CSIRO PUBLISHING

PERSPECTIVE
https://doi.org/10.1071/PC22050

PACIFIC CONSERVATION BIOLOGY

Resilience of a giant clam subsistence fishery in Kiribati to climate change

Jacob G. Eurich[A,B,*], Aranteiti Tekiau[C], Katherine L. Seto[D], Erietera Aram[C], Toaea Beiateuea[C], Christopher D. Golden[E,F], Bwebwenikai Rabwere[C] and Douglas J. McCauley[B,G]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Jacob G. Eurich
Environmental Defense Fund, Santa Barbara, CA, USA
Email: jeurich@edf.org

Handling Editor:
Graham Fulton

Received: 30 July 2022
Accepted: 10 April 2023
Published: 31 May 2023

Cite this:
Eurich JG *et al.* (2023)
Pacific Conservation Biology
doi:10.1071/PC22050

ABSTRACT

Changes in sea surface temperature have historically impacted the coral reef habitats of giant clams in Kiribati. However, across many islands of Kiribati, the four species of giant clam have largely withstood these environmental changes. We adopted and applied a comprehensive resilience framework to assess attributes conferring and limiting resilience in the Kiribati giant clam data-limited fishery and used knowledge co-production and the precautionary principle approach to better understand resilience. We found that the resilience of the fishery to climate and anthropogenic impacts, as highlighted by local stake- and rightholders, will depend on the ability of fishery actors to act collectively to implement adaptive governance. We used a gradient of human pressure to identify approaches and pathways for improving and operationalising climate resilience. Climate change, coupled with human impacts, have reduced ecological resilience in the urbanised island of South Tarawa. In South Tarawa, governance and social processes are less flexible, leading to declines in the local subsistence clam fishery. Conversely, on several remote outer islands, where the social-ecological system has shown promise in combating these anthropogenic influences, the ecological resilience has improved through adaptive community-based fisheries management, and the subsistence clam fishery has persisted. Our case study demonstrates the importance of a participatory approach and local knowledge when assessing climate resilience and identifies a pathway of resilience in a data-limited small-scale fishery.

I-KIRIBATI ABSTRACT

Ni boong ma taai aika a bwakanako ao bibitakin kabuebuen taari ea bon tia n roota maiun te were nte aro are ea karika te ane ba ena mainaina. E ngae n anne ao utun te were aika a aua (4) aika a kuneaki i Kiribati, a tia n aitara ma kangangan korakoran bibitakin te enwaromenta. Rinanon aia konabwai ni waaki ma bitaki ao a tia naba ni kona ni kaaitarai aia mwakuri ni kabarekareka ao ni karawawata te bota n aomata. Bibitakin kanoan boong, n raonaki ma rikiraken te bota n aomata, ea tia ni kataia ni kauarerekea te konabai ni kaitarai kanganga iaon Tarawa Teinainano ni kabotauaki ma aban Kiribati ake tabeua are e a raroa riki. E korakora te kerikaki ni mwaitin te were iaon Tawara Teinainano ngkai e korakora anaakina ba te amwarake ao ni marau ke ni karako te baronga n aron anaakina. N aban Kiribati ake tabeua ao ea tia ni kakoauaaki ba te baaronga ma te katei n aroaro rinanon kaawan abamakoro ea tia ni kaoka rikiraken ao teimatoan te were bwa te amwarake, e ngae ngke e korakora ana urubwai bibitakin kanoan bong. N taraakin aron bibitakin kanoan boong i Kiribati ma akawan te were, ao e kuneaki ba aron te were ni kona ni kaitara kabuebuen taari ma rikiraken kakangin taari ena boboto man oioi irouia naake a kabongana ke n akawa te were. Te kamatebai aei e riki ba te katoto n aron taneiei ni kaaitarai bitakin kanoan bong n irekereke ma akawa aika a uarereke.

Keywords: adaptive capacity, coastal communities, fisheries management, global change, knowledge co-production framework, precautionary principle, small-scale fisheries, social-ecological systems.

Theoretical framework of climate resilience in fisheries

Climate change has substantially affected marine ecosystem services through changes in sea surface temperature, acidification, and deoxygenation (Hollowed *et al.* 2013; Free *et al.* 2019; Malhi *et al.* 2020). These changes have threatened diverse provisioning ecosystem services, altering ocean ecosystems and transforming fishery stocks (Pinsky *et al.* 2013; Myers *et al.* 2017). Climate-induced losses are known to disproportionately impact the regions and people most dependent on fish for protein and micronutrients – predominantly small-scale fishers in developing, small-island nations in the tropics (Golden *et al.* 2021*a*; Tigchelaar *et al.* 2021; Andrachuk *et al.* 2022). However, by building climate-resilient fisheries, people and ecosystems that are most at risk may be better sustained, even under changing ocean conditions.

Climate-adaptive fisheries science and management is an approach to offset regional impacts of climate change (Gaines *et al.* 2018; Burden and Fujita 2019). Adaptive management approaches with early warning indicators support more prompt and proactive management responses (Kritzer *et al.* 2019). However, fisheries data collection and monitoring are required to effectively model climate projections. When baseline data and active monitoring are unavailable, participatory approaches, which increase participant diversity and inclusive research practices (Halpern *et al.* 2023), can be used to identify and understand resilience in a system (Mills *et al.* 2023; Carroll *et al.* 2023) and inform precautionary measures (Deville and Harding 1997). The precautionary principle aims to assess preventative actions in data-limited systems when there is a scientifically plausible threat human health or the environment (Deville and Harding 1997). In the case of fisheries science and management, precautionary actions informed by stakeholders can minimise risks, protect fishery stocks, and increase resilience to climate change (Latifah and Imanullah 2018) while awaiting definitive data.

Resilience encompasses the ability to prepare for, resist, cope with, recover from or adapt to a given stressor (IPCC 2022). In fishery systems, resilience ensures the sustainability of marine ecosystems, fishery resources, and human benefits. Fisheries are complex social-ecological systems; therefore, operationalising resilience measures is challenging. Understanding resilience of what, to what and for whom, the bounds of the system, and the time scale of responses is important for evaluating the feasibility of management interventions (Plagányi *et al.* 2014). Recent work has identified fisheries-specific aspects of social-ecological resilience to understand the feedbacks and linkages across the ecological, socio-economic and governance dimensions of fishery systems (Ojea *et al.* 2017; Golden *et al.* 2021*b*; Mason *et al.* 2022). Mason *et al.* (2022) reviewed and defined 38 resilience attributes, *italicised* in the present study, that should be accounted for when trying to build resilience. Research has also outlined the need for further holistic empirical studies – including comparative cases – of how attributes confer resilience (Kleisner *et al.* 2022). To advance climate resilient fisheries 'from theory to practice,' success stories with standardised language that define attributes and linkages are needed to better understand resilience in fishery systems.

Here, we use the Kiribati giant clam fishery as a case study to identify resilience-enhancing measures for the ecological, socio-economic, and governance dimensions of a fishery system. We conducted this work through knowledge co-production (Mills *et al.* 2023) with local fishers, Kiribati government officials, and fishery scientists to outline the coupled natural and human elements of the data-limited fishery system. Using a Climate-Resilient Fisheries Planning Tool designed by a Science for Nature and People Partnership (SNAPP) Climate Resilient Fisheries Working Group in 2020–2022[1], we gathered information on the strength, importance, and data quality of the 38 resilience attributes identified by Mason *et al.* (2022) for the case of the Kiribati giant clam fishery. We employ the Mason *et al.* (2022) comprehensive resilience framework to highlight attributes conferring and limiting resilience and use a precautionary principle framework (Deville and Harding 1997) to justify the current management approaches used in a data-limited fishery.

Fishery background

Four species of giant clam occur in the Gilbert Islands, Kiribati (Fig. 1), all of which are heavily harvested for subsistence purposes (by body size, large to small; International Union for Conservation of Nature status is noted; IUCN 2016): *Tridacna gigas* (Vulnerable), *Hippopus hippopus* (Lower risk/Conservation dependent), *Tridacna squamosa* (Lower risk/Conservation dependent), *and Tridacna maxima* (Lower risk/Conservation dependent). The clams' primary habitat is on structured coral reefs and back reefs in both the fore-reef and lagoon reef habitats (Watson and Neo 2021). Giant clams represent a key function within the coral reef community and support the functional integrity of coral reefs (Wolfe *et al.* 2020). Their tissues are food for a wide array of predators and scavengers (Neo and Todd 2011), while their discharges of faeces, gametes, and zooxanthellae (endosymbiotic dinoflagellates

[1]SNAPP CRF Working Group convened from 2020 to 2022 through the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, California. The working group was led by KM Kleisner, KE Mills, and P Sullivan. Other group members were invited to contribute based on their expert judgement, with the general goal of assembling a team of scientists representing diverse geographies, disciplines, institution types, and career stages. For a full list of working group members and advisors see: https://snappartnership.net/teams/climate-resilient-fisheries/. The Climate-Resilient Fisheries Planning Tool Workbook is available at https://ClimateResilientFisheries.net/.

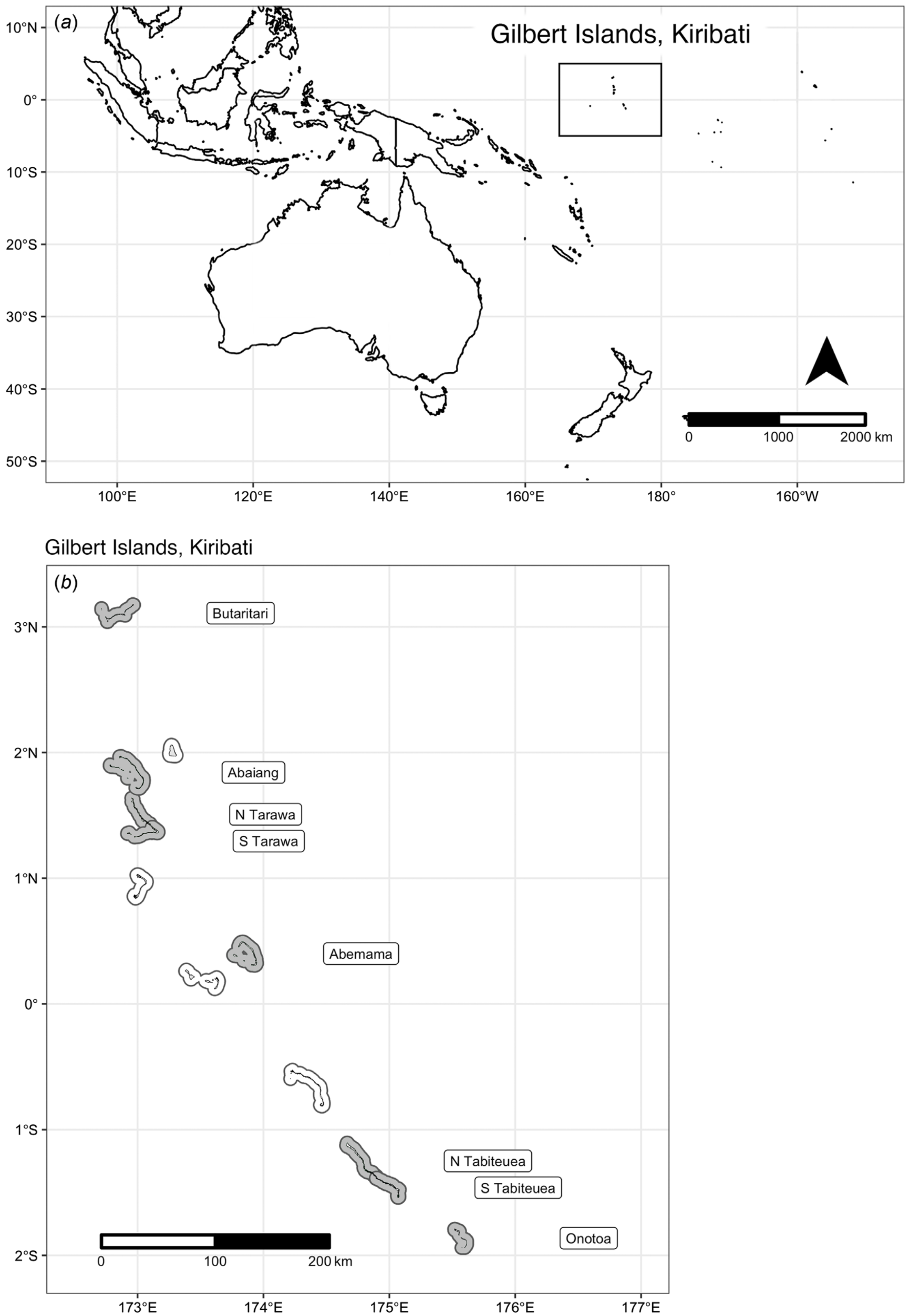

Fig. 1. (*a*) Location of Gilbert Islands, Kiribati and (*b*) the eight Gilbert Islands studied as a part of the Pacific Planetary Health Initiative (grey, labelled; Golden *et al.* 2022; https://www.pacificplanetaryhealth.com), which represents the background for the present study.

from the family Symbiodiniaceae) are eaten by opportunistic feeders and can be transported to corals (Umeki *et al.* 2020). They increase the topographical heterogeneity of the reef, act as reservoirs of zooxanthellae, and potentially counteract eutrophication via water filtering (Neo *et al.* 2015; Umeki *et al.* 2020; Watson and Neo 2021). The shells also provide substrate for commensal and ectoparasitic organisms (Neo *et al.* 2015). However, giant clams are at risk to climate stressors, such as ocean warming. Elevated sea surface temperature impacts giant clam physiological responses, including decreased fertilisation success (Armstrong *et al.* 2020), increased juvenile mortality (Watson *et al.* 2012), altered growth rates (Armstrong *et al.* 2022), and changes in shell mineral structure (Warter *et al.* 2018). Their heavy reliance on phototrophy, where energy from the sun is captured and converted into chemical energy, also makes the species sensitive to increases in sea surface temperatures (Watson and Neo 2021; referencing Andréfouët *et al.* 2013; Van Wynsberge and Andréfouët 2017; Van Wynsberge *et al.* 2018). Despite this, the Kiribati Fisheries Division from the Ministry of Fisheries and Marine Resources Development (MFMRD) has conducted limited monitoring, due to logistical and financial constraints, and the first national baseline assessment of giant clam diversity and abundance was conducted in 2019–2020 (Fig. 1*b*; Golden *et al.* 2022). There is limited to no data on historical catch or stock status, number of fishers involved, episodes of mortality due to heat stress, spatial patterns for giant clams, or levels of inter-island exports for this fishery.

Parallel to their key functional role on coral reefs, giant clams represent a traditionally and culturally important food source in the Pacific and in Kiribati (Fig. 2; Andrew *et al.* 2022). This contribution is particularly important on remote outer islands, where clams are used in traditional dances, served as a delicacy on special occasions or feasts, and contribute substantially to nutrition, as molluscs are rich in micronutrients (i.e. omega-3 and vitamin B_{12}; Golden *et al.* 2021*a*). Additionally, because clams are often dried, salted, and stored, they play a key role in food security, providing calories and nutrients at critical times when a 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, and the fishery is generally understood to have been in decline since 2004 (Delisle *et al.* 2016). Further, in 2008 *T. gigas*, or *te kima* in I-Kiribati, was thought to be nearly locally extinct from the urbanised and densely populated island of South Tarawa and the neighbouring islands of North Tarawa and Abaiang (Awira *et al.* 2008; Preston 2008*a*, 2008*b*). Across all islands, species' body size has similarly declined (A. Tekiau, T. Beiateuea, pers. obs.). Small-scale aquaculture of these clams was attempted by the private sector in 2002 (Atoll Beauties); however, the primary purpose was to export cultured clams for the global marine aquarium trade and not for a restocking program (Kinch and Teitelbaum 2009). While clams are harvested for use by multiple small operators, including commercial small-scale fishers, the majority of fishing pressure comes from subsistence fishers (Preston 2008*a*).

In response to these declines, MFMRD prepared the Kiribati National Giant Clam Fishery Management Plan (FMP) in 2013 (MFMRD 2013), which followed the 2010 Fisheries Act and a large-scale coral bleaching event in 2008 that caused a decline in habitat quality. The primary purpose of the giant clam FMP Coastal Fisheries Regulation was to establish an effective and enforceable management structure to ensure the sustainable development, conservation, and management of the Kiribati giant clam fishery. The giant clam FMP proposed a fishing ban for *T. gigas*, harvest restrictions for other giant clam species, and increased monitoring and reporting through an ongoing program for improving scientific information. However, despite the creation of tangible action items through the giant clam FMP, no national regulations were immediately approved or implemented. The recent 2019 Fisheries Regulations, now endorsed by the Office of Te Beretitenti and Cabinet (President and national government), includes the proposed *T. gigas* fishing ban from 2013, export restrictions for other giant clam species, and a size and daily bag limit of 15 cm total length and 2 kg, respectively, for personal consumption (MFMRD 2019).

Participatory assessment of climate resilience

The theoretical framework of climate resilience (Mason *et al.* 2022) was employed for the Kiribati giant clam fishery using a participatory workshop (Carroll *et al.* 2023) and knowledge co-production (Mills *et al.* 2023). Mills *et al.* (2023) defined knowledge co-production as an iterative, collaborative process of building partnerships that bring together multiple sources and types of knowledge to develop a systems-oriented understanding of a problem and identify potential solutions (adapted from Armitage *et al.* (2011) and Norström *et al.* (2020)). Input of the Indigenous community also helps to justify the precautionary measures applied by local managers in a data-limited and uncertain fishery (Latifah and Imanullah 2018) and informs the precautionary principle (Deville and Harding 1997).

We assembled a group of eight I-Kiribati fisheries scientists, managers, and local experts from the Kiribati Fisheries Division from the MFMRD (co-authors or acknowledged based on preference) for a workshop. This combination of scientific knowledge and local Indigenous expertise helped develop a comprehensive and complementary picture of climate change and its likely impacts on giant clams throughout Kiribati. This group was engaged in discussions around study design as well as the theoretical framework of climate resilience (Mason *et al.* 2022), before convening virtually in October 2020 to exchange information

Fig. 2. (*a*) Giant clam underwater visual census monitoring for the first national baseline assessment (Golden *et al*. 2022; A. Tekiau pictured). (*b*) Abaiang traditional village with raised huts *te buia* pictured. (*c*) Fisher displays their catch (*Tridacna maxima*) after harvesting on the Onotoa fore-reef. (*d*) Giant clam processing on Aiwa, Tabiteuea. Giant clams are sold for $1.00 to $1.50 AUD as strings of 10 (J. G. Eurich interviews 2019). (*e*) Kiribati Fisheries Division from the Ministry of Fisheries and Marine Resources Development (MFMRD) Fisheries Officers (A. Tekiau), the Abemama Island Council, and scientists (J. G. Eurich) meet to discuss fishery goals and community-based fishery management at Abemama, where clams are salted and traded to South Tarawa. All photographs by J. G. Eurich with expedition and equipment support from The Explorers Club, Original Watermen, DJI, and GoPro.

on giant clams, climate change impacts, and contextualise and refine attribute scores.

The group used a pilot version of the Climate-Resilient Fisheries Planning Tool (CRFP Tool; https://ClimateResilientFisheries.net/), which guides users through the framework of climate resilience to assess their fishery's climate resilience and identify approaches and priority actions to help build resilience in their fishery. The CRFP Tool is a product of the SNAPP Climate Resilient Fisheries Working Group and helps users identify and focus their efforts on attributes of the fishery system that have the greatest potential to strengthen climate resilience. The tool facilitates an assessment of ecological, governance, and socio-economic dimensions of a fishery system that enables users to prioritise interventions across these dimensions based on the planning goals, expected climate impacts, and resilience attributes present in the fishery (Mason *et al*. 2022). The CRFP Tool workbook is available online and provides worksheets for reviewing or completing the six-step process used here: (1) specify the fishery system; (2) set long-term goals; (3) identify climate impacts; (4) evaluate climate-resilient attributes; (5) brainstorm climate-resilience actions; and (6) identify priority actions (see Supplemental materials for the pilot tool).

Resilience attributes in practice

Of the 38 resilience attributes (Mason *et al.* 2022), local experts and I-Kiribati fishery scientists identified six ecological, five governance, and five socio-economic attributes thought to be critical in conferring resilience (attributes *italicised* and defined in Table 1). Each attribute's strength (score), importance, and data quality were evaluated (Fig. 3). Attribute scores were recorded using a 4-option Likert scale (very low, low, moderate, or high). Importance was recorded with a 3-option Likert scale (low, medium, or high). Data quality was recorded with a 5-option Likert scale of: no data; unconfident expert judgment (low); fairly confident expert judgment (fair); expert judgment and limited data (good); and adequate/reliable data (excellent). Important attributes were identified across all resilience domains: agency (red): the capacity and freedom of people to make and act on choices; underpins people's ability to operationalise different aspects of resilience; assets (brown): resources that can be drawn upon to buffer impacts or respond to change; flexibility (green): the ability to switch strategies or make other adjustments in the face of change; learning (blue): the process by which people and institutions recognise and identify factors contributing to change and analyse possible responses; organisation (pink): the social and ecological relationships, networks and institutions that operate at different spatial and temporal scales to confer resilience. In the following sections, we provide an overview of how key attributes, as outlined by knowledge co-production, function and interact in each dimension to contribute to the fisheries' resilience.

Ecological dimension

Both South Tarawa and the outer Gilbert Islands have experienced system-wide shocks with high year-to-year climate variability (Donner 2011; Cannon *et al.* 2021). Particularly,

Table 1. Attributes that confer resilience to climate change in the Kiribati giant clam fishery.

Ecological dimension	
Plasticity	The capacity for one genotype to yield more than one phenotype in response to environmental cues.
Evolutionary potential	The capacity of a population to evolve in response to environmental change.
Ecosystem connectivity	The degree to which an ecosystem facilitates the structural and physical connection among suitable, adjacent, and/or available ecosystem functions and components.
Larval dispersal	The degree to which eggs or larvae spread from a spawning site to a settlement location.
Population abundance	The abundance or biomass of a species present in a defined geographical range.
Age structure	The age distribution of individuals within a population.
Governance dimension	
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.
Leadership and initiative	A system that legitimises and supports the development of leaders who are guided by collective interests, who mobilise and direct responses to disruptions and who take responsibility and act when necessary.
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.
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-mobilisation.
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.
Socio-economic dimension	
Resilience mindset	The degree to which individuals accept 'resilience thinking' from a perspective that recognises characteristics of complexity, uncertainty, non-linearity, thresholds, feedbacks, irreversibility, and multi-scale and multi-level interactions in a changing world.
Learning capacity	The degree to which individuals and communities are able to perceive risk, learn from experience, synthesise information and grow their own knowledge.
Place attachment	The extent to which individuals and 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.
Agency	The capacity of individuals and communities to negotiate, make decisions and act on their own free will.
Social capital	The strength of networks of relationships among people and organisations who live and work in a particular community.

Resilience attributes were developed and defined by Mason *et al.* (2022) as a component of the comprehensive resilience framework evaluated here. Only resilience attributes mechanistically explained in the main text, *italicised*, are defined above. See Mason *et al.* (2022) for a complete list of the 38 attributes, specific context, definitions, capacities, scale, and more on the framework's approach.

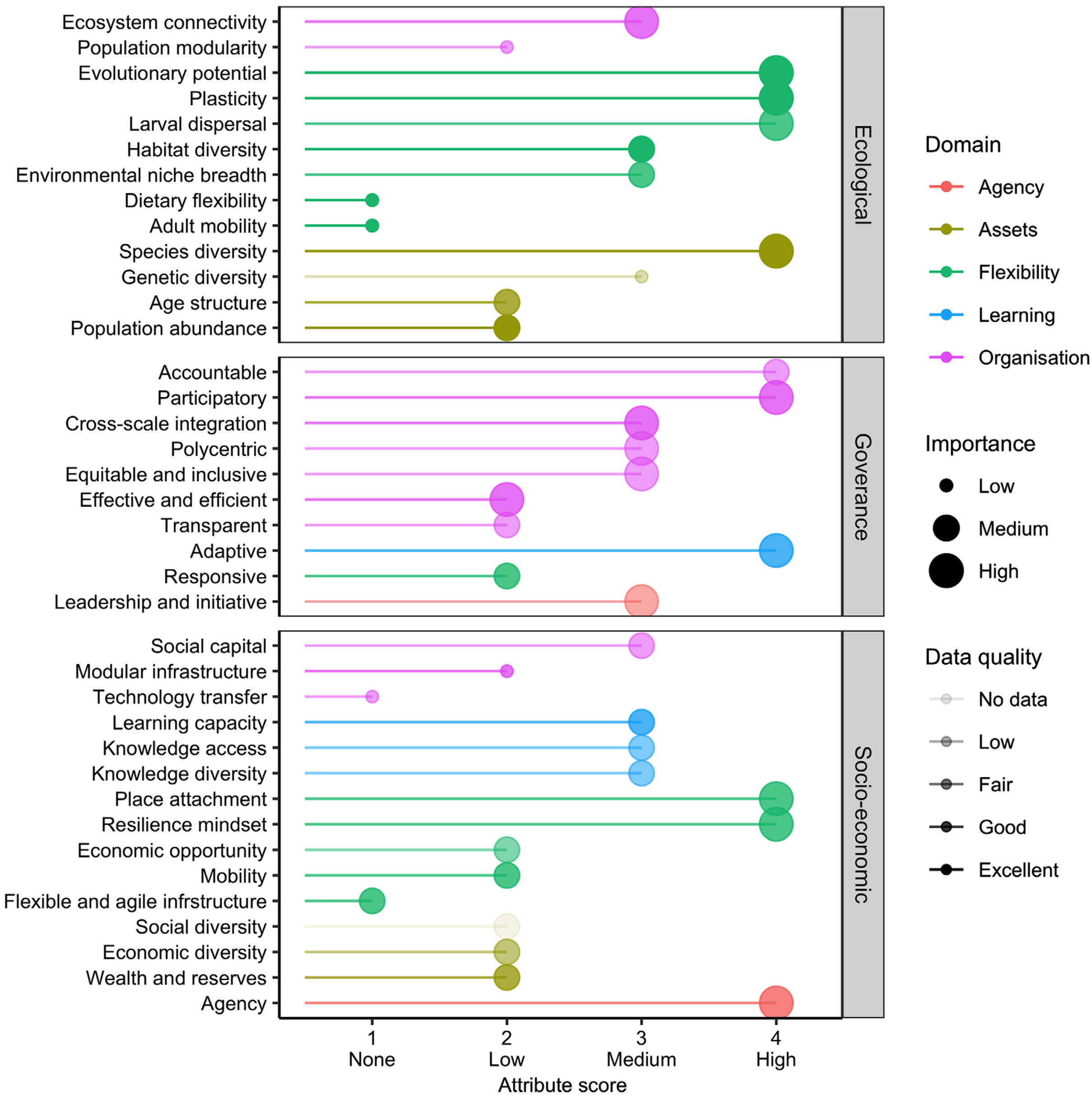

Fig. 3. Resilience attribute scores for the Kiribati giant clam fishery, as determined by knowledge co-production compared to other fisheries. The 38 attributes are ordered by dimension, domain, and score (defined and described in Mason *et al.* (2022)). Line plot is coloured by domain (red: agency; brown: assets; green: flexibility; blue: learning; pink: organisation), shaded by data quality (no data, low, fair, good, excellent), and weighted by importance of the attribute within the fishery (low, medium, high).

climate change in Kiribati has resulted in habitat degradation following large-scale coral bleaching events, and resulted in a shift from a diverse and complex coral community to 'weedy' stress-tolerant coral species (Donner and Carilli 2019). Coral bleaching, as seen in Kiribati, can result in a high loss of coral cover (a key habitat component of giant clams) and reduced structural complexity (Richardson *et al.* 2018). These events can directly or indirectly lead to reduced giant clam settlement and future recruitment if the *population abundance* is not stable (Neo *et al.* 2013). Physiological stress from changes in sea surface temperature (which impact symbiotic associations with photobionts) and ocean acidification (which impact calcareous growth) will continue to increase through the Anthropocene and threaten giant clam populations in Kiribati (Watson and Neo 2021). However, recent studies have shown that giant clams, in the absence of additional anthropogenic pressures, are highly 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 (Neo *et al.* 2013; Soo and Todd 2014; Watson 2015; Morishima *et al.* 2019). For example, Morishima *et al.* (2019) hypothesised that under elevated temperatures, heat-resistant photosynthetically active zooxanthellae could be passed to adjacent juveniles through faecal pellets. This pathway of viable symbionts has been shown to occur between clams and corals, which can increase ecosystem resilience (Umeki *et al.* 2020). Additionally, as broadcast spawners, clams respond positively to networked marine reserves, where increased reproductive outputs can disperse as populations and age structure stabilises (low densities inhibit natural recovery; Neo *et al.* 2013), improving connectivity and supporting populations outside reserve boundaries (Roberts *et al.* 2017). Thus, the ecological attributes of giant clams in Kiribati offer pathways of resilience for the species, which can be further improved through governance strategies.

Governance dimension

Local government in Kiribati is established primarily in the form of Island Councils, which while present in both rural and urban settings, act as the primary presence of the Kiribati government on the remote outer Gilbert Islands. Island Councils act at the scale of a single small island, allowing them to make *adaptive* decisions quickly (Delisle *et al.* 2016). Additionally, on many islands, there is strong *leadership and initiative* through traditional leaders (unimane) and village elders, who play an important role in the overall allocation of rights to resources and continue the tradition of adaptive management as well as presiding over conflicts and traditional law, ensuring a balance of ecological and social outcomes from the fishery (Campbell and Hanich 2014; Mangubhai *et al.* 2019). The high *polycentricity* allows authority to be transferred to different levels, which enhances adaptive capacity by diversifying potential options for responding to uncertainty or change. Key informant interviews in Kiribati highlighted that the acceptance and enforcement of community-driven resource management requires strengthened connections and support within and between villages, as well as across levels of government and regulation (Delisle *et al.* 2016). On outer islands where Island Councils and traditional leadership are most influential, decision making is the result of a *participatory* approach, which maintains *accountability*. Across different outer islands, Island Councils have implemented giant clam fishing quotas, permanent or rotational no take areas, and even banned the take of *T. gigas*. The application of both traditional and decentralised state governance approaches have resulted in the implementation and success of customary and community-based fisheries management. In contrast, in urbanised South Tarawa, where traditional communities have become blurred, governance operates more regularly through the central government, and the fishery has continued to decline. Semi-structured interviews of local I-Kiribati community members emphasised that the success of community-based conservation projects relies on village practices, leadership, and previous experiences (Teuea and Nakamura 2020). While the concept of traditional management is generally understood in Kiribati (Delisle *et al.* 2016; Teuea and Nakamura 2020), successful initiatives are influenced by hierarchical status, leadership quality, and the level of power and direct benefits (e.g. financial incentives) granted from initiatives. Emphasising these attributes of effective, dynamic, connected, and just governance in future conservation measures is key to the success of adaptive management.

Socio-economic dimension

The governance dimension demonstrates that adaptive management using closures, quotas, and species-specific regulations can increase resilience in the clam fisheries across the Gilbert Islands. However, underpinning these approaches are *place attachment*, *learning capacity*, a *resilience mindset*, and *agency* at the local scale as the primary drivers of resilience. Teuea and Nakamura (2020) similarly found that community members wish to be consulted over the implementation, progress, and effect of conservation projects, noting a sense of ownership. Despite the near local extinction of giant clams on the island of Abaiang in 2008 from fishing pressure (Fig. 2*b*), the fishery is an example of socio-economic resilience. Through the community-led implementation of specific governance approaches, specifically fisher-driven no-take marine protected areas, Abaiang today has a stable giant clam population and associated fishery, despite the <50 km proximity to South Tarawa (participatory workshop consensus; J. G. Eurich, pers. obs.). The success of the local governance approaches prompted the aquaculture unit under the Coastal Fisheries Division of MFMRD to initiate an aquaculture program for *T. maxima* restocking in Abaiang, Tarawa, and nearby islands (Mies *et al.* 2017). Additionally, in 2022 following an MFMRD study confirming species decline, the village of Kabuna, North Tabiteuea initiated the 'Nei Tengarengare Project' to protect clams for 4 years using community-based fisheries management approaches and regulating trade (MFMRD 2022). The village of Autukia, Nonouti similarly implemented a 'Nei Tengarengare Committee' to lead a new management plan to improve the health of bivalve fisheries, restore habitat, and maintain Autukia's traditional practices (B. Rabwere, unpubl. data; MFMRD 2020). Creating or maintaining strong local capacity, agency, and sense of place will be key to overcoming climate-related impacts, avoiding a social-ecological trap (Golden *et al.* 2021*b*), and increasing long-term resilience for North Tabiteuea and other islands in the future.

Conclusion

The participatory workshop found that 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 community-based fisheries management was successfully implemented. Ecologically, the species fished are generally resilient to climate change; however, anthropogenic impacts have pushed this fishery past the threshold of ecological resilience in the urbanised island of South Tarawa, where the governance and socio-economic dimensions are less adaptive (Delisle *et al.* 2016). In South Tarawa, these feedbacks between coupled socio-economic and natural dynamics have led to a social-ecological trap within the fishery resulting in reduced access to giant clams, a traditional food resource (Golden *et al.* 2021*a*). Conversely, on remote outer islands, flexible and adaptive governance structures with strong ties to place attachment and stakeholder participation have the strongest potential to implement the governance approaches necessary to ensure climate-resilient clam fisheries. While governance effectiveness in turn may not in itself confer resilience (Andréfouët *et al.* 2013), other ecological and social attributes provide the necessary structures for knowledge transfer to link awareness about the social-ecological system and its stressors to adaptive actions.

Our results highlight an example of resilience attributes in practice and identify pathways towards increasing climate resilience in other small-scale fisheries. We demonstrate the power of coupling a comprehensive resilience framework with a participatory workshop and use the precautionary principle (Deville and Harding 1997, see fig. 7 for steps) to justify an assessment of current management approaches in a data-limited fishery, where uncertainty or possible impacts were high (precautionary principle step 1). Knowledge co-production is integral to building governance and management strategies that will remain effective in the face of climate change. By eliciting local expert and Indigenous knowledge and long-term perspectives, we identified ecological, governance, and socio-economic relevant attributes of climate resilience (information generated for precautionary principle steps 2, 3, and 4). While field or experimental data are required to quantify resilience and confirm the existence of giant clam tolerance, our results here highlight successful initiatives in Kiribati, based on real-time and place-based observations (precautionary principle steps 3 and 4), that can be applied in other Pacific small-scale fisheries. For example, elevating local community members' motivation and support (Teuea and Nakamura 2020) coupled with giant clam aquaculture and restocking programs (Mies *et al.* 2017) or conservation planning that includes functional trait contributions and evolutionary diversity (Tan *et al.* 2022) may lead to successful giant clam conservation outcomes despite limited resources. Lastly, the precautionary principle assumes that future action will be undertaken to reduce uncertainty in the precautionary measures, facilitating a transition from precaution to prevention. As the first national baseline assessment of giant clam diversity and abundance was launched in 2019 (Golden *et al.* 2022), these learnings will be modified as data become available (precautionary principle transition from precaution to prevention) and eventually be scaled up across systems to provide policy directions. Ultimately, the research outlined by Golden *et al.* (2022) will create a baseline to simultaneously monitor change in ecological, socio-economic, and human health conditions associated with the giant clam fishery and how they co-vary over time.

While the process of co-producing knowledge and management strategies requires considerable investments of time, participatory work offers a promising approach to design effective and equitable pathways (Carroll *et al.* 2023). The tools employed here – Mason *et al.* (2022) comprehensive resilience framework and the Climate-Resilient Fisheries Planning Tool (https://ClimateResilientFisheries.net/) – can be used elsewhere to identify context-specific resilience strategies. As climate anomalies and mass mortalities will continue to impact fisheries (e.g. giant clam fisheries in French Polynesia; Andréfouët *et al.* 2013; Van Wynsberge *et al.* 2018), knowledge co-production can increase collaborations between scientists, policy experts, leaders, managers, and practitioners. Thus, we highlight the need to combine place-based historical perspectives with inference-based and model-based methods to better understand the impacts of climate variability on management decisions (Mills *et al.* 2023). As fishery stakeholders continue to develop national climate-resilience plans and advance solutions to support healthy marine ecosystems the knowledge of adaptive actions can be distributed to advance climate resilience in marine fisheries.

Supplementary material

Supplementary material is available online.

References

Andrachuk M, Peckham H, Box S, Campbell S, Cramer K, Darling E, Dougherty D, Geers T, Hicks C, Kleisner K, Mangubhai S, Mason J, Matthews E, Rife A, Rivera A, Robinson J, Tilley A, Wabnitz C (2022) The role of coral reef small-scale fisheries for addressing malnutrition and avoiding biodiversity loss. Wildlife Conservation Society.

Andrew NL, Allison EH, Brewer T, Connell J, Eriksson H, Eurich JG, Farmery A, Gephart JA, Golden CD, Herrero M, Mapusua K, Seto KL, Sharp MK, Thornton P, Thow AM, Tutuo J (2022) Continuity and change in the contemporary Pacific food system. *Global Food Security* **32**, 100608. doi:10.1016/j.gfs.2021.100608

Andréfouët S, Van Wynsberge S, Gaertner-Mazouni N, Menkes C, Gilbert A, Remoissenet G (2013) Climate variability and massive mortalities challenge giant clam conservation and management efforts in French Polynesia atolls. *Biological Conservation* **160**, 190–199. doi:10.1016/j.biocon.2013.01.017

Armitage D, Berkes F, Dale A, Kocho-Schellenberg E, Patton E (2011) Co-management and the co-production of knowledge: learning to adapt in Canada's Arctic. *Global Environmental Change* **21**, 995–1004. doi:10.1016/j.gloenvcha.2011.04.006

Armstrong EJ, Dubousquet V, Mills SC, Stillman JH (2020) Elevated temperature, but not acidification, reduces fertilization success in the small giant clam, *Tridacna maxima*. *Marine Biology* **167**, 8. doi:10.1007/s00227-019-3615-0

Armstrong EJ, Watson S-A, Stillman JH, Calosi P (2022) Elevated temperature and carbon dioxide levels alter growth rates and shell composition in the fluted giant clam, *Tridacna squamosa*. *Scientific Reports* **12**, 11034. doi:10.1038/s41598-022-14503-4

Awira R, Friedman KJ, Sauni S, Kronen M, Pinca S, Chapman L, Magron F (2008) Kiribati country report: profiles and results from survey work at Abaiang, Abemama, Kuria and Kiritimati (May to November 2004). Pacific Regional Oceanic and Coastal Fisheries Development Programme, Secretariat of the Pacific Community.

Burden M, Fujita R (2019) Better fisheries management can help reduce conflict, improve food security, and increase economic productivity in the face of climate change. *Marine Policy* **108**, 103610. doi:10.1016/j.marpol.2019.103610

Campbell B, Hanich Q (2014) Fish for the future: fisheries development and food security for Kiribati in an era of global climate change. WorldFish, Penang, Malaysia.

Cannon SE, Aram E, Beiateuea T, Kiareti A, Peter M, Donner SD (2021) Coral reefs in the Gilbert Islands of Kiribati: resistance, resilience, and recovery after more than a decade of multiple stressors. *PLoS ONE* **16**, e0255304. doi:10.1371/journal.pone.0255304

Carroll G, Eurich JG, Sherman KD, Glazer R, Braynen MT, Callwood KA, Castañeda A, Dahlgren C, Karr KA, Kleisner KM, Burns-Perez V, Poon SE, Requena N, Sho V, Tate SN, Haukebo S (2023) A participatory climate vulnerability assessment for recreational tidal flats fisheries in Belize and The Bahamas. *Frontiers in Marine Science* **10**, 1177715. doi:10.3389/fmars.2023.1177715

Delisle A, Namakin B, Uriam T, Campbell B, Hanich Q (2016) Participatory diagnosis of coastal fisheries for North Tarawa and Butaritari island communities in the Republic of Kiribati. Program report: 2016–24. WorldFish, Penang, Malaysia.

Deville A, Harding R (1997) 'Applying the precautionary principle.' (The Federation Press: Sydney)

Donner SD (2011) An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. *Ecological Applications* **21**, 1718–1730. doi:10.1890/10-0107.1

Donner SD, Carilli J (2019) Resilience of Central Pacific reefs subject to frequent heat stress and human disturbance. *Scientific Reports* **9**, 3484. doi:10.1038/s41598-019-40150-3

Free CM, Thorson JT, Pinsky ML, Oken KL, Wiedenmann J, Jensen OP (2019) Impacts of historical warming on marine fisheries production. *Science* **363**(6430), 979–983. doi:10.1126/science.aau1758

Gaines SD, Costello C, Owashi B, Mangin T, Bone J, Molinos JG, Burden M, Dennis H, Halpern BS, Kappel CV, Kleisner KM, Ovando D (2018) Improved fisheries management could offset many negative effects of climate change. *Science Advances* **4**(8), eaao1378. doi:10.1126/sciadv.aao1378

Golden CD, Gephart JA, Eurich JG, McCauley DJ, Sharp MK, Andrew NL, Seto KL (2021*a*) Social-ecological traps link food systems to nutritional outcomes. *Global Food Security* **30**, 100561. doi:10.1016/j.gfs.2021.100561

Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF, Matthey H, Eurich JG, Gephart JA, Fluet-Chouinard E, Nyboer EA, Lynch AJ, Kjellevold M, Bromage S, Charlebois P, Barange M, Vannuccini S, Cao L, Kleisner KM, Rimm EB, Danaei G, DeSisto C, Kelahan H, Fiorella KJ, Little DC, Allison EH, Fanzo J, Thilsted SH (2021*b*) Aquatic foods to nourish nations. *Nature* **598**, 315–320. doi:10.1038/s41586-021-03917-1

Golden CD, Ayroles J, Eurich JG, Gephart JA, Seto KL, Sharp MK, Balcom P, Barravecchia HM, Bell KK, Gorospe KD, Kim J, Koh WH, Zamborain-Mason J, McCauley DJ, Murdoch H, Nair N, Neeti K, Passarelli S, Specht A, Sunderland EM, Tekaieti A, Tekiau A, Tekoaua R, Timeon E (2022) Study protocol: interactive dynamics of coral reef fisheries and the nutrition transition in Kiribati. *Frontiers in Public Health* **10**, 890381. doi:10.3389/fpubh.2022.890381

Halpern BS, Boettiger C, Dietze MC, Gephart JA, Gonzalez P, Grimm NB, *et al.* (2023) Priorities for synthesis research in ecology and environmental science. *Ecosphere* **14**(1), e4342. doi:10.1002/ecs2.4342

Hollowed AB, Barange M, Beamish RJ, Brander K, Cochrane K, Drinkwater K, *et al.* (2013) Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science* **70**(5), 1023–1037. doi:10.1093/icesjms/fst081

IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. Contribution of Working group II to the sixth assessment report of the intergovernmental panel on climate change. IPCC.

IUCN (2016) The IUCN red list of threatened species. Version 2016–2. Available at www.iucnredlist.org

Kinch J, Teitelbaum A (2009) Proceedings of the regional workshop on the management of sustainable fisheries for giant clams (Tridacnidae) and CITES capacity building. Aquaculture Technical Papers, Secretariat of the Pacific Community.

Kleisner KM, Ojea E, Battista W, Burden M, Cunningham E, Fujita R, Karr K, Amorós S, Mason J, Rader D, Rovegno N, Thomas-Smyth A (2022) Identifying policy approaches to build social-ecological resilience in marine fisheries with differing capacities and contexts. *ICES Journal of Marine Science* **79**, 552–572. doi:10.1093/icesjms/fsab080

Kritzer JP, Costello C, Mangin T, Smith SL (2019) Responsive harvest control rules provide inherent resilience to adverse effects of climate change and scientific uncertainty. *ICES Journal of Marine Science* **76**(6), 1424–1435. doi:10.1093/icesjms/fsz038

Latifah E, Imanullah MN (2018) The precautionary principle in fisheries management under climate change: how the international legal framework formulate it? *IOP Conference Series: Earth and Environmental Science* **129**, 012038. doi:10.1088/1755-1315/129/1/012038

Malhi Y, Franklin J, Seddon N, Solan M, Turner MG, Field CB, Knowlton N (2020) Climate change and ecosystems: threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences* **375**, 20190104. doi:10.1098/rstb.2019.0104

Mangubhai S, Lovell E, Abeta R, Donner S, Redfern FM, O'Brien M, *et al.* (2019) Kiribati: atolls and marine ecosystems. In 'World seas: an environmental evaluation'. (Ed. C Sheppard) pp. 807–826. (Elsevier: London) doi:10.1016/b978-0-08-100853-9.00054-3

Mason JG, Eurich JG, Lau JD, Battista W, Free CM, Mills KE, Tokunaga K, Zhao LZ, Dickey-Collas M, Valle M, Pecl GT, Cinner JE, Mcclanahan TR, Allison EH, Friedman WR, Silva C, Yáñez E, Barbieri MA, Kleisner KM (2022) Attributes of climate resilience in fisheries: from theory to practice. *Fish and Fisheries* **23**, 522–544. doi:10.1111/faf.12630

MFMRD (2013) Kiribati national fisheries policy 2013. Ministry of Fisheries and Marine Resources Development, Government of Kiribati, Bairiki, Tarawa.

MFMRD (2019) Fisheries (Conservation and Management of Coastal Marine Resources) regulations 2019. Ministry of Fisheries and Marine Resources Development, Public Office of the Beretitenti, Government of Kiribati, Bairiki, Tarawa.

MFMRD (2020) Autukia village fisheries management plan. Ministry of Fisheries and Marine Resources Development, Government of Kiribati, Bairiki, Tarawa.

MFMRD (2022) Mamautari newsletter: the process of recovering the population of Giant Clams in Kabuna. Ministry of Fisheries and Marine Resources Development, Government of Kiribati, Bairiki, Tarawa.

Mies M, Dor P, Güth AZ, Sumida PYG (2017) Production in giant clam aquaculture: trends and challenges. *Reviews in Fisheries Science & Aquaculture* **25**, 286–296. doi:10.1080/23308249.2017.1285864

Mills KE, Armitage D, Eurich JG, Kleisner KM, Pecl GT, Tokunaga K (2023) Co-production of knowledge and strategies to support climate resilient fisheries. *ICES Journal of Marine Science* **80**, 358–361. doi:10.1093/icesjms/fsac110

Morishima S-Y, Yamashita H, O-hara S, Nakamura Y, Quek VZ, Yamauchi M, Koike K (2019) Study on expelled but viable zooxanthellae from giant clams, with an emphasis on their potential as subsequent symbiont sources. *PLoS ONE* **14**, e0220141. doi:10.1371/journal.pone.0220141

Myers SS, Smith MR, Guth S, Golden CD, Vaitla B, Mueller ND, Dangour AD, Huybers P (2017) Climate change and global food systems: potential impacts on food security and undernutrition. *Annual Review of Public Health* **38**(1), 259–277. doi:10.1146/annurev-publhealth-031816-044356

Neo ML, Todd PA (2011) Predator-induced changes in fluted giant clam (*Tridacna squamosa*) shell morphology. *Journal of Experimental Marine Biology and Ecology* **397**, 21–26. doi:10.1016/j.jembe.2010.11.008

Neo ML, Erftemeijer PLA, van Beek JKL, van Maren DS, Teo SL-M, Todd PA (2013) Recruitment constraints in Singapore's fluted giant clam (*Tridacna squamosa*) populations – a dispersal model approach. *PLoS ONE* **8**(3), e58819. doi:10.1371/journal.pone.0058819

Neo ML, Eckman W, Vicentuan K, Teo SL-M, Todd PA (2015) The ecological significance of giant clams in coral reef ecosystems. *Biological Conservation* **181**, 111–123. doi:10.1016/j.biocon.2014.11.004

Norström AV, Cvitanovic C, Löf MF, West S, Wyborn C, Balvanera P, *et al.* (2020) Principles for knowledge co-production in sustainability research. *Nature Sustainability* **3**, 182–190. doi:10.1038/s41893-019-0448-2

Ojea E, Pearlman I, Gaines SD, Lester SE (2017) Fisheries regulatory regimes and resilience to climate change. *Ambio* **46**, 399–412. doi:10.1007/s13280-016-0850-1

Pinsky ML, Worm B, Fogarty MJ, Sarmiento JL, Levin SA (2013) Marine taxa track local climate velocities. *Science* **341**(6151), 1239–1242. doi:10.1126/science.1239352

Plagányi ÉE, Punt AE, Hillary R, Morello EB, Thébaud O, Hutton T, Pillans RD, Thorson JT, Fulton EA, Smith ADM, Smith F, Bayliss P, Haywood M, Lyne V, Rothlisberg PC (2014) Multispecies fisheries management and conservation: Tactical applications using models of intermediate complexity. *Fish and Fisheries* **15**(1), 1–22. doi:10.1111/j.1467-2979.2012.00488.x

Preston G (2008*a*) Coastal fisheries development and management. Institutional strengthening scoping study report. Ministry of Fisheries and Marine Resources Development, Government of Kiribati, Bairiki, Tarawa.

Preston G (2008*b*) Coastal fisheries activities proposed for incorporation into an institutional strengthening project for the Kiribati fisheries sector. Institutional strengthening scoping study report. Ministry of Fisheries and Marine Resources Development, Government of Kiribati, Bairiki, Tarawa.

Richardson LE, Graham NAJ, Pratchett MS, Eurich JG, Hoey AS (2018) Mass coral bleaching causes biotic homogenization of reef fish assemblages. *Global Change Biology* **24**, 3117–3129. doi:10.1111/gcb.14119

Roberts CM, O'Leary BC, McCauley DJ, Cury PM, Duarte CM, Lubchenco J, Pauly D, Sáenz-Arroyo A, Sumaila UR, Wilson RW, Worm B, Castilla JC (2017) Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences of the United States of America* **114**, 6167–6175. doi:10.1073/pnas.1701262114

Soo P, Todd PA (2014) The behaviour of giant clams (Bivalvia: Cardiidae: Tridacninae). *Marine Biology* **161**, 2699–2717. doi:10.1007/s00227-014-2545-0

Tan EYW, Neo ML, Huang D (2022) Assessing taxonomic, functional and phylogenetic diversity of giant clams across the Indo-Pacific for conservation prioritization. *Diversity and Distributions* **28**, 2124–2138. doi:10.1111/ddi.13609

Teuea T, Nakamura N (2020) Motivations to support marine conservation projects in North Tarawa, Kiribati. *Conservation and Society* **18**, 161–171. doi:10.4103/cs.cs_19_51

Tigchelaar M, Cheung WWL, Mohammed EY, Phillips MJ, Payne HJ, Selig ER, *et al.* (2021) Compound climate risks threaten aquatic food system benefits. *Nature Food* **2**, 673–682. doi:10.1038/s43016-021-00368-9

Umeki M, Yamashita H, Suzuki G, Sato T, Ohara S, Koike K (2020) Fecal pellets of giant clams as a route for transporting Symbiodiniaceae to corals. *PLoS ONE* **15**, e0243087. doi:10.1371/journal.pone.0243087

Van Wynsberge S, Andréfouët S (2017) The future of giant clam-dominated lagoon ecosystems facing climate change. *Current Climate Change Reports* **3**, 261–270. doi:10.1007/s40641-017-0078-6

Van Wynsberge S, Andréfouët S, Gaertner-Mazouni N, Remoissenet G (2018) Consequences of an uncertain mass mortality regime triggered by climate variability on giant clam population management in the Pacific Ocean. *Theoretical Population Biology* **119**, 37–47. doi:10.1016/j.tpb.2017.10.005

Warter V, Erez J, Müller W (2018) Environmental and physiological controls on daily trace element incorporation in *Tridacna crocea* from combined laboratory culturing and ultra-high resolution LA-ICP-MS analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* **496**, 32–47. doi:10.1016/j.palaeo.2017.12.038

Watson S-A (2015) Giant clams and rising CO_2: light may ameliorate effects of ocean acidification on a solar-powered animal. *PLoS ONE* **10**, e0128405. doi:10.1371/journal.pone.0128405

Watson S-A, Neo ML (2021) Conserving threatened species during rapid environmental change: using biological responses to inform management strategies of giant clams. *Conservation Physiology* **9**, coab082. doi:10.1093/conphys/coab082

Watson S-A, Southgate PC, Miller GM, Moorhead JA, Knauer J (2012) Ocean acidification and warming reduce juvenile survival of the fluted giant clam, *Tridacna squamosa*. *Molluscan Research* **32**, 177–180. Available at https://www.mapress.com/mr/content/v32/2012f/n3p180.htm

Wolfe K, Anthony K, Babcock RC, Bay L, Bourne DG, Burrows D, *et al.* (2020) Priority species to support the functional integrity of coral reefs. In 'Oceanography and marine biology: an annual review, Vol. 58'. (Eds SJ Hawkins, AL Allcock, AE Bates, LB Firth, IP Smith, S Swearer, A Evans, P Todd, B Russell, C McQuaid) pp. 179–318. (CRC Press) Available at https://library.oapen.org/handle/20.500.12657/43148

Data availability. Data sharing is not applicable as no new data were generated or analysed during this study.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. We are grateful for the financial support of the National Science Foundation (CNH 1826668 to JGE, KLS, CDG, DJM; https://nsf.gov/awardsearch/showAward?AWD_ID=1826668) and the Explorers Club (2020 OceanX to JGE).

Acknowledgements. This paper resulted from a National Science Foundation grant (CNH 1826668) and the Science for Nature and People Partnership (SNAPP) Climate Resilient Fisheries Working Group. SNAPP is a partnership of The Nature Conservancy and Wildlife Conservation Society. This SNAPP working group is part of a cohort of research funded by the David and Lucile Packard Foundation Grant #2018-68222 to address the theme of Oceans, Climate, and Equity. The manuscript greatly benefited from all working group leaders, members and advisors who assisted in the development of the resilience attributes and template. We are particularly grateful to Jessica A. Gephart for comments that improved the manuscript, Rateiti Vaimalie, Manibua Rota Kanoua, Karibanang Tamuera, for thoughtful advice and participation in the participatory workshop, and Christopher M. Free for code development of Fig. 3. The manuscript greatly benefited from the input of Mike Calver, Graham Fulton, and three anoyonomous reviewers.

Author affiliations

[A]Environmental Defense Fund, Santa Barbara, CA, USA.

[B]Marine Sciences Institute, University of California, Santa Barbara, Santa Barbara, CA, USA.

[C]Ministry of Fisheries and Marine Resource Development, Coastal Fisheries Division, Bikenibeui, Tarawa, Republic of Kiribati.

[D]Environmental Studies Department, University of California at Santa Cruz, Santa Cruz, CA, USA.

[E]Department of Nutrition, Harvard T.H. Chan School of Public Health, Boston, MA, USA.

[F]Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA.

[G]Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, Santa Barbara, CA, USA.