the Japanese coastal waters, which play a substantial role in shaping the coastal environment. Fish abundance and distribution are significantly impacted by changes in the frequency and intensity of the coastal environment and the marine ecosystem structure. Due to this unique coastal environment, coastal communities in Japan have developed multispecies fisheries that catch and exploit various fish species year-round, all of which are largely distributed for and consumed as Japanese cuisine.

Japan's large-scale, set-net fishery is the most important fishing sector amongst its coastal fisheries. This fishery involves a unique Japanese fishing method that targets diverse fish species that shift with the ever-changing coastal marine environment. The large-scale, set-net method was designed to guide pelagic and demersal fish into nets (International Center for

Living Aquatic Resources Management 1980). Through this process, the set-net gears are fixed at a designated location during a certain fishing period. As a designated fishing area, the prefecture government grants set-net fishing rights to fishers (Makino 2011). The fishery is characterized by a completely passive approach with no fish chasing or landings of multiple species.

Todohokke, located in South Hokkaido, Japan, is known for its large-scale, set-net fishery, whose structure extends over 2~4 km. For more than 100 years, it has been sustained as a traditional fishery that catches more than 100 fish species commercially. They are blessed with abundant fishing grounds due to the nutrient-rich waters produced by the two ocean currents that meet there. A cold ocean current, the Oyashio Ocean Current of the North Pacific, flows southwestward along the coast of eastern Hokkaido before meeting a warm ocean current, which splits off from the Tsushima Warm Current, which flows northward across the Sea of Japan. As a result, large-scale, set-net fisheries in Todohokke catch both fish migrating through the Tsugaru Strait and from the North Pacific Ocean.

It may also be fair to argue that various currents flowing along Japan's coastline, including Kuroshio, Oyashio, Tsushima Currents, and Liman Currents, affect the various pelagic fish species that migrate along the coast.

The fishery is characterized by these two features.

- High *species diversity* (ecological)
- No *mobility* (social-economic)

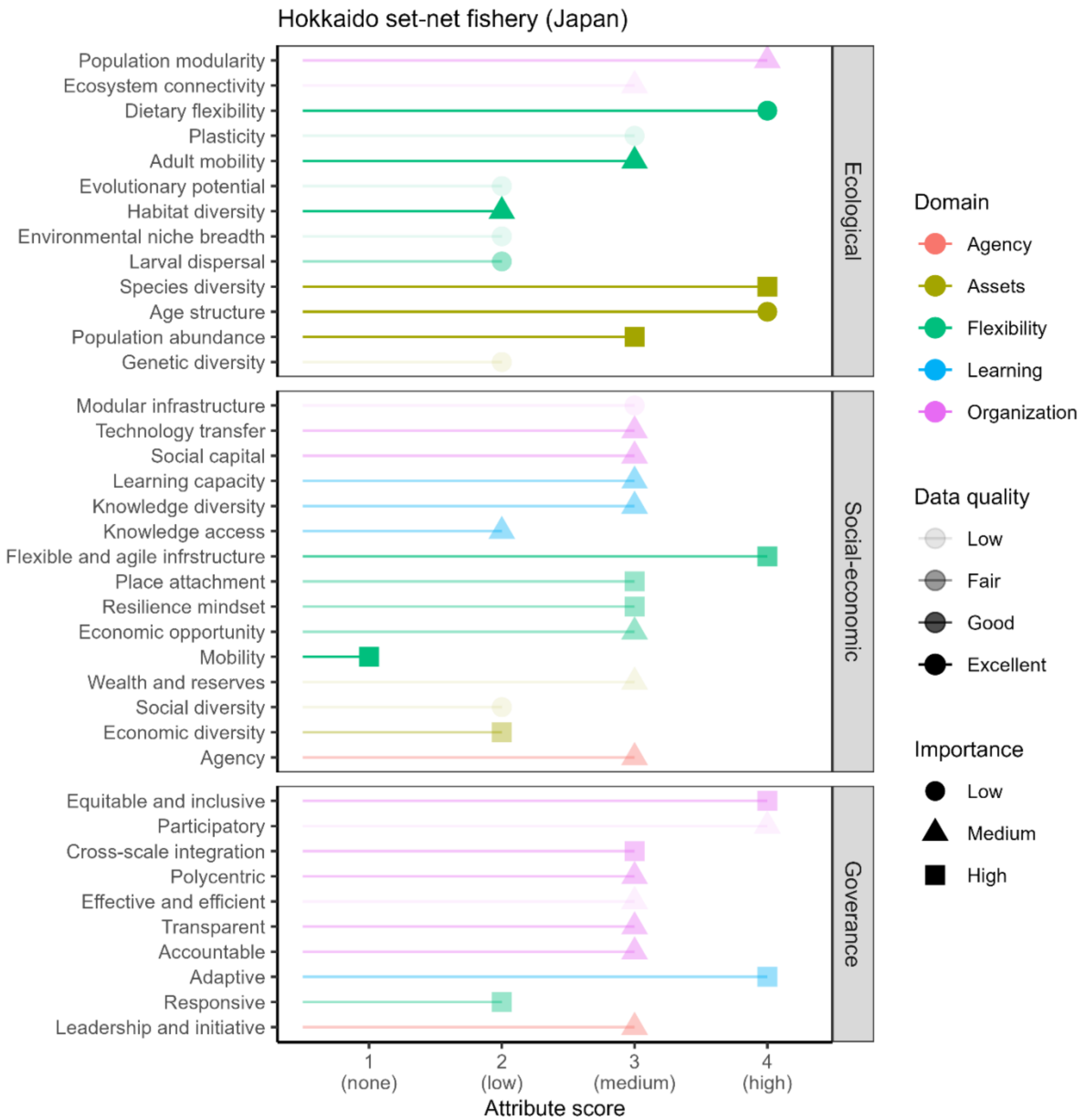
Climate change has led to a pronounced shift in the composition of fish species landing in this fishery in recent years. In large-scale, set-net fisheries, the nets are fixed to a specific fishing ground. As a consequence, changes in the migration patterns and distribution of fish species have a direct impact on this fishery's landings. The catch of Japanese common squid, *Todarodes pacificus*, the most important species caught for the local processing industry, has declined sharply since 2015, while the catch of yellowtail, *Seriola quinquerasiate*, has increased since 2010, indicating a species shift. Squid landings have declined because of changes in spawning habitat and migration patterns associated with climate change (Sakurai et al. 2002), while yellowtail catches have risen significantly because of ocean heatwaves that occurred between 2010 and 2016 as a result of a warm water eddy caused by the Kuroshio Current which prevented the Oyashio Current from moving southward (Miyama et al. 2021).

The large-scale, set-net fishery in Todohokke is resilient in the social-economic dimension to changes in species diversity caused by climate impacts. As squid landings decrease, ex-vessel prices (i.e., sales price upon landing) increase, complementing the decrease in squid landings as a percentage of total income. Meanwhile, the local fish market develops an appropriate ex-vessel price for yellowtail, so that the ex-vessel price does not decline with a sudden increase in yellowtail landings, as the main catch shifts to yellowtail. As a result of this mechanism, even if the landings of the main fish species changes, total income does not significantly decrease.

This fishery is resilient to changes in species diversity in their landings as a result of climate change because a flexible market system is vertically linked to local industries. Vertically integrated local industries allow unit prices to adapt to changes in species composition with agility and flexibility. As a result, the annual landing value of the Todohokke set-net fishery is relatively stable and resilient to changes in the species composition of their landings.

Attributes that characterize this flexible market system and that may have had a positive impact on resilience are summarized below.

- High *flexible and agile infrastructure* (social-economic)
- High *resilience mindset* (social-economic)
- High *place attachment* (social-economic)



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Mie spiny lobster fishery (Japan)

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Abstract

This case study examines the climate resilience of the Japanese spiny lobster fishery in Wagu, Mie, Japan. This fishery is a representative case of Japanese coastal fisheries that exhibit a high degree of harvester collaboration (Ishihara et al., 2021). Ecologically, Kuroshio current plays important roles in larval transport to impact stock recruitment and in water temperature to impact critical seaweed habitat that spiny lobsters depend on (Yamakawa, 1997). Specifically, Kuroshio's large meander negatively impacts this fishery in both aspects. In recent years, this region has experienced a decline of seaweed bed, termed 'iso-gare' or ocean deforestation (Kurashima, 2017). It is likely that climate change-induced ocean warming can exacerbate this. This fishery is data limited and has no formal stock assessment. While the harvesters are highly collaborative and can respond to the changes they observe and experience themselves, lack of scientific information such as stock forecasts limit their ability to plan and take proactive adaptation actions.

Executive summary

The Japanese spiny lobster fishery in Wagu, Mie, Japan is a co-managed fishery. Like in all other coastal fisheries in Japan, this fishery is managed as a territorial use rights fishery, where harvesters take a lead in the management (Ishihara et al., 2021; Makino & Matsuda, 2005). In Wagu's spiny lobster fishery (TURF), however, they operate under a unique management regime. Wagu's lobster fishers have implemented a management regime that consists of two operational schemes. In the first half of the fishing season, the fishery operates under a ‘pooling scheme’ where harvesters pool fishing efforts and landings and share revenues evenly. In the latter half of the fishing season, the fishery operates under a competitive ‘open-access scheme’ where each harvester operates individually and competitively. The fishery has been operating under this regime since the early 2000s, and this regime has contributed to achieve multiple objectives including 1) earning stable income and 2) reducing effort inputs to require less labor activities (Ishihara et al., 2021). These are critical because their stock is volatile as the lobster settlement in their TURF is driven by Kuroshio Current path. Compared to the neighboring TURFs that are both managed bottom-up by harvesters taking lead but operate mostly as open-access throughout the fishing season, Wagu’s landings are more stable over the years (Ishihara et al., 2021).

While the case study examines a very specific fishery, some of the lessons drawn from this fishery can be generalized to understand climate resilience in a fishery that is managed by co-management that has a characteristic of high level of cooperation among harvesters. This fishery also represents data-poor fisheries where routine stock assessment and fishery-specific climate changes are mostly scientifically unknown. Through this case study, I explored what climate resilience looks like in the fishery that is relatively well-managed through fish harvesters exhibiting high levels of cooperation but lacking scientific information.

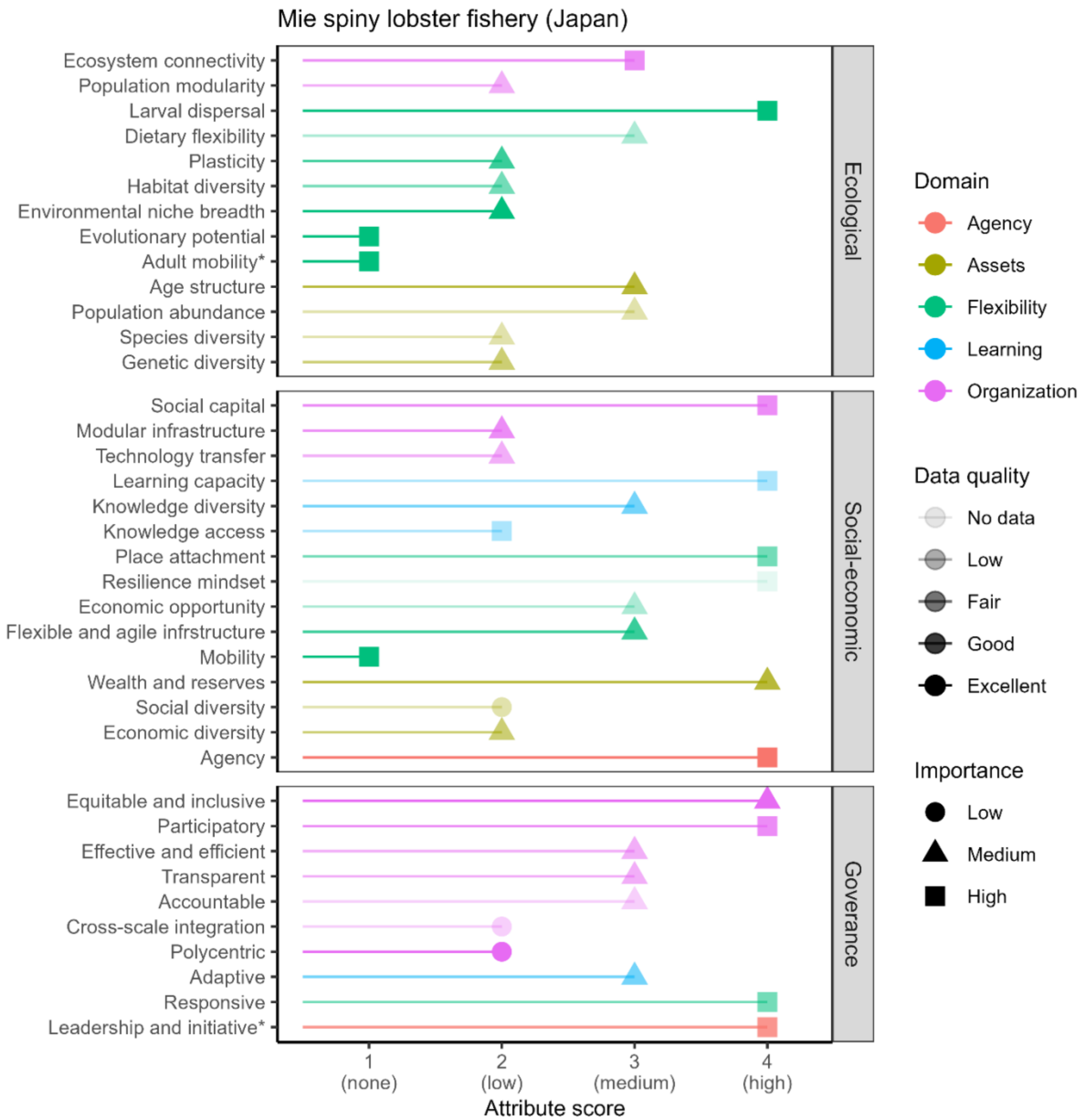
In recent years, the lobster harvesters in Wagu have reported changes in seaweed habitat that spiny lobsters depend on. The harvesters are experiencing a decline in catch in the offshore and deeper parts of their TURF. A researcher at Mie Prefectural Fisheries Research Institute commented that the region’s water has been warmer due to Kuroshio current meander, and this could be a cause of the changes in seaweed habitat. In broader coastal areas in Mie, a phenomenon called ‘iso-yake’ or coastal deforestation (Kurashima, 2017). No formal scientific studies have been conducted to scope the possibility of this linked to climate change, but a recent increase in water temperatures caused by prolonged period of Kuroshio large meander event seem to be associated with the changes in seaweed habitat. Thus, a possible first impact of climate change will be felt through the changes in seaweed habitat in TURF.

The key attributes and their impact on resilience can be summarized as follows:

- Strong larvae dispersal (ecological 4.1.2.4) and Low genetic diversity (ecological, 4.1.3.3) and Low evolutionary potential (ecological, 4.1.1.3) → opposing impacts
- Low Adult Migration Capacity (ecological, 4.1.2.5), Low Mobility (social-economic, 4.2.2.1), and High Place Attachment (social-economic, 4.2.2.5) → positively impact resilience
- High Social Capital (social-economic, 4.2.2.2), High Agency (social-economic, 4.2.2.4), and Highly Participatory Governance (governance-management, 4.3.2.1) → positively impact resilience

- High Learning Capacity (social-economic, 4.2.4.2), High Resilience Mindset (4.2.5.1), and Highly Responsive Governance (governance-management, 4.3.3.2) , but Limited Access to Knowledge (social-economic, 4.2.4.1) → opposing impacts

Larvae is transported through Kuroshio current system, this means that larvae that are spawn in different regions mix before settling at coastal regions in Japan (Yamakawa, 1997). A study also indicates that no genetic differentiation for this species (Inoue et al., 2007), which I interpreted to indicate a low evolutionary potential. A study have indicated a low adult mobility and stochastic recruitment contribute to the effectiveness of the co-management as the habitat boundary of the adult lobsters match the boundary of the management (Ishihara et al., 2021). Thus, low adult mobility in conjunction with social-economic attributes of low mobility and high place attachment can be regarded as a contributing attribute of resilience. The system also exhibits high social capital, agency, and participatory governance, which can contribute to resilience. However, lack of scientific knowledge limits their ability to take precautionary measures. For instance, lack of routine stock assessment and habitat assessment limit fishers' ability to plan ahead. These lobster fishers are highly cooperative and have a propensity to take collective action and coordinate their fishing activities to respond to climate change. Yet, these fishers currently can rely on their own experience to adapt. They share their own observations and experience with other fishers in the fishery, thus they are usually 'on the same page' and are very observant in terms of noticing ecosystem changes in their TURF as a whole. They also regularly communicate with prefectural researchers and officers as well as some university researchers. Yet, they all lack financial support to conduct formal scientific studies to understand how climate change may impact their fishery. Thus, they are not able to shape adaptation plans for the future.



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Juan Fernandez Islands demersal fisheries (Chile)

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System overview

The Juan Fernandez Islands (JFI) are located off the coast of central Chile between 32.81°S and 33.81°S and include the Robinson Crusoe and Santa Clara Islands (RC-SC) subsystem and the Alejandro Selkirk Island (AS). The distance from shore of these islands and seamounts and the presence of unique oceanographic features has promoted strong *connectivity* within and between other systems, which supports a high degree of marine and terrestrial endemism. In 1935, the Chilean government declared the JFI as a National Park, and in 1977 they were designated a UNESCO Biosphere Reserve due to their significant biodiversity and ecological importance. More recently, in 2016 and with community support, the Chilean government designated a multipurpose marine protected area and several marine parks around the islands and seamounts in the archipelago. In 2018, a collaboration between the community members and the government led to the development and management of one of the world's largest multipurpose MPA (National Geographic, 2015; Mongabay, 2019; Ernst-Elizalde et al., 2020); 262,000 square kilometers of ocean around the Juan Fernández archipelago was declared a fully protected marine park by the Chilean government. The MPA is multi-use, encompassing no-take zones and allowing sustainable fishing by the artisanal fleet within the archipelago area (Muñoz, 2021). Since its inception, the Juan Fernandez National Park has become an exemplary model for spatial management approaches.

There are two main towns within the JFI, Juan Bautista in the RC-SC and Rada de la Colonia, which is a temporary fishing village inhabited from October to May on AS. For more than 100 years, fishing on these isolated islands has traditionally been by locals who possess an effective tenure system of almost 4,000 'Marcas', which are unique family-owned fishing areas (Zylich and van der Meer, 2015). These Marcas are transferable through inheritance only to family members by local agreement. This arrangement has discouraged outsiders and newcomers from fishing and has kept effort levels and fishing fleet size regulated. In addition, lobster fishing is regulated by seasonal closures, gear restrictions, minimum size limits, and restrictions for egg-carrying females (Eddy et al., 2010; Ernst-Elizalde et al., 2010). The success of the lobster fishery can be credited to a tenure system, simple regulations, and respect for the environment (Ernst et al., 2013). Due to the isolation of the JF islands, the community tends to be very tight-knit, and the fishery, which is run by locals, is highly organized and well-enforced. Monitoring is by a local syndicate and individuals in the fishery who are part of the syndicate are compensated for monitoring efforts.

Resilience attributes and linkages

It is the combination of strong ecological resilience assets, in particular high biodiversity and a healthy ecosystem, with strong social-ecological resilience attributes, including *social cohesion and capital*, a strong sense of *place attachment* and stewardship for natural resources, a *resilience mindset* and high *learning capacity*, that has conferred resilience to the JFI demersal fisheries to climate change and other stressors. Additionally, relatively high levels of *agency* and *leadership and initiative* have contributed to effective governance. While there is limited *infrastructure* on the island and not a lot of *technology transfer*, governance tends to be *participatory*, *equitable and inclusive*, and enables strong local leadership and initiative of locals.

The location of the JFI fisheries inside a protected area confers a good deal of ecological resilience. In particular, in Chile, fisheries recognized by the government are required to have a fishery management plan (FMP). Fisheries that are located within an MPA and have conservation objectives within the government endorsed FMP will also develop a MPA management plan (Gaymer et al., 2021). Traditionally, lobster was the only commercial fishery, and the multispecies demersal fishery was considered subsistence (Porobic et al. 2019; Karr et al. 2021). Since 2016, the demersal fishery was recharacterized as commercial and the local community and the national government are in the process of designing a 'climate resilient' FMP for this fishery (Karr et al., 2021), that will include ecosystem-based management principles, a comprehensive plan for data collection and monitoring and *adaptive* harvest control rules that should be more *responsive* to climate and other effects on abundance levels (Kritzer et al. 2019). The demersal fishery is targeted by small-scale artisanal fishers and fishing pressure has remained low. There were two stocks, orange roughy (*Hoplostethus atlanticus*) and alfonsino (*Berix splendens*), targeted by the mainland-based industrial fishery, which operates on seamounts. However, both of these fisheries are considered over-exploited and are currently closed. Among the local JF fishers, there's good compliance with the spatial protections in place and they are committed to the rules and self-enforcement.

With the commercial designation of the multispecies finfish fishery, the JF community is in the process of building additional infrastructure to add value to the fishery. In particular, they are building a processing plant to be able to fish and process new species with a goal of getting higher prices by exporting to the mainland. The JF islanders have traditionally exported lobster as it was the most valuable stock they fished. However, there was a realization that this focus on a single species was limiting their resilience, especially to shocks such as El Niño Southern Oscillation (ENSO), tsunamis, and the global pandemic. Diversification of the demersal fishery and development of the supply chain for these stocks is therefore seen as an economic safety net, helping to confer socio-economic resilience.

A more recent stressor has been observed with a tsunami that hit in 2010, which is believed to be contributing to an ecosystem shift exemplified by an outbreak of urchins. The JF fishers would like to reap some benefit from the urchin outbreak and have been contemplating the development of a new fishery. However, there is a catch: while it’s ideal to harvest the urchins at a younger age to prevent overgrazing on the reefs, the gonads are then not large enough to be valuable on the export market. There are also logistical challenges to exporting the gonads to the mainland.

Given the limited socio-economic flexibility in terms of *income diversity*, combined with a strong sense of place attachment, there is a clear understanding of the need for strong, forward-looking fisheries management and conservation to preserve stocks and assets long-term under climate change and other stressors. For this reason, the JF islanders place high value on an effective administration plan for the MPA that is congruent with the FMP, and the need for management of all resources on the island to be governed at a systems level. The locals want more *responsive* governance at the national and regional scales and are actively seeking out ways to make this happen. They understand that there is a lot to do to ensure that the science and monitoring of their fisheries are in place to allow for more *responsive* management, but they see this as a long-term investment in their well-being. *Participation* and *equitability* are prized within the governance system. However, there are limited opportunities for women, who are active in the fishery, so this is an area where *inclusion* could be improved. Overall, the tight-knit societal connections and strong sense of resource stewardship has supported the development of leaders in the community who have helped to catalyze the uptake of a strong management and conservation ethic.

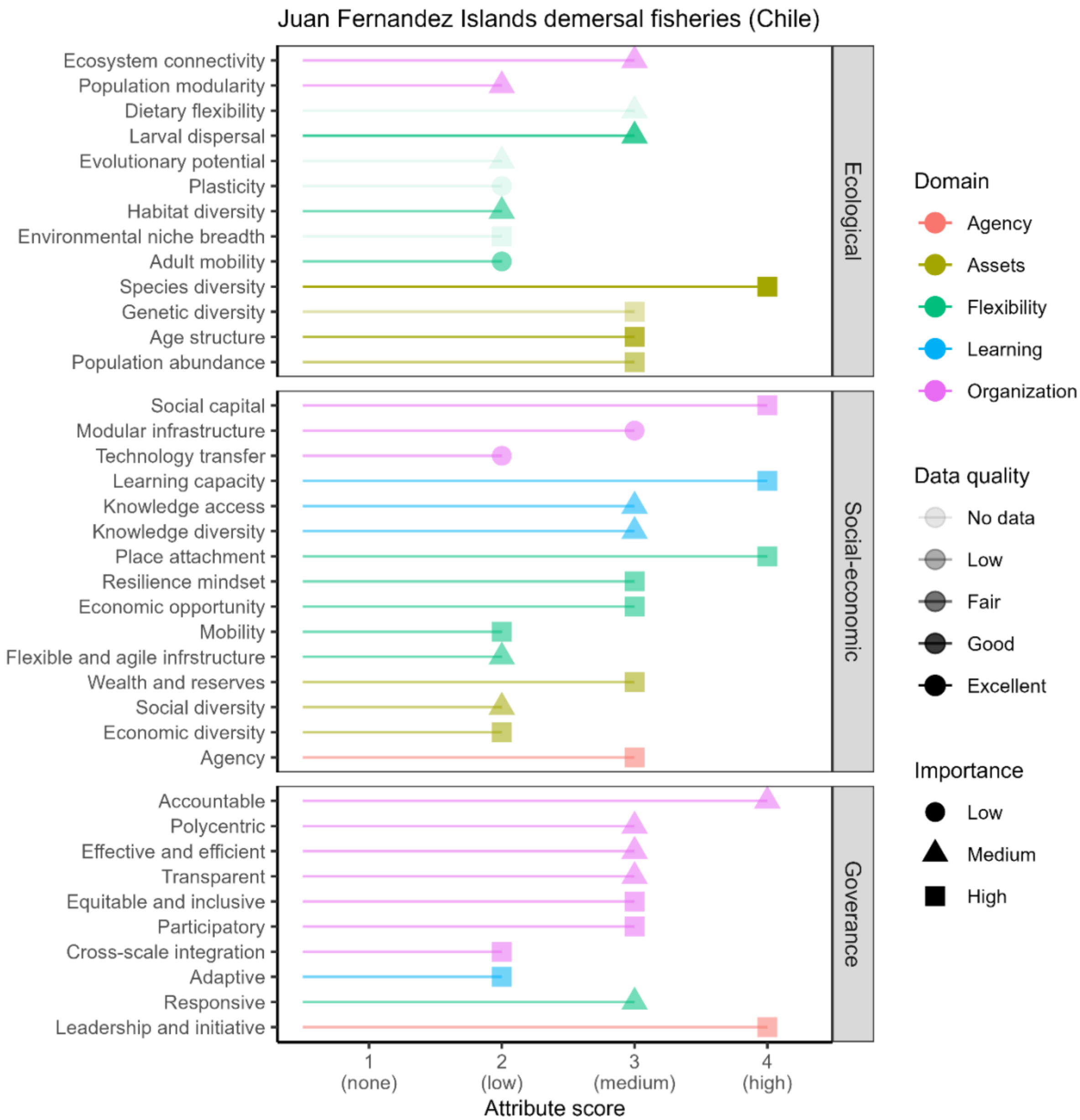
Historically, the strong social network and cohesion within the local community in combination with the strong sense of place and appreciation for the cultural and ecological value of the marine resources in the JF islands has likely contributed to the drive for education and knowledge among the islanders. Many of the locals leave the island to receive higher education, including graduate degrees. Local and traditional knowledge of the fisheries and associated resources is also highly prized. Additionally, the JF fishers have welcomed knowledge and learning from researchers and scientists from universities and NGOs on the mainland, especially as they develop aspects of their climate resilient FMP.

Conclusion

Overall, the JFI fisheries are a unique example of resilience in practice. The location of these biodiverse fisheries inside a marine reserve in combination with the locals' strong sense of stewardship toward their resources has helped to confer strong protection to the marine resources and maintain robust stock sizes over time. Additionally, the incredibly strong social bonds, resilience mindset and desire for knowledge are all critical factors contributing to the improvement of the resilience of the JF islanders and their resources. While many of the adaptive management approaches are still in the design phase, the dedication and passion of the locals for their home and the important natural resources it offers give hope that when implemented the resilience of fisheries to climate change and other acute stressors will be bolstered.

Acknowledgments

We are grateful for detailed knowledge of the Juan Fernandez Island fisheries, which was provided by interviews with three experts: Erica Cunningham, Kendra Karr and Layla Osman who have worked closely with local fishers and fisheries experts groups representing the Juan Fernandez Archipelago since 2017. These local experts groups include: the Juan Fernández Archipelago Fishermen Association, the Independent Fishermen's Union of Alejandro Selkirk Island, the University of Conception, the Undersecretary of Fisheries and Aquaculture (Subpesca; La Subsecretaria de Pesca y Acuicultura), and the National Fisheries and Aquaculture Service (Sernapesca; Servicio Nacional de Pesca y Acuicultura).



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United States Bering Sea groundfish fisheries

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System overview

Groundfish fisheries in the United States portion of the eastern Bering Sea are federally managed by the North Pacific Fishery Management Council (NPFMC), one of eight regional councils created by the Magnuson-Stevens Fishery Conservation and Management Act (Witherell et al., 2000). The eastern Bering Sea groundfish fisheries are prosecuted by three different fleets that employ bottom and pelagic trawl gear with median vessel lengths between 38 m and 100 m. These fisheries are managed by the Bering Sea Aleutian Islands (BSAI) Groundfish Fishery Management Plan (BSAI FMP). This FMP is guided by the ten National Standards for sustainable and responsible fisheries management as set forth in the Magnuson-Stevens Fishery Management and Conservation Act (MSA) of 1976 and subsequent reauthorizations. Harvest specifications are based on best scientific information available (BSIA). Harvest specifications are reviewed annually based on scientific reviews conducted by the Bering Sea and Aleutian Islands Groundfish Plan Team (BSAI GPT) and the Scientific and Statistical Committee (SSC) of the NPFMC.

Portions of the Bering Sea groundfish fisheries are managed through two catch share programs outlined in the BSAI FMP and through U.S. Congressional action (Fissel et al. 2019). The American Fisheries Act (AFA) was passed by Congress in 1998 and provided an opportunity to form fishing cooperatives for walleye pollock. The AFA Pollock fleet comprises two sectors, catcher vessels (CV) with a median length of 38m that deliver to shoreside processors as well as at-sea motherships and catcher-processors (CPs) with a median length of 100 m, also targeting walleye pollock. The pelagic trawl fishery primarily targets walleye pollock, and is the largest groundfish fishery in the EBS and largest by volume in the U.S. The other main catch share program in the EBS is the non-AFA groundfish catcher-processor bottom trawl catch share program, which was authorized through the 80th amendment to the BSAI FMP and is also known as Amendment 80 or A80. The A80 fleet has a median vessel length of 57 m and primarily targets flatfish, Pacific cod, and Atka mackerel (Atka mackerel fisheries operate predominantly in the Aleutian Islands). The primary flatfish species of interest are yellowfin sole, arrowtooth flounder, flathead sole, northern rock sole, Greenland turbot, Alaska plaice, and other flatfish. The third fleet fishing for groundfish in the EBS is the BSAI CV bottom trawl fleet which has a median length of 44 m and primarily targets flatfish and Pacific cod (Fissel et al., 2022). These fleets also to a lesser degree target rockfish species in the eastern Bering Sea including: Pacific Ocean perch, northern rockfish, blackspotted-rougheye rockfish, other rockfish and Atka mackerel. The AFA and A80 Programs both operate with cooperative structures and the individual vessels have “sideboard” restrictions that limit their ability to expand fishing beyond historical norms outside of the programs, but both fleets rely substantially on non-catch share species program revenues (both in the BSAI as well as the Gulf of Alaska (GOA)) for their operations. Some species such as Pacific cod are targeted using multiple gears and this case study considers non-trawl fisheries only within the context of the portfolio of possible adaptation options available to groundfish fishers.

In addition to the protection measures put in place by National Standard 8 to ensure the sustained participation of place-based fishing communities, the NPFMC also developed the community development quota (CDQ) program, implemented in 1992, to provide opportunities for Bering Sea and Aleutian Islands coastal communities to benefit from the harvest of, as well as begin participation in the processing of, BSAI groundfish fisheries. Approximately 10% of the annual quotas for BSAI groundfish and crab are allocated to the 6 regional economic development entities authorized by the CDQ Program.

Following the provisions of the MSA, the Total Allowable Catch (TAC) limits are less than or equal to the Acceptable Biological Catch (ABC) which is set lower than the Overfishing Limit (OFL). A system level overall Optimal Yield provision caps total EBS groundfish catch at 2 million tons. This OY cap is a major constraint to expansion of groundfish fisheries in the EBS as aggregate single species ABCs have averaged 2.9 million tons from 2000-2022 (NMFS, 2022). A Tier system of catch constraints provides rules for setting the OFL and the maximum permissible ABC given the information available to estimate these reference points. Most of the stocks are managed using biomass and fishing mortality targets and limits and generally decrease fishing mortality when stocks fall below prescribed biomass targets, and prohibit directed fishing when stocks fall below biomass limits. Retention of target species is prohibited when catch exceeds the ABC and directed fisheries are closed in-season when the catch exceeds the OFL. Compliance to these various catch constraints is achieved through in-season monitoring of the catch through the deployment of at-sea observers, electronic monitoring, shoreside observers, log-books and fish tickets.

Numerous gear and time-area provisions have been established to reduce bycatch, reduce gear conflicts and protect essential fish habitat (Hollowed et al., 2011). Groundfish fisheries are constrained by prohibited species catch quotas which limit the amount of Pacific halibut, salmon, crab and herring that can be caught during directed groundfish fishing. Pacific halibut bycatch is the primary constraint on flatfish fisheries. Salmon bycatch is the primary constraint on pollock fisheries. Directed fisheries for forage fish (capelin, krill, smelt, eulachon) or squid are prohibited and bycatch of forage fish and squid in directed groundfish fisheries is monitored. In the early 2000s spatial closures, seasonal allocations of the TAC and minimum stock size thresholds for opening directed fisheries of pollock, cod and Atka mackerel were put in place to protect endangered Steller sea lions.

Collectively, time, area, and catch constraints have proven successful in sustaining viable groundfish populations and fisheries. The non-pelagic trawl groundfish fishery primarily targets flatfish and Pacific cod (also targeted by pot and longline) across time and space spreading the footprint of trawl impacts (Smeltz et al., 2019). The major flatfish stocks exhibit evidence of niche partitioning and can be targeted effectively during some seasons. However, Pacific halibut (a prohibited species) exhibits a broad spatial distribution making time or area partitions an ineffective management tool for managing halibut bycatch (Baker & Hollowed, 2014). Therefore, managers rely on prohibited species catch limits as the main constraint to the catch of halibut in groundfish trawl fisheries in the EBS. To date, spatial closures for reducing crab bycatch (the Bristol Bay Red King Crab Savings Area) have been effective when coupled with prohibited species caps in limiting crab bycatch.

As in most high latitude marine ecosystems, the eastern Bering Sea stocks are influenced by interannual and multi-year shifts in ocean conditions. In recent years, extreme events (marine heat waves) have resulted in marked shifts in reproductive success, spatial distribution and growth of several key groundfish. These serve as a harbinger for future changes in these fisheries. To address these issues, the NPFMC considers the ecosystem status report (ESR) prior to setting harvest specifications and documents assessment related considerations, population dynamics, ecosystem considerations and fishery performance. The NPFMC proactively considers how it can improve ecosystem approaches to fishery management within its Bering Sea Fishery Ecosystem Plan (FEP) which includes task teams focused on climate change and improving ways to include Local knowledge, Traditional knowledge and the uses of these species for subsistence and food security purposes in decision making.

Resilience attributes and linkages

The current management system has sustained groundfish fisheries for over 40 years (MSA40Booklet). The degree of resilience in the groundfish trawl fishery varies across sectors. Past vulnerability analyses concluded that the vulnerability to climate risk in these domains was low, in both the ecological and socio-economic dimensions (Himes-Cornell & Kasperski, 2015; Spencer et al., 2019). However, recent heat waves have resulted in abrupt shifts in distribution and abundance of gadids and snow crab suggesting that it is unclear whether the management system is capable of sustaining fisheries under some climate change and ocean acidification scenarios (Holsman et al., 2020; Punt et al., 2016; Stevenson & Lauth, 2019).

Fishers, processors and distributors are highly organized and sophisticated. Many fishers have access to further financial knowledge and innovation capital. Processors have aligned their products to meet market demands. Provisions in the FMP prohibit discards and unused product is processed as fish meal and oil. A diverse product line has evolved to effectively process the fish to multiple markets. Alaskan groundfish is distributed to both domestic and international markets. Industry participants understand the fisheries management system and the importance of adapting and learning. They regularly attend North Pacific Fishery Management Council meetings and provide oral or written testimony on multiple decisions. However, while catch share programs retard entry into new fisheries (Szymkowiak & Rhodes-Reese, 2020), the harvest privileges for the major groundfish and crab fisheries in the EBS are already allocated to different fishers through limited access privilege programs (https://www.npfmc.org/allocation-and-program-review/).

The participatory management system allows managers to consider the opinions of multiple stakeholders and be advised by several independent bodies (SSC and Advisory Panel) as well as many standing and ad-hoc committees. This system adheres to the scientific advice of the SSC. The Advisory Panel (AP) allows for input on TAC setting, FMP amendments, and regulatory changes.

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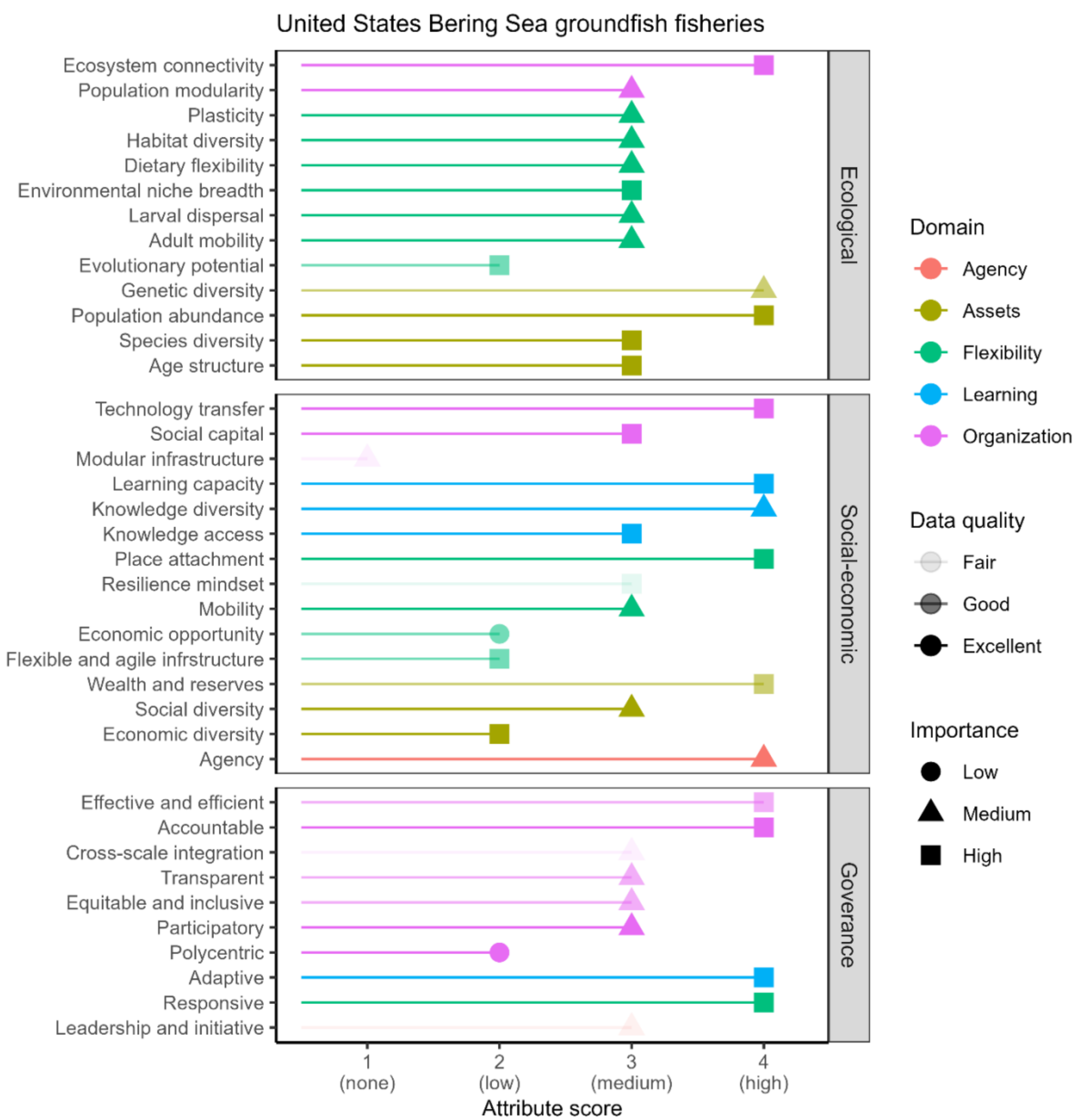

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Maine American lobster fishery (United States)

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Abstract

The American lobster (*Homarus americanus*) fishery in the state of Maine (US) was examined to identify ecological, socio-economic, and governance attributes that influence its resilience to ocean warming and marine heatwaves. The combination of warming trends and heatwave events have both benefitted and challenged the fishery, and the fishery has adapted to challenges in ways that have enhanced resilience, particularly to recent heatwaves. Conservation measures have enhanced *population abundance* under recent warming conditions, creating an ecological buffer that supports fishery resilience. The *polycentric*, *participatory* nature of the governance system aligns industry and agency approaches to managing the fishery, enabling adjustments to changing fishery conditions. Further, certain socio-economic attributes, such as *wealth and reserves* and *place attachment*, have supported fishery resilience, but others such as limited *mobility*, *economic opportunity*, and *economic diversity* may constrain resilience to future climate-related fishery changes.

Fishery background

American lobster (*Homarus americanus*) has supported the highest-value single-species fishery in the United States since 2014. Nearly 80% of U.S. landings occur in the state of Maine, where lobster alone represents over 75% of the value of all marine fishery landings (NMFS 2022). More than 6000 owner-operators are licensed to participate in the fishery (Maine

Department of Marine Resources 2022), which is largely prosecuted by small vessels that operate in coastal waters, but the number of larger vessels operating in offshore waters has increased in recent years. The fishery is of high economic, social, and cultural value in the state, particularly in coastal communities in midcoast and downeast Maine, where reliance on this fishery has grown in conjunction with increases in lobster abundance and declines of other species (Steneck et al. 2011).

The American lobster fishery is cooperatively managed by the Northeast U.S. states and the federal fishery management authority, NOAA Fisheries, through the Atlantic States Marine Fisheries Commission. Individual states manage the fishery out to three nautical miles from shore, and NOAA Fisheries manages it 3-200 nautical miles from shore. In Maine, the fishery is co-managed with lobster harvesters through a zone-based arrangement; state waters are divided into seven lobster management zones, each of which is managed by an elected council of lobster license holders that fish in that zone. The zone councils propose rules—including limited entry and trap limits—for managing the fishery in their zone that may then be adopted as regulations by the Maine Commissioner of Marine Resources (Acheson et al. 2000). This arrangement aligns with the place-specific nature of the fishery, while also creating a multi-level governance structure that spans local, state, and federal authorities.

Climate impacts and responses

The Maine lobster fishery operates in a rapidly changing ecosystem. Sea surface temperature in the Gulf of Maine has been warming three times faster than the global average for the past 40 years, and marine heatwaves have become a frequent occurrence in the past decade (GMRI 2022). This warming—in conjunction with benefits from long-standing industry conservation measures—supported growth of the lobster population and fishery in Maine over the past two decades (Le Bris et al. 2018). The resilience of the fishery system was tested by a marine heatwave in 2012, during which the early onset and high volume of landings created substantial supply chain disruptions that led to a price collapse (Mills et al. 2013, Pershing et al. 2018). Industry responses following the 2012 heatwave included (1) adapting handling practices on vessels to reduce temperature-related physiological stress experienced by lobsters, (2) establishing flexible transportation contracts to move lobster from the dock to processing facilities, (3) increasing processing capacity, and (4) pursuing marketing measures to expand outlets for the product (Pershing et al. 2018). In addition, scientific forecasting capacity was developed to predict the start of the high-landings period based on seasonal water temperatures (Mills et al. 2017). These responses have buffered impacts to the fishery during subsequent marine heatwaves (Pershing et al. 2018). However, multi-decadal population projections indicate a downturn in the lobster population with ongoing warming (Le Bris et al. 2018), as well as shifts in the spatial distribution of lobster, with the most substantial declines projected for coastal waters of southern Maine and moderate declines in the midcoast to downeast regions (Allyn et al. 2020, Tanaka et al. 2020).

Resilience attributes and linkages

Resilience of the Maine lobster fishery to ocean warming and marine heatwaves has been influenced by attributes of ecological, socio-economic, and governance dimensions of the fishery (Mason et al. 2022). Long-standing conservation measures initiated by the industry and incorporated into management measures have helped build a healthy lobster population in the Gulf of Maine (Acheson and Gardner 2011). Since 1917, reproductive female lobsters have been protected by 'v-notching', which entails harvesters cutting a v-shaped mark into the tails of egg-bearing female lobsters. Landing v-notched lobsters is prohibited, and the notch provides an indication to subsequent harvesters that those lobsters should be returned to the ocean. In addition, since the 1930s, the Maine lobster fishery has imposed harvestable size limits to ensure lobsters reach maturity and to protect the most reproductively-valuable large lobsters. These approaches were spurred by a *resilience mindset* in the industry, which led to management measures being formalized through a *polycentric, participatory* governance system that is *responsive* to industry needs and ideas. These measures have subsequently helped attain high *population abundance* in the Gulf of Maine lobster stock and provided a boost to the stock as water temperatures in the region warmed during the 2000s (Le Bris et al. 2018), yet v-notching compliance appears to be waning as the population has grown (Mazur and Johnson 2020). The abundant population—coupled with generally strong market conditions—have conferred economic benefits and supported growth of *wealth and reserves* in this fishery.

Additional socio-economic attributes have enabled industry actions that supported resilience during warming and marine heatwaves. During the 2012 marine heatwave, harvesters were able to catch and land large volumes of lobster, but the supply chain was not prepared to handle the amount of product so early in the season. Since then, efforts to move towards more *flexible and agile infrastructure* and *cross-scale integration* of actions by harvesters, dealers, processors and marketers have reduced the cascade of impacts during subsequent heatwaves (Pershing et al. 2018). In addition, this fishery generally benefits from high *knowledge diversity*, *knowledge access*, and *learning capacity* that arise from industry observations and long-term perspectives on ecosystem and fishery changes; scientist-industry partnerships; and a suite of monitoring and research efforts through governmental, academic, and non-profit institutions.

The success of this fishery—including the healthy stock and lucrative economic returns—have conferred benefits to its participants, but it has also led to even greater concentration of participation and high levels of social and economic reliance on the fishery in Maine's coastal communities. While this high reliance and strong sense of *place attachment* has driven a conservation ethos in this fishery, they may constrain resilience in the face of continued climate change. If the population declines or its distribution shifts, *place attachment* to specific lobster zones, as well as limited *mobility* of small vessels, will restrict options for the fishery to move with the stock as it shifts. Moreover, many of Maine's fishing communities currently have limited *economic opportunities* and *economic diversity* outside of the lobster fishery, as well as strong cultural identities associated with the fishery—situations that make it challenging to diversify livelihoods within and beyond fishing as has often been relied upon for resilience in many resource-based economies. Finally, climate-related changes in other fisheries, protected species, and ocean uses may create new challenges for the Maine lobster fishery, and governance frameworks are currently limited in their ability to support *cross-scale integration* of decision-making across sectors.

Conclusions

Ecological, socio-economic, and governance attributes of the Maine lobster fishery have all contributed to resilience of this fishery in the face of ocean warming and marine heatwaves, with stock health, industry actions, and governance arrangements being important to the success of the fishery through recent climate-related changes. A resilience mindset in the industry, coupled with participatory governance arrangements, supported growth of the lobster population. The healthy stock provided a basis for growth of the fishery, which has generated economic and social benefits across many coastal communities in Maine. Recent climate-related changes have been buffered by responsive industry actions across multiple levels of the supply chain. While these attributes have supported climate resilience in the fishery to date, projected changes in stock abundance and distribution as well as potential climate-related changes external to this fishery will require ongoing adaptation to buffer impacts and sustain benefits for fishery participants and their communities. Strong place attachment, limited mobility, few economic opportunities, and the lack of integrated governance that spans ocean sectors may constrain adaptation and resilience of this fishery into the future.

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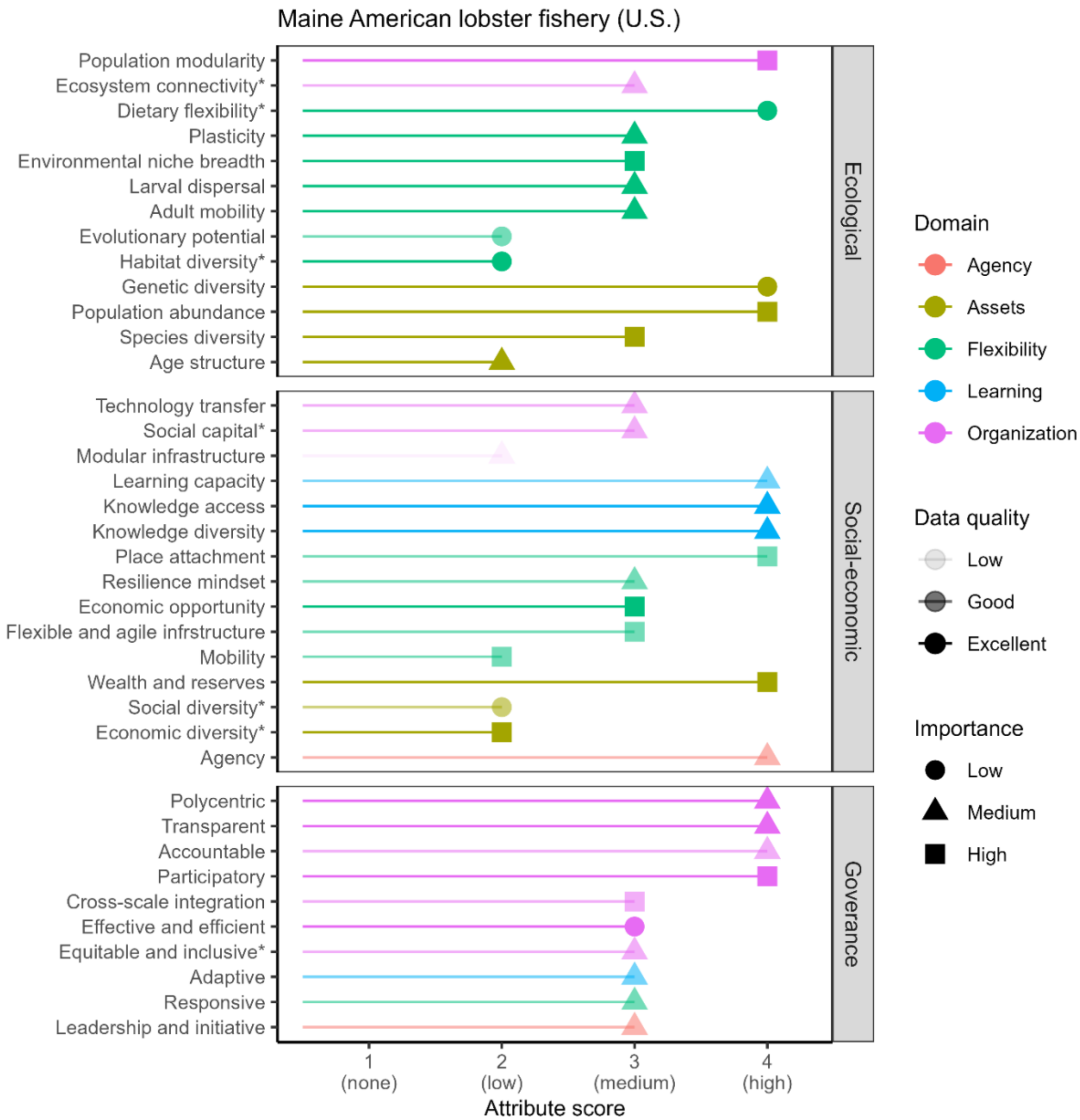

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California Dungeness crab fishery (United States)

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Abstract

Dungeness crab (*Metacarcinus magister*) support California's most lucrative commercial fishery and play a central role in the portfolio of species targeted by fishers. Recently, the fishery has experienced extensive closures and unpredictability resulting from heatwave-induced harmful algal blooms, which produce biotoxins that accumulate in crabs and present a public health risk if consumed, and increased entanglements of humpback whales and other protected species in Dungeness crab fishing gear, which presents a conservation risk. The massive economic importance of the fishery has catalyzed extensive government and stakeholder actions to increase the resilience of the fishery to these climate-induced stressors. The resilience of the fishery has depended on participatory management for guiding management of entanglement risks, expansions in the resolution of biotoxin management zones and the options for managing biotoxin risk in the fishery, and use of the federal fisheries disaster program to provide relief to impacted fishers, processors, and dealers. The fishery is insulated by the high productivity and economic importance of the resource. The resilience of the fishery to climate change could be further enhanced by reforming the federal fisheries disaster program to be more accurate, timely, and equitable, increasing the spatial-temporal resolution of biotoxin monitoring to enable more surgical management, and using quantitative tools to guide decisions around entanglement risk management.

Executive summary

Dungeness crab (*Metacarcinus magister*) range from Point Conception, California through the Alaskan Aleutian Islands (CDFW, 2011) and support one of the most economically important fisheries on the U.S. West Coast (NMFS, 2020). In California, Oregon, and

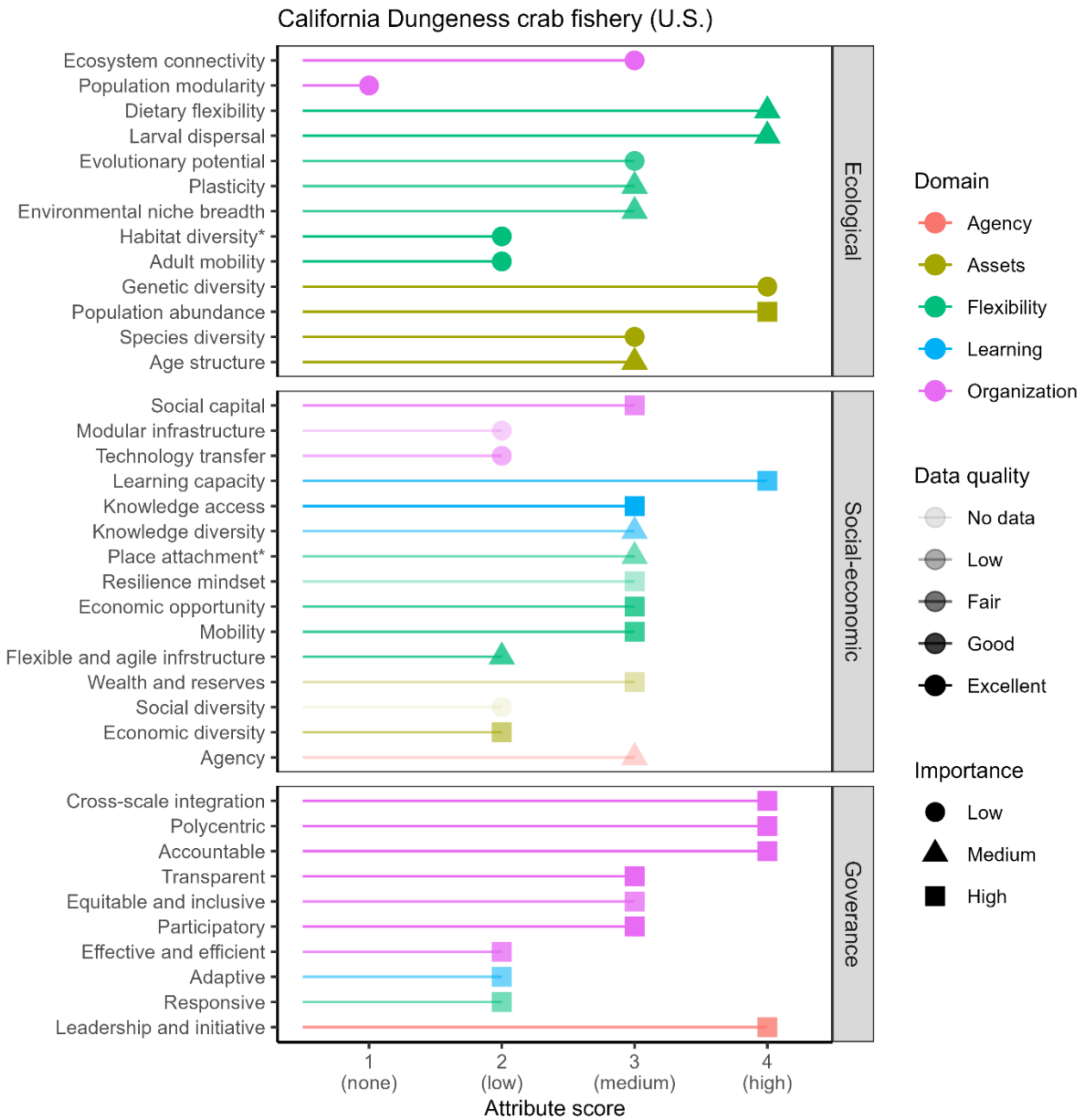
Washington, the commercial Dungeness crab fishery has generated ~$200 million in gross revenues every year since 2010, and annually supports over 1,000 participants (CDFW, 2020). As a result, the Dungeness crab fishery is central in fishing networks from Central California to Washington, which makes both fishers and adjacent fisheries sensitive to perturbations to this critical fishery (Fisher et al., 2021; Fuller et al., 2017). Landings (and likely the population size) of Dungeness crab have fluctuated through time as a result of environmental factors (Armstrong et al., 2011; Rasmuson, 2013). However, until recently, simple "3S" management -- which only allows harvest of male crabs (sex) larger than 6.25 inches (size) from midwinter through summer (season) -- has been sufficient to maintain a sustainable and profitable fishery (Richerson et al., 2020).

A recent marine heatwave nicknamed "the blob" (Bond et al., 2015) dramatically disrupted this traditionally sustainable, profitable, and relatively easily managed fishery through two indirect pathways. First, during the 2015-16 season, the marine heatwave caused a harmful algal bloom (HAB) of unprecedented size and duration (McCabe et al., 2016; McKibben et al., 2017), leading to extended coastwide closures of Dungeness crab and other critical fisheries (especially in California) as a result of dangerous levels of biotoxin contamination (Free et al., 2022). Then, in California, the opening of the delayed season in mid-April resulted in the inadvertently intensified overlap in fishing effort and humpback whale abundance, exacerbated by the heatwave-driven compression of humpback whale foraging grounds (Santora et al., 2020). This perfect storm of heatwave-sparked shifts resulted in a dramatic spike in the number of humpback whale entanglements, the majority of which were attributed to Dungeness crab fishing gear (Saez et al., 2020). This precipitated a lawsuit by the Center for Biological Diversity alleging that California's management of the Dungeness crab fishery threatened endangered species and was non-compliant with the Endangered Species Act (CA DOJ, 2017).

The economic impacts of HAB and whale entanglement closures have been significant. In California, revenues were 58% lower during the 2015-16 season than during the previous five years (PSMFC, 2021, p. 20). This led the Governor of California to request federal fisheries disaster assistance stating that the delay had cost an estimated $48.3 million in direct economic impacts (Brown, 2016). However, this pronouncement was made before the fishery even opened. A re-analysis that more accurately considered population size and participation in non-crab fisheries estimated that losses were closer to $26.1 million, with losses coming from the Dungeness crab fishery and other non-crab fisheries in nearly equal proportions (Holland & Leonard, 2020). Although this estimate is closer to the $25 million of disaster aid ultimately appropriated by Congress (Thom, 2018), the aid was not distributed to affected harvesters, processors, and dealers until more than three years after the disaster (C. Bonham, personal communication, July 19, 2018). Furthermore, smaller vessels -- potentially limited by their mobility -- were disproportionately impacted by the delay (Jardine et al., 2020) yet received less disaster relief than larger vessels (C. Bonham, personal communication, July 19, 2018). Furthermore, early closures of the fishery during the 2019-20 and 2020-21 fishing seasons to reduce whale entanglement risk cost the fishery an estimated $9.7 million and $14.4 million in revenues, respectively (Seary et al., 2022).

The resilience of the commercial Dungeness crab fishing fleet to these stressors has depended on a combination of fisher behavior, federal disaster relief, improvements to biotoxin monitoring and management, and the development of a particory adaptive management program for mitigating whale entanglement risk. During the 2015-16 season delays, the ability of fishers to move and target different species reduced the economic impact on the livelihoods of some fishers (Fisher et al., 2021). Furthermore, Congress declared the 2015-16 season a federal fisheries disaster and distributed $25 million in disaster aid to affected harvesters, processors, and dealers (Thom, 2018), easing revenue losses during the heatwave. The state also improved its biotoxin management program by establishing clear biotoxin management zones that are closed and opened based on the monitoring conducted within them (Free et al., 2022). This action increased transparency, consistency, and predictability for fishers and enabled more efficient management (i.e., management that eliminates public health risk through the lowest impacts to fishing communities). Finally, and perhaps most importantly, a multi-stakeholder working group was convened to inform an extensive and ongoing overhaul of California's marine life entanglement risk management plan (CDCFGWG, 2018). This working group includes representatives from the fishing industry and ensure that fishing industry interests, knowledge, and experience are represented in management decisions. Although the overwhelming economic importance of the fishery has made the fishery a high priority and enabled these resilience actions, it may inhibit long-term resilience if fishers are unable to escape the "gilded trap" of being so dependent on a lucrative but potentially volatile fishery.

Although these attributes have generally promoted the resilience of the California Dungeness crab fishery to extreme climate events, there are still several challenges to overcome. First, vessels that specialize in Dungeness crab were more likely to stop fishing during the 2015-16 season and smaller boats were less able to relocate or to new fishing grounds (Fisher et al., 2021). This will require management flexibility to allow fishers to diversify their portfolios, especially during challenging times. Second, federal fisheries disaster relief was not distributed to affected harvesters, processors, and dealers until more than three years after the disaster and smaller vessels received smaller payouts despite being disproportionately impacted (Bellquist et al., 2021). Ensuring more accurate, timely, and equitable disaster assistance will be necessary for this program to become an efficient instrument for enhancing climate resilience. Third, California lags behind the other West Coast states in the spatial-temporal frequency of its biotoxin monitoring, which could impede the efficiency of biotoxin management in the fishery (Free et al., 2022). Finally, recent research suggests that the management options considered by the whale entanglement working group would reduce entanglement risk but at considerable cost to the fishery (Free et al., in prep; Samhouri et al., 2021). Investment in new quantitative approaches for evaluating the performance of alternative strategies for preventing whale entanglements is necessary to guide informed management decisions.



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Galicia stalked barnacle fishery (Spain)

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Abstract

The stalked barnacle is a marine crustacean that inhabits exposed rocky shores in the northeast Atlantic. Galicia in NW Spain sustains the largest fishery for the resource through a co-management system based on the use of Territorial User Rights for Fishing (TURFs). Under climate change, warming and upwelling relaxation are expected to bring positive (productivity increases by ways of higher reproductive output and recruitment) and negative (reductions in the quality of the resource and in larval dispersal) effects to the system, which might synergistically interact with other stressors (e.g., overfishing). Resilience in the fishery is provided by the use of *adaptive* spatial management with nested scales at a regional, local (TURFs, 10-60 km) and patch/rock (2-10 km) level. This detailed spatial scale is only possible thanks to the close collaboration between fishers associations and managers. Ecologically, the high *plasticity*, *genetic diversity* and *larval connectivity* of the species contribute to resilience. The *learning capacity* and the consideration of ongoing change in management are key aspects of the fishery in preparation for climate change. However, the adaptive capacity of the system could be improved by a higher level of cooperation and knowledge exchange between TURFs.

Executive summary

The stalked barnacle (*Pollicipes pollicipes*) is a warm-temperate species that supports several small-scale fisheries that are commercially oriented across the Atlantic Rim from Brittany to southern Portugal (Aguión et al. 2022), as well as in some Northwest African countries like Morocco. However, a strong market demand for the resource only exists in Spain and Portugal where stalked barnacles are considered a delicacy and reach first sale market prices of EUR 200 per kg in the high season. In Galicia, 325 tons of stalked barnacles were harvested by 1,308 fishers yielding a profit of EUR 7.6 million between 2013 and 2016 (Aguión et al. 2022).

Future climate scenarios in Galicia predict decreases in coastal upwelling and increases in seawater temperature (Sousa et al. 2020) that have been already noted in the region (Gómez-Gesteira et al. 2011). Although the impacts of these changing trends are still not well studied for the species, productivity increases are expected in the fishery considering the positive relationship described between landings and upwelling relaxation (Molares et al. 2009). This prediction is supported by ecological studies that associate warming and/or decreases in upwelling with a longer and more intense recruitment season (Fernandes et al. 2021), a faster embryo development time and an increase in the number of broods (Macho 2006; Román et al. 2022). But despite this potential positive effect, climatic stressors might also be behind the increasing number of elongated barnacles with low commercial value (Molares et al. 2009) and potential reductions in resource quality (Bode et al. 2009) due to changes in the texture of the meat. A lower larval dispersal capacity is also expected due to a reduced duration of the larval pelagic time caused by seawater warming (Nolasco et al. 2022), potentially reducing the connectivity between populations.

Apart from climate-related stressors, the fishery has navigated through shocks like overfishing (1990s), oil spill pollution (2002) and a conflict with mussel seed harvesters (since the 2010s) maintaining a fairly stable trend in landings and revenues (Consellería do Mar 2020) on account of the stock ecological resilience and the governance system in place. On one hand, the important levels of *larval dispersal* (Nolasco et al. 2022), *genetic diversity* (Parrondo et al. 2022) and *plasticity* of the species support the capacity of the populations to adapt and recover from stressors. On the other hand, the implementation of TURFs where only licensed members are allowed access to the resource creates a sense of ownership and stewardship that fosters *place attachment* in the fishery. The fact that TURFs have been designed considering historical social and political aspects facilitates the creation of *social capital* and *participation*. This results in an *adaptive* and *responsive* system where fishers usually *lead* daily decisions such as reducing the daily quota or stop fishing if resource status or maker price are not good enough (Aguión et al. 2022). The technical assistant (biologist) present in most TURFs is a key figure in the fishery, providing management advice to fishers and facilitating communication between fishers, managers, scientists and other stakeholders (*cross-scale integration*) (Macho et al. 2013).

Considering the heterogeneous vulnerability of TURFs to climate change due to their differences in size, resource dependency, management strategies, etc. (Ruiz-Díaz et al. 2020), the development of a regional plan to tackle climate change that identifies 1) effective management responses implemented in some TURFs that could be extended to others and 2) promotes a higher level of cooperation and information exchange between TURFs, is likely to increase the resilience of the system. A good starting point for this is the organization of workshops where fishers, managers and technical assistants exchange knowledge to enable mutual learning and provide basic principles to overcome the common challenges that the fishery is increasingly facing.

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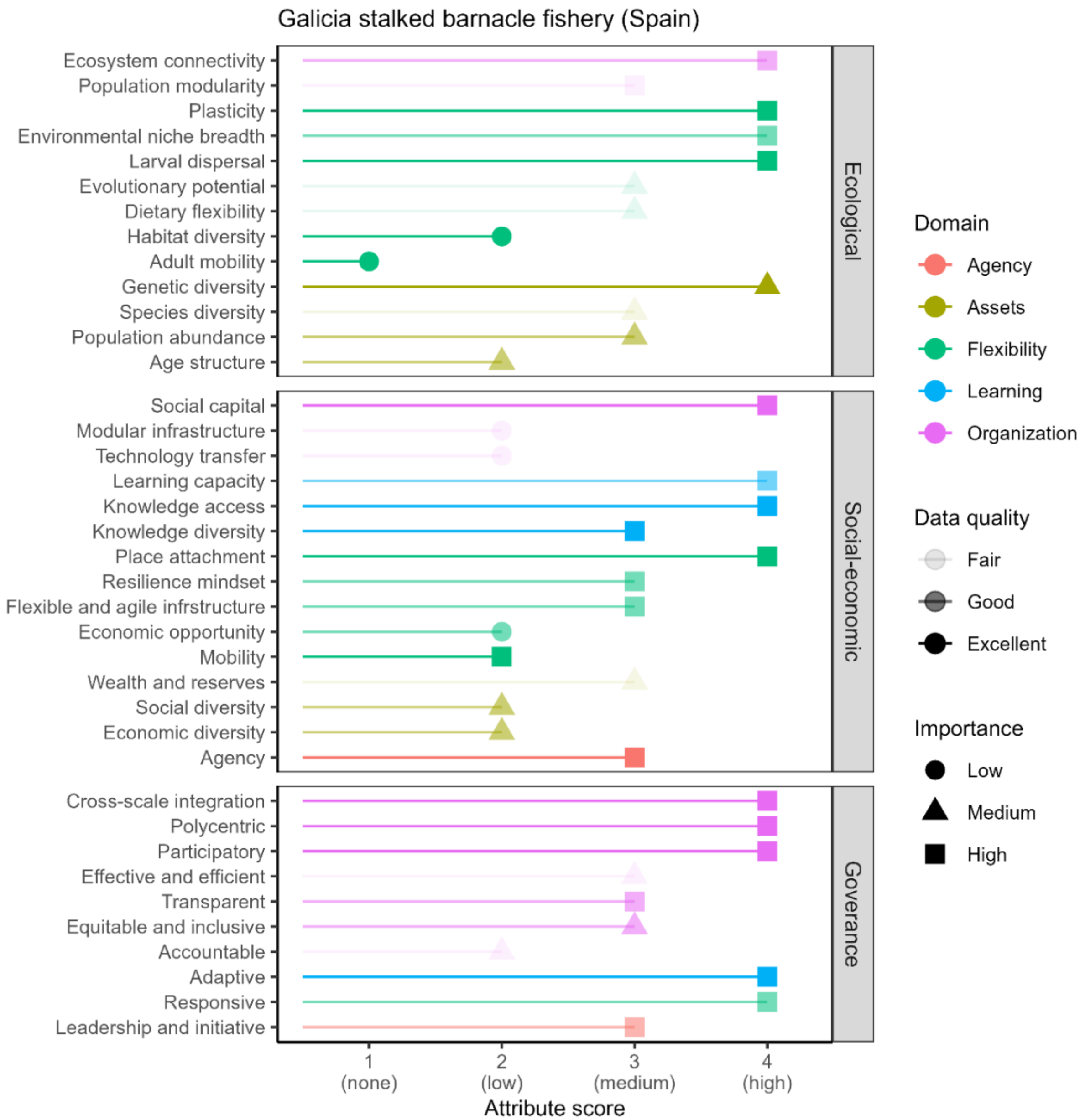

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