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Title: Social determinants of adaptive and transformative responses to climate change

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Social determinants of adaptive and transformative responses to climate change

Abstract: To effectively cope with the impacts of climate change, people will need to change existing practices or behaviours within existing social-ecological systems (adaptation), or enact more fundamental changes that can alter dominant social-ecological relationships and create new systems or futures (transformation). Here we use multilevel network modelling to examine how different domains of adaptive capacity—assets, flexibility, organization, learning, socio-cognitive constructs, and agency—are related to adaptive and transformative actions. We find evidence consistent with an influence process in which aspects of social organization (exposure to others in social networks) encourage both adaptive and transformative action among Papua New Guinean islanders experiencing climate change impacts. Adaptive and transformative action are also related to social-ecological network structures between people and ecological resources that enable learning and the internalization of ecological feedbacks. Agency is also key, yet we show that while perceived power may encourage adaptations, it may discourage more transformative actions.

Introduction

Climate change is already affecting the lives of people across the globe. Even under the most optimistic greenhouse gas emission reduction scenario in the Intergovernmental Panel on Climate Change Fifth Assessment Report [1], securing biodiversity and ecosystem services, safeguarding food and water security, and protecting the livelihoods and health of future generations presents significant challenges. As sea levels rise and global heating triggers an increase in climate-related disasters, it is imperative that people on the frontlines of climate change have the capacity to effectively respond in ways that reduce their vulnerability [2].

Whether and how people respond to environmental change (adaptive behaviour) is widely recognized to be driven by their adaptive capacity, broadly defined as the conditions that underpin people's ability to anticipate and respond to change; to recover from, and minimize the consequences of change; and to take advantage of new opportunities [3]. Access to capital, such as financial assets, has long been considered a crucial determinant of adaptive capacity [3,4]. However, research from across diverse social science disciplines has recently identified a much broader range of determinants that underpin whether and how people adapt to environmental change [5-8].

In addition to the assets people can draw upon to buffer shocks in times of need [4], adaptive behaviour can be driven by whether people have the flexibility to change strategies [6] (e.g., to move between livelihoods or between techniques and practices within livelihoods [9]), and the power or agency to influence change [10] or make their own free choices in determining whether to change or not [11]. Socio-cognitive constructs, such as risk attitudes and cognitive biases, can also play an important role in people's adaptive behaviour by influencing perceptions regarding the need to adapt to change (or not) and the costs and benefits of adaptation [7,8]. For example, decisions regarding whether and how to respond to changing environmental conditions can be driven by perceptions of the probability and severity of risk associated with change [12], as well as the closeness and intensity of previous related experiences [13]. Finally, adaptive behaviour can be influenced by the social and social-ecological ties binding people to each other and the environment [14,15]. These relationships shape processes of social influence that determine whether and how people access information, resources, and support (organization) [14-18], and the context in which people learn to recognize change and strategically absorb, process, and synthesize information in order to adapt to shocks and plan for uncertainties [6].

Thus, responses to environmental change can be driven by a multitude of interrelated factors, which can be categorized into six broad domains: assets, flexibility, organization, learning, socio-cognitive constructs, and agency [5,6]. However, most studies focus on how people's adaptive behaviours may be influenced by a single domain of adaptive capacity, rather than simultaneously examining the six domains outlined above. Which domains should be prioritized in policies and programs aimed at reducing climate vulnerabilities [7,8] is therefore unclear, despite substantial interest and ongoing investments in building adaptive capacity among local and national governments, non-governmental organizations, and development agencies [6,19]. Furthermore, much of the existing work on the relationship between adaptive capacity and adaptive behaviour has relied on hypothetical or intended responses to future impacts, rather than people's actual responses to change [7]. As a result, our understanding of how diverse domains of adaptive capacity simultaneously interact to shape realized responses to climate change remains limited [8].

A large body of work describes climate change adaptation as comprising a diversity of responses ranging from minor/moderate or incremental changes to existing practices and behaviours (often referred to as 'incremental adaptation', or simply 'adaptation'), to more fundamental changes that have the potential to create a new system or future (often referred to as 'transformational adaptation', or simply 'transformation') [20-23]. Yet debate remains regarding these concepts and when an action should be considered transformative as opposed to adaptive [21]. Following recent theoretical and empirical work in this area [20,23-25], we define adaptive actions as changes to existing practices or behaviours which allow existing social-ecological system structures to absorb, accommodate, or embrace change;

and transformative actions as more fundamental changes that can alter dominant social-ecological relationships and contribute toward the creation of a new system and/or future.

Both adaptive and transformative action are thought to be underpinned by adaptive capacity [20], yet the majority of the empirical work on adaptive capacity and responses to climate change has focused on adaptive action. Thus, a key unanswered question which we in part aim to address is whether different (or the same) capacities and domains of adaptive capacity are needed to enable transformative action.

Here, we sought to understand how the different domains of adaptive capacity drive varied household-level adaptive and transformative responses to climate change among a population (N = 138 of 140 households) on a tropical island in Papua New Guinea (Fig. 1a). Our study context is characteristic of many coastal and island communities across the global tropics in that the majority of households are primarily dependent on fishing and harvesting marine resources (particularly coral reef-associated resources) for livelihoods and food security, and the island is highly vulnerable to, and is indeed already experiencing the impacts of climate change; such as sea-level rise, coastal inundation and erosion [26], and disruptions to reef ecosystems and associated fisheries [27].

Fig. 1. Empirical context and examples of adaptive and transformative action. (a) An overhead view of the Papua New Guinean island where the research was conducted. (b) Construction of sea walls to protect existing land uses is an example adaptive action. (c) Engagement in atoll farming, a form of livelihood diversification which represented a fundamental departure from near complete dependence on traditional marine resource-based activities, is an example transformative action. Photo a by Dean Miller; photos b and c by Michele Barnes.

In this context, we integrate a full population census, semi-structured social surveys, key informant and expert interviews, observed fish landings, and published reports to document adaptive behaviours (Supplementary Table 1) and develop 20 key indicators (Table 1, Supplementary Tables 2-3; Fig. 2) representing the six broad domains of adaptive capacity (assets, flexibility, learning, organization, socio-cognitive constructs, and agency). Our indicators included social and economic characteristics, such as wealth and risk perceptions (Table 1, Supplementary Table 2), in addition to a household's position in a complex social-ecological network (Fig 2, Supplementary Table 3). Building on recent advances in network methodology (Autologistic Actor Attribute Models [28]), we then developed a multilevel social-ecological network modelling approach that enabled us to predict adaptive and transformative actions as a function of a household's adaptive capacity (Methods, Supplementary Methods). Adaptive actions included a range of behaviours such as technological fixes/mitigation (such as building sea walls, which in this case were considered adaptive in nature because the walls were built to protect existing land uses and they did not require major engineering projects; see Fig. 1b), adapting or intensifying fishing practices and effort, and seeking knowledge/creating awareness about climate change. Transformative actions included livelihood diversification that represent a fundamental departure from near complete dependence on traditional marine resource-based activities (i.e., engaging in atoll farming; Fig. 1c), and active engagement in long-term planning specifically aimed at managing climate change impacts on the community (e.g., developing novel community response plans and/or resettlement schemes, which in this case represented a departure from more general community planning which occurs regularly).

Table 1. Indicators of adaptive capacity. See Methods and Fig. 2 for further detail on individual indicators. Descriptive statistics are provided in Supplementary Table 2 and 3.

Adaptive Capacity Domain	**Indicators**	**Description**
Assets	1. Wealth 2. Access to credit 3. Remittances	Total value of household structures and possessions Access to credit through formal or informal means, e.g., banks/institutions, friends/family Remittance payments from family members living or working off island
Flexibility	4. Occupational multiplicity 5. Technological diversity 6. Age	Total number of different livelihood activities that bring food or money into the home Total number of different types of fishing gears owned Age of the primary decision maker in the household
Organization	7. Trust in institutions 8-11. Social networks	Median of Likert-scale responses regarding trust in community leaders, local government, and police Four network measures capturing aspects of social capital and key social relationships: i. social connectivity, ii. social-ecological connectivity, iii. linking ties, iv. network exposure (see Fig. 3, b – e)
Learning	12-15. Social-ecological ties 16. Education	Four network configurations capturing key social-ecological relationships: i. social-ecological triangle, ii. ecological-social triangle, iii. social-ecological square, iv. open social-ecological square (see Fig. 3, f – i) Years of schooling

Socio-cognitive constructs	17. Past experience 18. Risk perception	Perception of severity of past climate change impacts compared to others on the island Perception that climate change impacts are getting better, worse, or staying the same
Agency	19. Active in decision-making 20. Power/influence	Actively involved in decision-making about marine resource management Perception of power and influence to change or guide the management of marine resources

[1] Note that assets are sometimes broadly defined to include social, human, and financial capital. Here, we focus on financial capital. Aspects of human and social capital are captured under other domains. For example, education (commonly referred to as a form of human capital) is an indicator of learning, and trust (commonly referred to as a form of social capital [18]) is an indicator of organization.

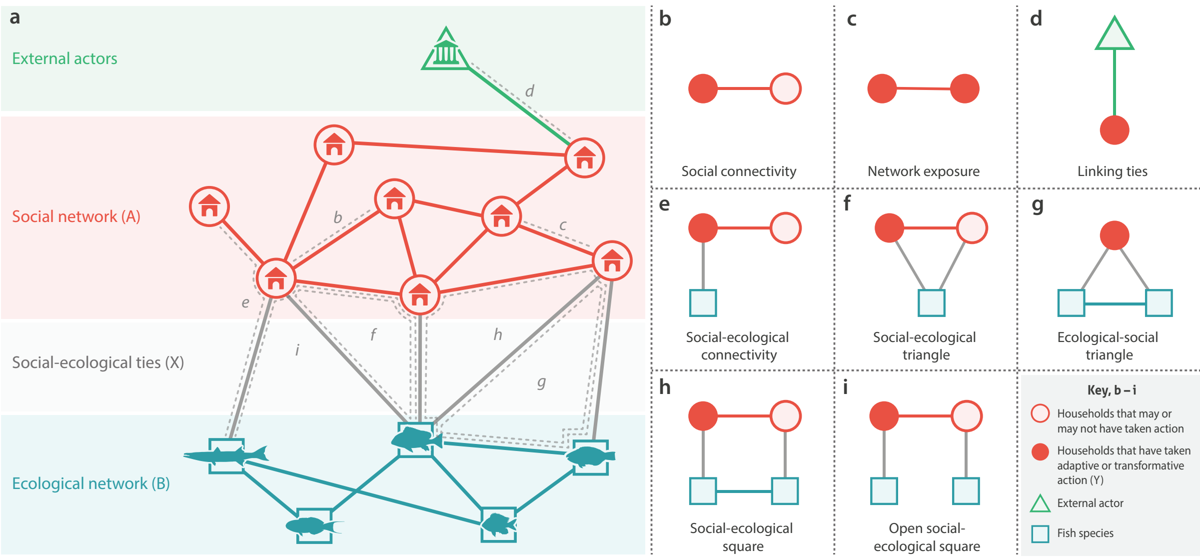

Fig. 2. The potential role of social-ecological networks on responses to climate change. (a) A graphical depiction of our social-ecological network capturing trophic interactions among coral reef fish species (ecological network – B, blue); communication relationships between coastal fishing households (social network – A, red); the links households have to specific fish species based on their fishing behaviours (social-ecological ties – X, grey); and the links households have to external actors (green), such as government officials or individuals working with non-governmental organizations. (b-i) Network configurations we hypothesize play a role in driving adaptive and transformative action (Y) in response to climate change by supporting the organization and learning domains of adaptive capacity; where (b) *social connectivity* captures connectivity in the social network which can provide access to information and resources [29], (c) *network exposure* captures social processes such as social influence via social network partners or the selection of network partners with the same beliefs or behaviours, both mechanisms which can play a key role in shaping human behaviour [30], (d) *linking ties* captures ties to external actors (e.g., government officials/NGO representatives/business leaders) which can provide access to a diversity of information and support [29], (e) *social-ecological connectivity* accounts for social connectivity that extends to the ecological system, (f) *social-ecological triangle* captures a form of social-ecological alignment [31,32] which may facilitate social learning about shared

ecological resources [15], (g) *ecological-social triangle* captures a form of social-ecological alignment which may help to build knowledge about interconnected resources and enable individuals to internalize ecological feedbacks [33,34]; (h) *social-ecological square* captures a form of social-ecological alignment which may enable social learning about interconnected resources and the internalization of ecological feedbacks [15], and (i) *open social-ecological square* captures linked households with many ties to divergent resources which may facilitate social learning about broader ecological trends [29,35]. Dashed lines in (a) represent examples of each of the network configurations (b-i); where two overlapping dashed lines are present, two different configurations are highlighted.

Exposure to others in social networks

We found that three key domains of adaptive capacity crosscut both adaptive and transformative action: organization, learning, and agency. First, we found that network exposure – related to the organization domain of adaptive capacity (Table 1, Fig. 2) – played a key role on both adaptive and transformative action (Table 2). Social networks have long been identified as a source of social capital that can act to support adaptation in the context of climate change (e.g., by providing access to resources and social support [14]), yet existing research has generally not considered the prospect of them having a more direct relationship with adaptive behaviour via network exposure. Interestingly, none of our network measures that are characteristic of social capital were significant in our model (e.g., connectivity, linking ties; Fig. 2); while network exposure was (Table 2).

Table 2. Key factors shaping adaptive and transformative action. Results from our Multilevel Autologistic Actor Attribute Models on (a) adaptive and (b) transformative action. N = 138 households. Goodness-of-fit tests demonstrate that these models provide a good fit to the empirical data (Methods, Supplementary Methods). Conditional log-odds are presented in Supplementary Table 5.

Effects	Effect term in MPNet	Parameter	Stderr	t-ratio	SACF
a. Adaptive action					
Density (akin to constant)*	DensityA	-3.5651	1.1445	0.0938	-0.0373
Education*	---	0.1917	0.0976	0.0782	-0.0357
Past experience*	---	1.3911	0.5888	0.0368	0.0826
Active in decision-making	---	0.5419	0.4807	0.0298	-0.0525
Power/influence*	---	1.2722	0.4923	0.0792	-0.0031
Social connectivity_a[1]	ActivityA	-0.1680	0.1380	0.0594	-0.0435
Social connectivity_b[1]	Ego-2StarA	0.0098	0.0082	0.0349	-0.0216

Network exposure*	ContagionA	0.3286	0.1099	0.0661	-0.0518
Social-ecological connectivity	Star2-AX-EgoA	-0.0086	0.0073	0.0524	-0.0276
Social-ecological triangle	TXAX-1A	0.0072	0.0153	0.0430	-0.0104
Ecological-social triangle	TXBX-A	0.0090	0.0184	0.0562	0.0360
Closed social-ecological square*	C4AXB-1A	-0.0070	0.0042	0.0487	-0.0078
Open social-ecological square*	L3XAX-1A	0.0013	0.0006	0.0579	-0.0312
b. Transformative action					
Density (akin to constant)*	DensityA	-3.9734	1.3126	0.0087	-0.0564
Remittances	---	0.7324	0.4661	-0.0008	-0.0652
Age	---	0.0148	0.0169	0.0231	-0.0472
Linking ties	---	0.0947	0.0682	0.0189	-0.0543
Active in decision making	---	0.6599	0.5058	0.0646	-0.0320
Power/influence*	---	-1.1345	0.5832	0.0423	-0.0218
Social connectivity_a[1]	ActivityA	0.0705	0.1251	0.0341	-0.0670
Social connectivity_b[1]	Ego-2StarA	-0.0024	0.0071	0.0299	-0.0532
Network exposure*	ContagionA	0.2460	0.1235	0.0347	-0.0755
Social-ecological connectivity	Star2-AX-EgoA	-0.0019	0.0065	0.0017	-0.0929
Social-ecological triangle	TXAX-1A	0.0037	0.0151	0.0075	-0.0705
Ecological-social triangle*	TXBX-A	0.0366	0.0172	0.0036	-0.0612
Closed social-ecological square	C4AXB-1A	-0.0022	0.0041	0.0168	-0.0819
Open social-ecological square	L3XAX-1A	0.0000	0.0006	0.0116	-0.0914

* indicates significance at the 10% level

[1] Our model specification follows a general hierarchy of complexity, with both the interaction effects between the outcome variable and the network activity effect (ActivityA, or 'social connectivity_a') and a star effect (Ego2StarA, or 'social connectivity_b') included to capture social connectivity.

'Network exposure' captures social processes that result in observed 'homophily', which is the propensity for like-minded people to be connected [36]. There are two ways to interpret our network exposure term: social influence, whereby households are influenced by those they are exposed to in their social networks; and social selection (also referred to as 'choice homophily'), whereby households preferentially choose to interact with households similar to themselves (i.e., like attracts like). An analysis of a subset of the social networks examined here from two distinct time periods shows that some communication partners and key social nodes (i.e., highly connected respondents) in our study community remain stable over time (Supplementary Methods). This suggests that our network exposure effect is likely capturing some degree of social influence (i.e., households are influenced by the adaptive and/or transformative behaviour of their network partners). Yet the full effect is likely a combination of social influence and social selection, which are known to co-occur [37].

Thus, our result that network exposure is significantly correlated with adaptive and transformative action (Table 2), indicates that adaptive behaviour is being reinforced, either through the formation of new ties (selection) or the changing attitudes in existing ties (influence). This result represents an example of cultural change [38,39] in response to climate change. Our results thus lend some weight to recent calls for the development and implementation of social influence approaches that use the power of networks to catalyse action in response to climate change [8]. Such approaches have proven to be successful in reducing bullying in classrooms [40], and our results suggest they may help to encourage adaptive and transformative action among those most vulnerable to the impacts of climate change. Caution in warranted in applying social influence approaches however, as some literature has shown that the co-occurrence of social influence and social selection can lead to segmented networks and polarization [37,39], where behaviours and opinions are divided amongst contrasting groups. Importantly, increasing polarization may create challenges for coordinating larger-scale (e.g., community-wide) adaptive and transformative action over time.

Social-ecological feedbacks and learning

Our second key result is that social-ecological network structures supporting the learning domain of adaptive capacity played a critical role on both of our studied responses. Specifically, socially linked households with many ties to divergent resources were more likely to have adapted than those linked to interconnected resources (combined effects of open social-ecological square and closed social-ecological square, Fig. 2; Supplementary Methods); whereas households directly linked to interconnected ecological resources (ecological-social triangle) were more likely to have transformed (Fig. 2; Table 2, Supplementary Table 5).

People are known to learn through different types of interaction and experience, both with the environment and with peers [35]. Our results indicate that social learning involving many independent resources (in this case households sharing and building knowledge with each other about several different fish species and potentially their different ecosystem functions and/or parts of the ecosystem they inhabit) may contribute understanding about broader ecological trends, thereby prompting households to adapt to changing environmental conditions. In contrast, our results suggest that knowledge built through personal connections with interconnected resources (personal learning about trophically linked fish species in this case) may enable people to internalize ecological feedbacks [34], catalysing more transformative action in response to environmental change. Given the complex, micro-level interactions likely to be occurring between two interlinked species, such ecological knowledge is likely gained through personal experience built up over years of observation and reflection [33], and people may not be consciously aware of it or how it impacts their behaviour [8].

The role of power

Our third key result provides evidence that perceived power – a key indicator of agency – plays a critical role when it comes to encouraging, or discouraging, adaptive behaviour. Specifically, we found that households that felt they had power or influence over decisions about marine resources (the primary source of income and food) were more likely to adapt, but less likely to transform (Table 2, Supplementary Table 5). Moreover, power played a disproportionate role on the adaptive behaviour of households with less exposure to others who had taken action in response to climate change (Fig. 3, Methods, Supplementary Methods). By definition, transformative action supports moves to reorder social-ecological relationships, thereby challenging existing structures [20,23,25]. Yet people can be resistant to fundamental change, particularly those in powerful positions who may stand to lose from such changes, which often involve shifts in power [8,25]. Our results thus critically underscore the importance of carefully considering the role of local power dynamics in shaping responses to climate change, as these dynamics can affect the ability of people, communities, and entire social-ecological systems to deal with dramatic change which may require more fundamental action extending beyond what is typically understood as adaptive in order to sustain livelihoods and ecosystems [15,25].

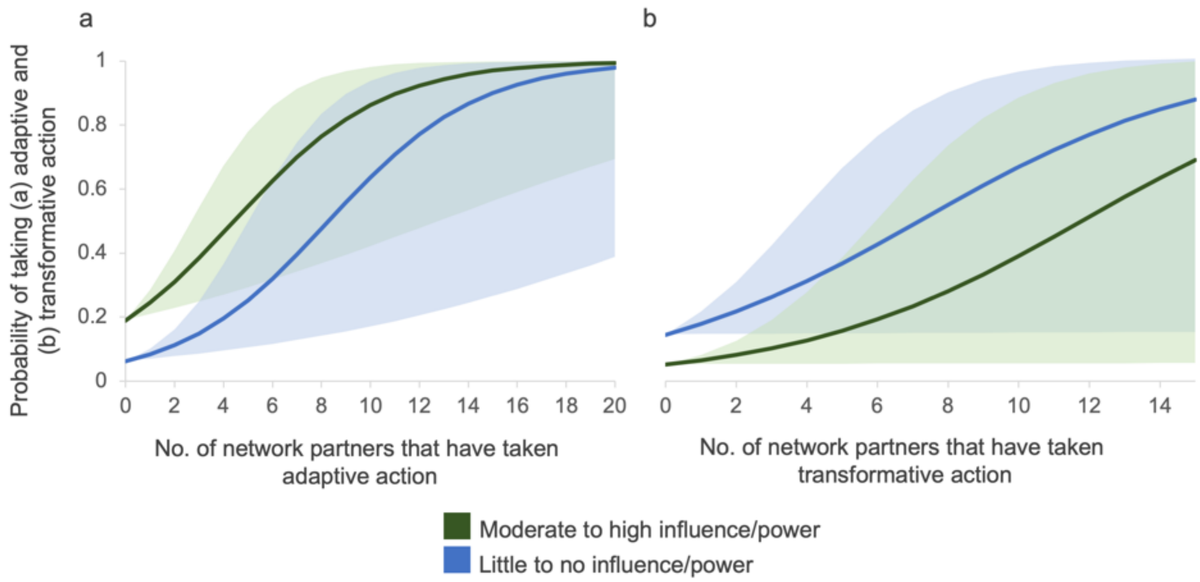

Fig. 3. The impact of power and network exposure on adaptive and transformative behaviour. Differences in the probabilities of taking (a) adaptive and (b) transformative actions depending on the number of network contacts a household has that is also engaged in similar action(s), and the perceived power or influence a household has over decisions about marine resource management. Shaded regions represent 95% confidence intervals calculated based on the estimated standard error for the network exposure effect.

Surprisingly, we found that none of our indicators of flexibility or financial assets were significantly related to adaptive or transformative action (Table 2, Supplementary Table 5). In line with recent research highlighting the important, yet often overlooked role of socio-cognitive constructs in supporting adaptive behaviour [7,8], we also found that perceptions of past experience with more severe impacts were significantly related to adaptive action. Yet neither of our indicators of the socio-cognitive domain were significantly related to transformative action. Developing a better understanding of when and how transformative action may be shaped by past experience, and other socio-cognitive factors like risk perception, is an area ripe for future research.

Conclusion

Financial assets have long been emphasized as a crucial component of adaptive capacity [3,4]. As such, many adaptation programs have focused heavily on building financial assets as well as fostering the flexibility for people, households, and communities to adjust to current and future changes [6,41]. By simultaneously examining six domains of adaptive capacity, we show that adaptation programs that focus heavily on building financial assets could benefit extensively if they accounted for the organization, learning, and agency domains of adaptive capacity. Case studies, such as ours of a Papua New Guinean tropical island community, are critical to building the evidence base on complex social-ecological interactions and how they relate to human behaviour [42]. We therefore believe our results are likely to be of wide interest and may have relevance to other similar contexts. Indeed, many island communities around the globe, particularly across the tropics, face similar climate change challenges and need the capacity to adapt. In this context, our results suggest that harnessing the influence of networks, facilitating individual and social learning, and carefully considering power dynamics could add considerable value to existing approaches aimed at reducing climate vulnerabilities.

Methods

Summary of empirical strategy. This research was conducted in a low-lying coral island in the Manus province of Papua New Guinea. The island is home to a population of approximately 700 people living in 140 households. To understand responses to climate change in this context, we collected a combination of quantitative and qualitative interdisciplinary data including a full population census, semi-structured social surveys with household heads as representatives of their household (N = 138 out of 140 households), key informant interviews (N = 3), and observed fish landings (N = 2469 individual fish). We also constructed full social-ecological networks akin to Fig. 3A using information from our census, semi-structured surveys, fish landings data, expert knowledge, and published reports. Using this information, we employed novel multilevel network modelling methods in order to simultaneously test how adaptive and transformative action were shaped by twenty key indicators of six broad domains of adaptive capacity, including a household's position in a complex social-ecological network and the behaviour of other households in the network (i.e., network exposure [30]). The census, surveys, and interviews were conducted from May – June 2018 in the local language.

Responses to climate change. A broad understanding of responses to climate change among island households was gained via key informant interviews. We captured specific household-level responses in our semi-structured surveys by pooling information from two questions: (1) we directly asked households whether they had made any changes in response to the impacts of climate change; and if so, we asked them to recall what those changes were; and (2) we asked about specific livelihood activities that brought food or money into the household. (2) was included because key informants identified atoll farming as a response to climate change, which was initially introduced on the island by The Nature Conservancy (TNC) in 2017 as an alternate food and income source (see [43]). Historically there had been little to no engagement in agriculture due to land shortages and poor soil quality, and the island community had been almost entirely dependent on fishing and related activities. Responses were coded as adaptive and/or transformative following the definitions in the main text (see Supplementary Methods and Supplementary Tables 1 and 2 for a summary and descriptive statistics of identified responses). We gathered additional information directly from TNC about how atoll farming was introduced on the island in order to ensure it did not introduce any bias into our results. We found that many who were initially trained in atoll farming methods through the TNC initiative (6 months prior to our fieldwork) either did not adopt and/or continue the practice; yet the activity spread well beyond those initially trained (Supplementary Methods). Importantly, attending a training session was not meaningfully correlated with our transformative action variable ($r = 0.15$) nor was it is significant ($p = 0.12$) in a binary logistic regression on our transformative action variable that included our social and economic indicators of adaptive capacity (Table 1, Supplementary Methods).

Constructing the social-ecological networks. We collected detailed social network data capturing both informal and fishing-related communication relationships between households on the island (i.e., the social network *A*, Fig. 3). We first conducted a full census of the island. We then asked respondents (the household head, typically male) (1) who they sat and talked with a big community events or gatherings (e.g., church, the weekly soccer game, or community meetings), (2) who the female/other household head sat and talked with at big community events or gatherings (e.g., church, the weekly soccer game, or community meetings), and (3) who they shared important information and advice with about fishing and fishery management (e.g., rules, gears, and fishing locations). The census ensured we were able to link all individuals nominated in the network to specific households. Due to the undirected nature of the communication ties [(1) and (2) above], all social ties were symmetrized and treated as undirected, with edges representing communication relationships between household-level nodes (Supplementary Figure 1, Supplementary Methods). We also asked about the relationships households had with external actors (such as government officials, non-government organizations, and business leaders). Ties to external actors were summed and treated as the node-level attribute 'linking ties' (Fig. 3d).

The island is primarily a fishing community, with fish comprising the primary source of both income and protein. The ecological network (*B*, Fig. 3) thus captures trophic interactions (i.e. predator-prey relationships) among target fish species comprising the majority of catch by all fishing gears employed on the island with the exception of gillnets, which were excluded due to strong traditional customs that limit when gillnets can be used and by whom (N = 60 species, Supplementary Methods). Target species for each gear type were identified using detailed catch surveys collected in the same timeframe the social surveys were performed (Supplementary Methods). Trophic interactions capturing predator-prey relationships among the 60 primary target fish species were estimated based on a combination of diet, relative body size, and habitat use (likelihood of encounter, Supplementary Methods) [44]. The corresponding ecological network was thus undirected, with edges representing trophic interactions between fish species (Supplementary Figure 1). Social-ecological ties (*X*, Fig, 3) were identified by linking individual fish species to households via the fishing gears they used, as identified in our semi-structured social surveys. In other words, if household A_i used gear type G_t, which targets fish species B_u, a social-ecological link would exist between household A_i and fish species B_u.

Capturing each domain of adaptive capacity. We developed 20 key social, economic, and social-ecological network indicators (Table 1, Fig. 3) to capture the six broad domains of adaptive capacity [5,6]: (1) assets, (2) flexibility, (3) organization, (4) learning, (5) socio-cognitive constructs, and (6) agency. Descriptive statistics of all indicators are provided in Supplementary Tables 2 and 3.

(1) Assets. We focused on financial assets by measuring wealth, access to credit, and remittances. We used a material style of life index for *wealth* [45] that included measurements of housing materials (e.g., types of roofing, walls, and floors) and material assets (e.g., boats, generators, solar panels, and agricultural assets like chickens [46]). A*ccess to credit* was a binary variable measuring whether households had access to credit through formal (i.e. banks and financial institutions) or informal (e.g. friends and family) means. *Remittances* was a binary variable measuring whether the household receives remittance (cash) payments from family off-island, of any amount or frequency.

(2) Flexibility. We measured technological diversity (i.e. flexibility within fishing livelihoods), occupational multiplicity (i.e. having two or more livelihood options), and the *age* of household heads. Age of primary decision-makers was included because it has been shown to influence planning horizons, skills, experience [47,48], behavioural barriers [49], and the propensity to adopt innovations [50] in ways that influence adaptive strategies [24]. *Technological diversity* measured the number of different types of fishing gears (e.g. spear gun, net) owned by a household [9]. *Occupational multiplicity* was the total number of livelihood activities that brought food or money into the household (with the exception of atoll farming, which was captured as one of our transformative responses).

(3) Social organization. We measured levels of trust in institutions. We also used four network configurations capturing aspects of social capital (defined here as including networks, norms, and trust [16,17] and key social relationships: i. social connectivity (how well connected households were in the social network, which can provide access to information and resources [29]; Fig. 3b); ii. social-ecological connectivity

(which extends the idea of social connectivity to the ecological system [15]; Fig. 3e); iii. linking ties (ties to external actors, which can provide access to a diversity of information and support [29]; Fig. 3d), and iv. exposure via network contacts ('network exposure', which can capture effects of social influence [30] and social selection; Fig. 3c). For *trust in institutions*, we calculated a continuous indicator based on the median of three Likert-scale questions that gauged how much household heads trusted locally-relevant institutional actors (i.e., those who would be responsible for supporting and/or safeguarding adaptive and transformative actions); these were community leaders, local government, and police [9]. *Linking ties* was a continuous variable capturing the number of relationships the household had with external actors, such as government officials, non-government organizations, and business leaders (Fig. 3d). We used a continuous indicator because as the number of external ties increase, so too does the potential exposure to outside ideas and influence. *Social connectivity*, *social-ecological connectivity*, and *network exposure* were measured using structural parameters in our multilevel network model (see 'Modelling procedure' below).

(4) Learning. We measured years of formal schooling of household heads (*education*, which can help train people to learn [51,52]); and used four network configurations capturing the manner in which households are connected with ecosystems and each other, which can facilitate social and individual learning about ecological states and trends [15]. These were: i. social-ecological triangle (where households linked to the same resource are socially connected, which may facilitate social learning about shared ecological resources [15,31]; Fig. 3f), ii. ecological-social triangle (where a household is connected to two interdependent resources), which may help to build knowledge about interconnected resources and provide the necessary structural foundation for households to internalize ecological feedbacks [34], Fig. 3g), iii. social-

ecological square (where socially connected households are connected to interdependent resources, which may enable social learning about interconnected resources and provide the necessary structural foundation for the internalization of ecological feedbacks [15,34]; Fig. 3h), and iv. open social-ecological square (which captures linked households with many ties to divergent resources which may facilitate social learning about broader ecological trends [29,35]; Fig. 3i). These hypothesized configurations were identified in existing literature (e.g., [6,15]) and further developed through a workshop conducted in 2018. We measured them using structural parameters in our multilevel network model (see 'Modelling procedure' below).

(5) Socio-cognitive constructs. We measured both past experience and future risk perceptions because existing research has demonstrated that adaptive behaviour is often positively correlated with the physical closeness and/or intensity of previous related experiences [13] and the perceived severity of future impacts (risk appraisal) [12,53]. *Past experience* was a binary indicator of previous experience with severe climate change impacts. We used a relative measure based on whether household heads (as representatives of their household) felt they had been impacted by climate change worse than most others in the community (1), compared to whether they felt they had been impacted the same or less than others (0). A relative measure for past impacts was used because research in psychology on risk and social comparison suggests that people often compare their relative standing to others in order to form judgements [54], and the manner in which people view the impacts of climate change are often socially mediated [55]. *Future risk perception* was a binary indicator measuring whether households felt that climate change impacts were getting worse (1), compared to staying the same or improving (0).

(6) Agency. We measured active (involvement) in decision-making and perceived power/influence over decision-making [56]. *Active in decision-making* was a binary variable measuring whether household heads were actively involved in decisions about marine resources (1), as opposed to only being passively involved (e.g. attended meetings but did not speak) or not involved at all (0). *Power/influence* was a binary indicator that captured whether household heads felt they had some or lots power/influence over decisions about marine resources (1), or little or no power/influence (0).

Modelling procedure. We employed novel multilevel network modelling methods that explicitly account for network dependencies in order to simultaneously test how adaptive and transformative action were shaped by our indicators described above. We took a two-stage approach to our analysis to ensure these models were not overparametrized. Firstly, we ran logistic regression models on adaptive and transformative action including all non-(structural) network indicators of adaptive capacity (indicators 1 – 7, 10, and 16 – 20 in Table 1). Structural social and social-ecological network effects (i.e., indicators 8 – 9 and 11 – 15 in Table 1, which are depicted as network configurations in Fig. 3b – c and e – i) could not be included at this stage because they can only be modelled using specific network-based models that account for the structure of the multilevel social-ecological network and the interdependencies among the adaptive or transformative actions of networked actors (households in this case). Linking ties (indicator 10 in Table 1 and depicted in Fig. 3d) was included in the initial logistic regressions because it was measured as continuous covariate (and treated as a node-level attribute), as described above. Results of our logistic regressions are included in Supplementary Table 4. All indicators that were significant at the 10% level were included as candidate predictors in our final multilevel network models. We choose a significance level of 10% in order to reduce the chance that a potentially important indicator was overlooked in our final models. Following this criteria, the following non-structural network indicators (i.e., node-level attributes) were included in our final multilevel network models: (a) for adaptive action: education, past experience, active in decision-making, and power/influence; (b) for transformative action: remittances, age, linking ties, active in decision-making, power/influence.

Secondly, in our final models we extended the current functionality of the Autologistic Actor Attribute Model (ALAAM) [28] to account for a complex, multilevel (social-ecological) network structure (Supplementary Methods). ALAAMs model the behaviour of network actors as a function of the network structure and other actor (node-level) attributes (or covariates). Compared with traditional logistic regression, ALAAMs explicitly account for network positions as well as how the behaviour of networked partners may be dependent on one another (i.e., network exposure). For multilevel networks, we used ALAAM to test how the relationships defined in the social and ecological system affected individual household's behaviour, with effects represented by network configurations Fig. 3b, d - i. We label the outcomes or actors who have taken the actions as (Y), the social network as (A), the ecological network as (B), meso-level social-ecological interactions as (X), and other actor attributes (i.e., other non-network indicators of adaptive capacity) as (Y^c). The multilevel ALAAM can thus be expressed as

$$\Pr(Y = y | A, B, X, Y^c) = \frac{1}{\kappa} \exp \sum_Q \theta_Q z_Q(Y, A, B, X, Y^c)$$

where $z_Q(Y, A, B, X, Y^c)$ are graph statistics counting the number of the configurations of type Q as listed in Figure 2. θ_Q are parameters determining the predominance of various configurations contributing to the overall outcome (Y). A positive and significant parameter estimate suggests the corresponding configuration occurs more than we expect by random conditioning on the rest of the model, whereas negative estimates mean the opposite. κ is a normalizing constant which allows the ALAAM to follow a proper probability distribution. We estimated the ALAAM parameters using Markov Chain Monte Carlo (MCMC) maximum likelihood methods [57] implemented in the MPNet software [58]. Following [59,60], model convergence and goodness of fit (GOF) tests were assessed using the procedure presented by Koskinen and Snijders [61], which compares the observed network statistics with simulated samples from the converged model using t-ratios as testing statistics, where t-ratios smaller than 0.1 in scale indicate model convergence. Though this procedure is most commonly known for its application to exponential random graph models (ERGMs), an ALAAM can be considered as a special case of a bipartite ERGM for a *n* (individual) by 1 (outcome) bipartite network, while using the one-mode *n* by *n* network as a covariate [28]. The definitions of the various configurations in ALAAMs and ERGMs can be the same, and the estimation and GOF test techniques applied in ERGMs are equally applicable to ALAAMs [58], with the implementation in MPNet sharing the same technical approaches [58]. Table 2 presents full model results for our ALAAMs on adaptive and transformative action.

Model interpretation. The estimated effects in our ALAAMs can be interpreted as the predominance of various attributes and social-ecological network positions affecting individual household's adaptive behaviour. Using the network exposure effect as an example, it has a positive and significant estimate in both of our final models (Table 2), suggesting a household is more likely than we would expect at random (given the rest of the model) to have taken adaptive and/or transformative action if they are connected to network partners that have taken similar actions. This is a general statement across the overall network. Fig. 4 compared households whom feel they have power or influence over decisions about marine resources verses others in terms of their adaptive and transformative action taking probabilities depending on the number of network partners they have who have taken similar action, given all else being equal, such as average education levels or average numbers of social-ecological squares a household is involved in. The probabilities are calculated by the original likelihood $\Pr(Y_i = 1|X, Y^c) = 1/\left\{1 + \exp\left\{-\left(\theta_{density} + \theta_Q z_Q(Y_i, X, Y^c)\right)\right\}\right\}$, where $z_Q(Y_i, X, Y^c)$ is the number of configuration of type Q node i is involved. As we can see from Fig. 4**,** having different numbers of network partners that have taken action will have different associations with the probabilities for a household to have undertaken adaptive and/or transformative action themselves.

Ethics statement. Research protocols were approved by the Human Ethics Committee at James Cook University. Informed consent was obtained from all respondents.

Data Availability. Summary data that support the findings of this study are available within the paper and its Supplementary Information file. Raw ecological network data have been deposited in the Tropical Data Hub and can be accessed at https://doi.org/10.25903/5ecf39990a0bb. Raw social and social network data are available upon request from the corresponding author M.L.B. with reasonable restrictions, as these data contain information that could compromise research participant privacy and consent.

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