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RESEARCH ARTICLE

'Bunkering down': How one community is tightening social-ecological network structures in the face of global change

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Abstract

1. Complex networks of relationships among and between people and nature (social-ecological networks) play an important role in sustainability; yet, we have limited empirical understanding of their temporal dynamics.
2. We empirically examine the evolution of a social-ecological network in a common-pool resource system faced with escalating social and environmental change over the past two decades.
3. We first draw on quantitative and qualitative data collected between 2002 and 2018 in a Papua New Guinean reef fishing community to provide contextual evidence regarding the extent of social and environmental change being experienced. We then develop a temporal multilevel exponential random graph model using complete social-ecological network data, collected in 2016 and 2018, to test key hypotheses regarding how fishing households have adapted their social ties in this context of change given their relationships with reef resources (i.e. social-ecological ties). Specifically, we hypothesized that households will increasingly form tight-knit, bonding social and social-ecological network structures (H1 and H3, respectively) with similar others (H2), and that they will seek out resourceful actors with specialized knowledge that can promote learning and spur innovation (H4).

4. Our results depict a community that is largely 'bunkering down' and looking inward in response to mounting risk to resource-dependent livelihoods and a breakdown in the collaborative processes that traditionally sustained them. Community members are increasingly choosing to interact with others more like themselves (H2), with friends of friends (H1), and with those connected to interdependent ecological resources (H3)—in other words, they are showing a strong, increasing preference for forming bonding social-ecological network structures and interacting with like-minded, similar others. We did not find strong support for H4.
5. Bonding network structures may decrease the risk associated with unmonitored behaviour and help to build trust, thereby increasing the probability of sustaining cooperation over time. Yet, increasing homophily and bonding ties can stifle innovation, reducing the ability to adapt to changing conditions. It can also lead to clustering, creating fault lines in the network, which can negatively impact the community's ability to mobilize and agree on/enforce social norms, which are key for managing common resources.

KEYWORDS
adaptation, coastal communities, social capital, social network, temporal exponential random graph model, transformation

1 | INTRODUCTION

Communities around the globe are facing unprecedented social and ecological change, including rapid population growth, advances in technology and deteriorating environmental conditions (Berkes, 2017; Steffen et al., 2015). Episodic shocks and surprises are becoming more frequent as the global community grapples with the COVID-19 pandemic; extreme climatic events, such as cyclones, wildfires and floods; and rapid social and economic changes (Diffenbaugh et al., 2017; van Barneveld et al., 2020). The ways in which people respond and adapt to these changes has important implications for long-term sustainability because ecosystems and the people who depend on them are inextricably linked (Anderies, 2015; Boonstra et al., 2016; Folke et al., 2010; Reyers et al., 2018). Yet, how people respond to and shape periods of change and how society reorganizes following change are still poorly understood (Folke, 2017). This is particularly important in the light of the many contemporary calls for the need of societies to transform toward sustainability. Without a better understanding of the various social processes that could inhibit or assist such fundamental changes, it will be difficult to provide informed guidance on how transformative changes can be accomplished (Scoones et al., 2020).

One way to view and understand the interlinked dynamics between people and nature is through a social-ecological network perspective (Bodin et al., 2019; Kluger et al., 2020; Schlüter et al., 2019). Social-ecological networks consider actors and biophysical entities as components of the same system (i.e. a social-ecological system) and emphasize their interactions and dynamics (Bodin & Tengö, 2012; Janssen et al., 2006; Sayles et al., 2019). Following this approach, the social domain is conceived as a set of social actors and key relationships (i.e. social networks) between them (Figure 1), such as communication or resource sharing between individuals (Barnes, Bodin, et al., 2019), households (Baggio et al., 2016) or organizations (Bodin et al., 2019). Similarly, the biophysical domain represents sets of key biophysical components and their interlinkages (Figure 1), such as trophic interactions between fish species (Bodin & Tengö, 2012), or free surface hydraulic connections between watersheds (Sayles & Baggio, 2017). Finally, the social-ecological network perspective also captures important interactions and feedbacks between the social and biophysical domains (Figure 1), such as resource extraction (Barfuss et al., 2017) or environmental management actions (Sayles & Baggio, 2017). This approach therefore explicitly highlights social-ecological interdependencies by examining how actors within the social domain are connected with each other and with components in the biophysical domain, and how, in turn, biophysical components are connected. As such, the social-ecological network approach allows for a rather comprehensive analysis regarding how social actors and biophysical entities interact and feedback on each other in different ways.

A growing body of research demonstrates that social networks play a key role in the sustainability of social-ecological systems because they support important social processes that underpin social and ecological outcomes; such as learning, cooperation, and innovation (Bodin & Crona, 2009; Groce et al., 2019; Partelow, 2021;

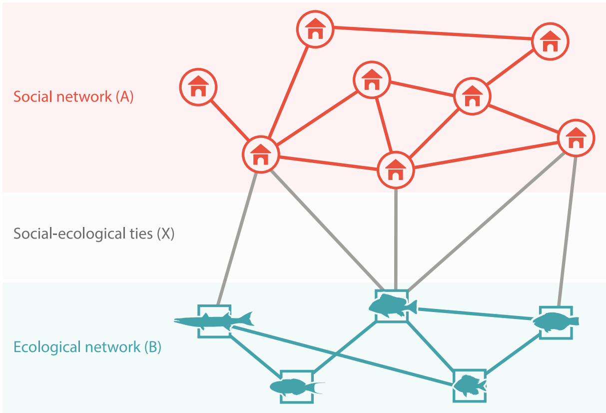


FIGURE 1 An illustrative example of a small-scale fishing community conceptualized as a social-ecological network. The social network (A) captures key communication relationships between fishing households. The ecological network (B) captures trophic interactions among target fish species. Fishing households are linked to the fish species they target (X; social–ecological ties) depending on the type of fishing gear they use. The multilevel network structure (A, B, X) identifies dependencies that exist within the system (Wang et al., 2013), illuminating how features of social and ecological systems are interrelated both within and across levels (note that conceptually this structure can also be understood as multiscale; Glaser & Glaeser, 2014). Smaller network building blocks, or key 'network configurations' (Table 1), form the foundation for the larger social-ecological system structure. Figure adapted from Barnes et al. (2020).

Pretty, 2003). Recent research has extended these insights to show that certain patterns or structures in *social-ecological networks* (i.e. social-ecological 'network configurations', see Table 1) can also be critical for sustainability (Kluger et al., 2020). For example, closed, 'bonding' network structures that link social actors and ecological resources (e.g. 'social-ecological triangle', Table 1) can support ecosystem health (Barnes, Bodin, et al., 2019; Bodin et al., 2014) and social adaptation (Barnes et al., 2017) by providing a foundation for cooperation over shared or interdependent resources. Bonding social-ecological structures can also play an essential role in adaptive approaches for regional ecosystem management, which tend to rely on collaboration among diverse actors to coordinate the implementation of multiple management actions at different scales (Guerrero et al., 2015). Existing research also suggests that when actors linked to many divergent ecological resources communicate with each other ('open social-ecological square', Table 1), this communication can promote adaptation by stimulating social learning (Barnes et al., 2020).

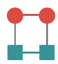
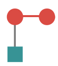
Although this body of research has been critical in beginning to build the knowledge base regarding the important role of social-ecological networks in supporting sustainability outcomes, it has largely been limited to cross-sectional data representing snapshots in time. Yet social and ecological networks are dynamic and known to evolve: over time some ties emerge and some ties dissolve (Doreian & Stokman, 1997; Olesen et al., 2008). Social networks often evolve in predictable ways driven by structural network properties and the characteristics of network actors; for example, people tend to form ties with friends of friends (i e. 'triadic closure'; Cartwright & Harary, 1956) and with similar others (i.e. 'homophily'; McPherson et al., 2001). Yet, when faced with social and ecological change, for example as resources become depleted, human populations increase, or a system becomes more integrated with global markets, people may choose to adapt their social relationships and their interactions with resources in distinct ways. Indeed, a handful of studies have argued that forming or re-forming (i.e. activating) social ties to gain access to information, resources and other forms of support can serve as an important climate adaptation strategy (Adger, 2003; Eriksen & Selboe, 2012; Erikson & Occhiuto, 2017) (Li & Tan, 2019; Nagel, 2020). Micro-level network adaptations made in response to change (broadly defined) can scale up to affect larger system structures, which in turn can affect social and ecological outcomes (Barnes et al., 2016). How people choose to adapt their relationships in response to drivers of change therefore has the potential to alter a system's trajectory—potentially steering it toward, or away from critical sustainability thresholds (Baggio & Hillis, 2018; Dakos et al., 2015; Janssen et al., 2006; Ringsmuth et al., 2019). Despite the importance of these dynamics, especially given the commonly argued need to initiate and nurture transformational changes toward sustainability (Westley et al., 2011), empirical information on how social-ecological networks evolve in the face of change remains nascent.

In this paper, we contribute to filling this gap by employing novel multilevel (Wang et al., 2013), temporal network analytic techniques to examine the dynamics of a social-ecological network characterizing a Papua New Guinean small-scale fishing community. As we discuss in the following section, the community we conduct our work in has experienced substantial ecological and social change over the past two decades, which has increased pressure on common-pool fishery resources and the ecosystem's ability to support people's livelihoods. In this context, we draw on comprehensive social and ecological data collected at multiple intervals over time to ask: in light of these escalating social and ecological changes, how do people adapt their social ties given their relationships with ecological resources (i.e. their social-ecological networks)?

2 | THEORETICAL FOUNDATION AND HYPOTHESES

How people chose to form ties—and the emergent, larger network structures these decisions create—has been the subject of a large body of literature in the social network sciences (Alexander et al., 2018; Lusher et al., 2012; Rivera et al., 2010). For example, research has shown that network tie formation often relies on individual attributes or characteristics; for example people may seek to establish ties with highly resourceful actors or with others more similar to themselves along some trait or set of traits ('homophily'; McPherson et al., 2001). The structural characteristics of existing networks can also influence tie formation; for example, people

TABLE 1 Social-ecological network structures. Network structures (i.e. configurations) of interest in this study are described and depicted. Red circles represent social nodes (fishing households in our empirical example) and blue squares represent ecological nodes (fish in our empirical example). The hypothesis that each configuration corresponds to is listed in the first column (e.g. H1 = hypothesis one)

Name	Configuration[a]	Description
Social network closure; H1		Social actors form closed social triangles (a friend of my friend is also my friend), argued to reflect bonding social capital and support cooperation and learning (Burt, 2005; Berardo, 2014a; Prell & Lo, 2016)
Social network centralization; H1[b]		Social actors form ties with popular others in the network, creating centralized structures argued to reflect bridging social capital and support coordination (Berardo, 2014a; McAllister et al., 2017)
Homophily; H2		Social actors form ties with others who are similar to themselves (i.e. they have the same attribute, such as clan members forming ties with others who are also members of their clan)
Social-ecological triangle; H3		Social actors linked to shared resources form ties with each other, which can enable cooperation (Bodin & Tengö, 2012; Barnes, Bodin, et al., 2019). Argued to reflect 'social-ecological bonding capital' (Barnes et al., 2017)
Closed social-ecological square; H3		Social actors connected to interdependent resources form ties with each other, which can encourage coordination and help people to recognize ecological feedbacks (Bodin et al., 2014)
Activity; H4		Social actors with specific attributes (i.e. elders, leaders and the wealthy) become more active in the network; that is, they attract more ties
Social-ecological brokerage; H4		Social actors connected to many resources become more active in the social network, enabling them to share diverse knowledge acquired through engagement with multiple resources (Barnes et al., 2017)
Open social-ecological square; H4		Social actors linked to independent resources form ties with each other, which can facilitate learning about broad ecological trends (Barnes et al., 2020)

[a] The idea that networks can be described in terms of the prevalence of small network substructures goes back to the foundations of social network analysis (Holland & Leinhardt, 1970; Moreno & Jennings, 1938), where these substructures were referred to as 'configurations'. More recently, the same idea has been discussed in the context of biological networks as the analysis of network 'motifs' (Milo et al., 2002).

[b] Under H1, we would expect more bonding structures rather than bridging structures to emerge; meaning we would expect *not* to see a positive, significant parameter for social network centralization.

are more likely to form ties with friends of friends ('triadic closure'; Lazarsfeld & Merton, 1954) and with highly active or popular others ('preferential attachment'; Barabási & Albert, 1999). Other exogenous contextual factors, such as spatial proximity or the unique characteristics of specific cultures, may also affect the emergence of social ties (Rivera et al., 2010). From a network perspective, less is known about how relationships with the ecological environment, and the interdependencies these create between people and ecosystems, factor into these decisions (but see Barnes, Bodin, et al., 2019; Bodin & Tengö, 2012); or about how people may choose to shift their social relationships when faced with different scenarios of change.

Here, we draw on and extend the 'risk hypothesis' (Berardo & Scholz, 2010) to propose three hypotheses regarding how social-ecological interdependencies may relate to people's decisions to form social ties. In doing so, we propose that the manner in which people are embedded within a complex social-ecological system, and the risk that they face in regard to sustaining their livelihoods dependent on this system, will impact on their decisions regarding tie formation—ultimately impacting how the structure of the social-ecological network evolves.

To understand the arguments we put forth, it is first critical to understand the context of a 'cooperation problem', which is present in our study community as well as many other environmental management and policy contexts across the globe. We will describe the context of a cooperation problem using our study community as an example. The community in which we conduct our work is highly marine-resource dependent, with members relying primarily on fishing and other marine-related activities (i.e. gleaning) to support their livelihoods. Akin to other small-scale fisheries across the tropics (Alexander et al., 2018; Jupiter et al., 2014), here the management of marine resources is primarily left in the hands of the community members; that is, top-down, institutional structures or agencies overseeing or guiding marine governance are largely nascent. Thus, the common-pool nature of resources (i.e. being rivalrous and nonexcludable; Gardner et al., 1990) requires community members to come together and act collectively to prevent overharvesting and resource degradation (Ostrom, 1990). This is often referred to as a collective action problem (Ostrom, 2010), a type of social dilemma, which describes situations where individual decisions to maximize personal, short-term benefits ultimately reduce or threaten collective benefits for everyone. For example, in fisheries such as our study context, decisions by individuals to harvest as much fish as possible—which can be individually beneficial in the short-run—can lead to overharvesting and the eventual collapse of fish stocks, having negative impacts on everyone in the long-run (Burgess et al., 2013). Collective action problems such as these tend to require cooperation among multiple actors in order to achieve the socially optimal outcome, for example fisheries sustainability (Ostrom, 2010). Yet in such instances, people have an incentive to free-ride off of the efforts of others. In other words, if some people behave in a manner that can be considered 'socially desirable' (e.g. limiting fishing in order to improve resource conditions), others may choose to reap the benefits of these efforts by continuing to capture more of the resource, eventually depleting it. Thus, in the policy and governance literature, these types of collective action problems are often referred to as 'cooperation problems' (Berardo & Scholz, 2010; Bodin, 2017).

The risk hypothesis (Berardo & Scholz, 2010) provides a testable set of theoretical expectations about how cooperation (and other types of) problems are linked to the types of relationships people build. Specifically, the risk hypothesis suggests that when people face cooperation problems where the risk of free-riding off the efforts of others is high (and the 'cost' inflicted on the others that did not defect is high), they will form bonding (closed, triadic/triangle) network structures (i.e., 'social network closure', Table 1) that tie people together in close-knit groups. The underlying assumption is that these bonding structures, reflective of bonding social capital (Putnam, 2000; Woolcock & Narayan, 2000), are likely to promote cooperation and deter people from free-riding due to the reputational costs they would pay in doing so (Berardo & Scholz, 2010). Alternatively, when people do not face cooperation but rather coordination problems (where everyone wants roughly the same thing, but do not agree on how to achieve it), they are expected to create ties that increase their bridging network capital (i.e. 'social network centralization', Table 1), thereby facilitating a 'search' strategy that allows access to more distant parts of the network where new, non-overlapping information could be obtained (thus spurring innovation in addressing joint problems; Burt, 2000; Granovetter, 1973).

While the risk hypothesis has attracted considerable attention over the last decade, and many studies have supported its basic expectations (Alexander et al., 2018; Angst & Hirschi, 2017; McAllister et al., 2020), the hypothesis is limited in a number of ways. First, research has not always empirically supported the clear expectations of the original risk hypothesis. Oftentimes, neither bridging (i.e. open, star-like) or bonding (i.e. closed, triangle) structures become dominant in networks; instead they coexist, indicating the presence of both cooperation and coordination problems (Berardo & Lubell, 2016; McAllister et al., 2017). The risk hypothesis is also limited in that it assumes tendencies to build bonding or bridging ties are independent of forces that likely shape the preferences for certain types of ties over others, such as homophily. Yet, homophily is ubiquitous in shaping social networks (Block & Grund, 2014; Marsden, 1987), and the perceived riskiness of the underlying collective action problem people face may further influence people's preferences to form homophilous ties with similar others whom they are more likely to inherently trust (Coffé & Geys, 2007; Fischer, 2015; Uslaner, 2002). Other contextual aspects of the collective action problem may also be important for structuring tie preferences; for example, in the context of global change where people face increasing impacts on common-pool resources that support their livelihoods (akin to our study context), people may be even more inclined to form tight-knit, bonding social structures—including ties with similar others—as a key source of support and to enhance mutual learning (Bodin et al., 2006; Prell & Lo, 2016; Woolcock & Narayan, 2000). Finally, the original version of the risk hypothesis focuses on how risk perceptions affect ties between social actors without considering their relationships or interdependencies with the ecological environment. This narrow social focus hinders our understanding of how social-ecological interactions are shaped and evolve, which is increasingly important in the context of global change.

We posit three key hypotheses that rest on, and extend the risk hypothesis. Our hypotheses are informed by the underlying assumption that community members (i.e. 'social actors') in our case primarily face a cooperation problem, and by the context of our study community. First, we examine the risk hypothesis in its classic interpretation under these conditions:

Hypothesis 1 (H1) *In the presence of a cooperation problem compounded by increasing drivers of change that threaten a common-pool resource base on which a community depends, we expect social actors to increasingly form closed, bonding structures that are better able to prevent defection and support cooperation and learning.*

Second, we systematically explore how the presence of a cooperation problem compounded by escalating social and ecological change may affect the evolution of networks when it interacts with the presence of homophily.

Hypothesis 2 (H2) *In the presence of a cooperation problem compounded by increasing drivers of change that threaten a common-pool resource base on which a community depends, we expect social actors to increasingly form social ties with others who are more similar to themselves (homophily) whom they are more likely to inherently trust.*

Third, we examine how the presence of a cooperation problem affects the formation of bonding network structures that extend across the social-ecological divide. In other words, we extend the risk hypothesis to explicitly include how actors' perception of defection risk is associated with the patterns describing their interdependencies with the biophysical environment.

Hypothesis 3 (H3) *In the presence of a cooperation problem compounded by increasing drivers of change that threaten a common-pool resource base on which a community depends, we expect social actors to form closed, bonding network structures that extend across the social-ecological divide in order to prevent defection, enable internalization of ecological feedbacks, and support cooperation and learning.*

Our final hypothesis (H4) departs from the risk hypothesis and the context of the cooperation problem to more explicitly focus on how social organization relates to learning in the context of adaptation (Cinner et al., 2018; Cinner & Barnes, 2019; Pelling et al., 2008). Specifically, we expect that as a common-pool resource base is increasingly threatened by drivers of global change, social actors dependent on this resource base will seek to connect with resourceful others that have access to specialized or new knowledge and/or resources that can support novel adaptation strategies (Barnes et al., 2017; Lebel et al., 2010; Nagel, 2020). This hypothesis rests on a long history of theoretical and empirical research showing how connections with diverse actors can support adaptation by equipping people to deal with complex challenges through learning and innovation (Burt, 2000; Granovetter, 1973).

Hypothesis 4 (H4) *In the presence of increasing drivers of change that threaten a common-pool resource base on which a community depends, we expect social actors to form ties with others that have access to specialized or new knowledge and/or resources; for example, formal leaders, elders, those connected to multiple or independent ecological resources.*

3 | DATA AND METHODS

3.1 | Study system

We conducted field work on a small tropical low-lying island in the Manus Province in Papua New Guinea (Figure 2), where our team has been engaged in research since 2002. The island is home to a community of ~952 people (estimate as of 2018) who are highly dependent on the marine environment and coral reefs. Alongside cultural attachment to the sea, people on the island rely on reef resources—primarily fish—as their main source of income and food (Lau et al., 2019). The island is an ideal setting to test our hypotheses as it and its community have been experiencing escalating ecological and social change over the past two decades that has put increasing pressure on the ecosystem's ability to support people's livelihoods. There are also constraints on migration in Papua New Guinea, meaning that out-migration (and the establishment of new ties to new groups as a potential adaptation strategy) is less of an option than it may be in other parts of the world (Cinner, 2009). We therefore expect to potentially see adaptation of networks within the community as a strategy to deal with the profound changes confronting the community. We describe these social and ecological changes and present data characterizing them in the beginning of Section 4.

3.2 | Data

Using primary quantitative data collected over a 16-year period (i.e. in 2002, 2009, 2012, 2016 and 2018; Table S1), we first examine key ecological and social metrics to demonstrate the degree of social-ecological change being experienced in our study community. This analysis provides context supporting the test of our hypotheses (which we describe below). Specifically, we draw on benthic community surveys conducted over this 16-year period to characterize changes in the ecological community structure among lagoonal reefs over time [see Supplementary Information (SI)]. Similarly, we examine broad sociodemographic trends (i.e. human population, the number of households and mean fortnightly expenditures per household) using data from systematically sampled household surveys conducted over the same period (see SI for a list of all survey questions used in this analysis). We complement this primary, quantitative data with information from published reports (MacNeil et al., 2015), and insights from participant observation and key informant interviews (Cinner, 2007; Cinner et al., 2005; Lau et al., 2020, 2021).

To test our hypotheses, we constructed full social-ecological networks using data collected in 2016 and 2018. Network data was not collected prior to 2016. Because this research was conducted in a fishing community where the primary source of food and protein is fish, we characterized the social-ecological network (i.e. ties) by measuring relationships related to fishing. For the social layer of the network, we collected data on communicative relationships among fishing households using structured surveys in both 2016 and 2018 (i.e. *the social network*, Figure 1A). Specifically, we asked heads of fishing households to represent their household in nominating up to ten individuals with whom they exchanged information and advice with about fishing and fishery management (e.g. rules, gears and fishing locations; see SI for more details). In this analysis, we only include information from households that were surveyed in both years; that is, the network and associated data represent a panel or time-series data structure, with observations of network phenomena collected from the same households over time. This resulted in a total of 11 households out of 82 initially surveyed in 2016 being dropped (see SI). Non-respondent network actors also were dropped and ties were symmetrized and treated as binary; in this way, ties represented the presence or absence of a communication link between households in each year. The corresponding social networks for each year were thus undirected, with edges representing information and advice relationships between respondent households A_i and A_j. Respondents were also asked to report what type of fishing gears were used within their household. In both 2016 and 2018, we also collected other

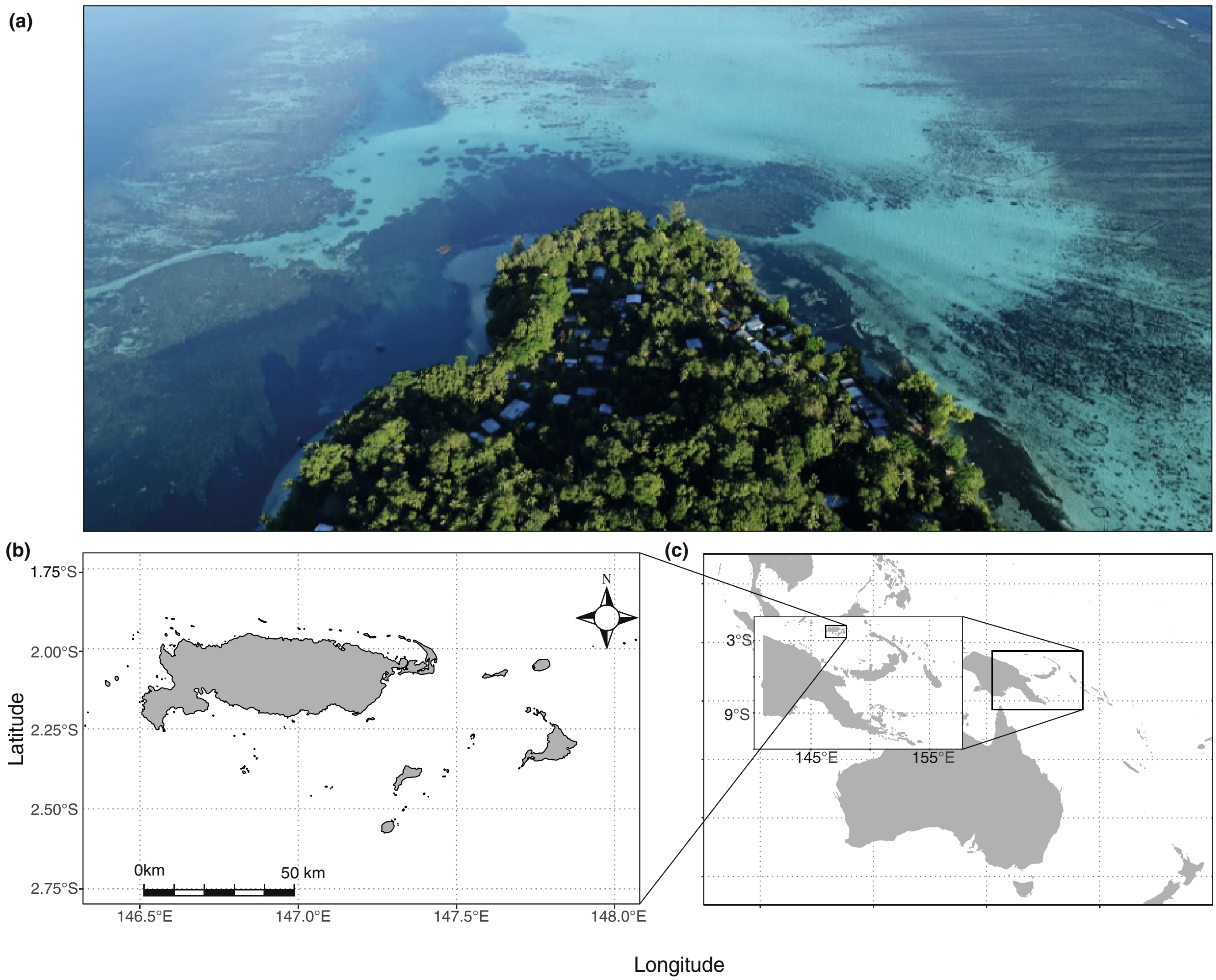


FIGURE 2 Context and location of the empirical research. We conducted our research on a small, tropical low-lying island (a), in the Manus province (b) of Papua New Guinea (c).

sociodemographic characteristics that existing research suggests plays a role in structuring social interactions in fishing communities, or are important in the context of dealing with change, for example, clan membership, leadership (see Table 2, Table S2).

The ecological layer of the network (Figure 1B) captured trophic interactions among target fish species comprising the majority of the community's fish catch (see SI). The corresponding ecological network was thus undirected, with edges representing trophic interactions between fish species B_u and B_v. Social–ecological ties (Figure 1X) were identified by linking individual fish species to respondents via the fishing gears they reported being used within their household (see SI). In other words, if respondent A_i used gear type G_t, and gear type G_t targeted fish species B_u, a social–ecological link would exist between respondent A_i and fish species B_u.

All surveys were conducted via in-person interviews in Tok Pisin. Research protocols between 2009–2018 were approved by the Human Ethics Committee at James Cook University (approval numbers: 2009 #H3020, 2012 #H4331, 2016 #H6461, 2018 #H6617). Fieldwork in 2002 was conducted through the Wildlife Conservation Society's field program, where standard human ethics practices were upheld. Prior informed verbal consent was obtained from all respondents (written consent was not sought due to low literacy rates).

3.3 | Dynamic network model

We used a temporal exponential random graph model (TERGM) for multilevel networks (see Wang et al., 2013) to test our hypotheses, which are dynamic model extensions to exponential random graph models (ERGMs). ERGMs model cross-sectional social network data and see the overall network structure at a given time point as accumulative and collective results of local social processes, such as network tie centralisation (i.e. ‘preferential attachment’; Barabási & Albert, 1999), or network closure (Newman, 2001). These local processes are represented by graph configurations (e.g. stars of various

TABLE 2 Description of social variables representing actor attributes in our models. Summary statistics are provided in Table S2

Variable	Description
Clan membership	Membership in one of four primary clans on the island, or other (e.g. from off-island). Clans represent important social groupings on the island and we expect them to be an important driver of tie formation (McPherson et al., 2001)
Age	Age of respondent in years. Age has been identified as an important factor shaping perceptions, cooperation and compliance with rules in our study community (Lau et al., 2021)
Chief	Whether the respondent is an acting clan chief. Clan chiefs are important for coordinating action and facilitating cooperation across clans. Leadership more broadly can be an important driver of social tie formation (Alexander et al., 2018)
Leader—other	Whether the respondent holds a different leadership position in the community, for example ward or church leader. Leaders can be important for coordinating action in response to change, and leadership has been identified as an important driver of social tie formation (Alexander et al., 2018)
Wealth	Total value of household structures and possessions measured using a material style of life (MSL) Index (Pollnac & Carmo, 1980). Wealth has been associated with network structure and indicates access to assets, which can play an important role in responding to change (Granovetter, 2005)
Alternative livelihood activity	Whether the respondent's household is engaged in any livelihood activities that do not directly depend on marine resources. Alternative livelihood activities may serve as an important adaptation strategy in facing social and environmental change (Barnes et al., 2020)
Linking ties	Total number of ties to external actors who reside off-island, for example business leaders and government representatives. Linking ties can provide access to a diversity of ideas and support (Borgatti et al., 1998)

sizes for tie centralisation, and triangles for network closure) where within each graph configuration the ties and attribute values are considered interdependent (where one network tie may be dependent on the existence of other ties in the network), making ERGMs more realistic models for many social processes which are inherently interdependent (Robins et al., 2007). The count of each configuration in a given network, also known as a graph statistic, is assigned a parameter in an ERGM. Positive and statistically significant parameter estimates indicate that the corresponding graph configuration is present in the empirical network more than we would expect by random chance conditioning on the rest of the model specification, hence the represented local tie formation process can be considered more relevant to the overall network structure (Lusher et al., 2012).

TERGMs identify and explain the network change processes that drive tie formation toward the structural features of current networks by taking into consideration the past network structure (the 'memory effect'), past attributes of nodes involved in the network, and changes in node attributes between time periods. Similar to ERGMs, TERGMs also account for the interdependent nature of social ties, hence follow similar model specifications as ERGMs based on graph configurations. Several versions of TERGMs have been developed (Krivitsky & Handcock, 2014; Leifeld et al., 2017); here, we follow Robins et al. (2001) and apply ERGM specifications for multilevel networks (Wang et al., 2013) to derive our final models. Specifically, we fit a TERGM for the social network change processes occurring between 2016 and 2018 (see SI). Specifically, we modelled the 2018 communication network structure while treating the rest of the variables as exogenous (i.e. the 2016 social network, the ecological $\{B\}$ network, the social-ecological $\{X\}$ network, and the 2016 attributes as well as the change in participants attributes, as described in Table 2). In other words, the social-ecological and ecological layer of the network represent ties present in 2016 and are purposely fixed in the model in order to exploit the longitudinal nature of our sample to see what influence the social-ecological network at 2016 exerts over the change in structure in the social network from 2016 to 2018 (Frank & Xu, 2020). This approach aligns well with our hypotheses, which focus on social tie formation given the underlying structure of social-ecological and ecological ties. Finally, we present results from an ERGM which models the structural features of the past network (in the year 2016) to provide a baseline description of the previous network structural features for comparison (an ERGM for the static network in 2018 is presented in the SI, though it is not the focus of this paper). Detailed further in the SI, we obtained our TERGM and ERGM parameter estimates and implemented a Goodness of Fit procedure to ensure the models we present provided adequate fit to all graph statistics through the MPNet software (Wang et al., 2013).

4 | RESULTS

The community we conducted our research in has experienced substantial ecological and social change over the 16-year study period.

The island's coral reefs have gone from being coral to macroalgal dominated, with coral cover dropping from 41% (±3.5 SE) in 2002 to 12% (±1.0 SE) in 2018, and macroalgae increasing from just 13% (±0.4 SE) to 27% (±2.4 SE) over the same timeframe (Figure 3a). Reef fish biomass is considered severely depleted (MacNeil et al., 2015), and a wide range of impacts from climate change are already being experienced, including coastal inundation and erosion (Barnes et al., 2020). Meanwhile, human population has increased ~50% in terms of both the number of households and the number of inhabitants on the island (Figure 3b). The community is also becoming more connected to a cash-based economy. However, fortnightly expenditures per household (consumer price index adjusted to 2018 and converted to $USD) experienced a slight rise up to 2012, yet have since been declining (Figure 3c).

Dynamic social-ecological network processes in light of these social and ecological changes are moderately in line with our expectations (Table 3). Our first hypothesis (H1), that individuals are responding to risk in their communities by forming closed, bonding structures, is supported in both the baseline model (2016) and our model of change over the intervening 2 years. This is demonstrated by the positive, significant parameter estimates for 'social network closure' in both models (Table 3). These results demonstrate that in 2016 there was already a tendency toward bonding network structures resulting in tight coupling between actors, and this preference became stronger between our two sampling periods. Specifically, individuals display an odds ratio of 1.61 to have added ties that formed densely bonded triangles between our two sampling periods,[1] and are more likely to have retained ties within triangles than other types of ties (odds ratio of 1.43 in 2016 vs. 1.65 in 2018). In contrast, we do not see a tendency for bridging network structures (captured by 'social network centralization') in our first sampling period (baseline model) or over time [temporal model, 2018/2016 (change)].

Our results also provide moderate support for the risk hypothesis extensions we put forth regarding homophily (H2, partial support) and closure across the social-ecological divide (H3, partial support). Specifically, we see a strong pattern of increasing homophily over time along the lines of clan membership (Table 3). Results from our temporal model did not indicate any significant patterns of homophily among other characteristics, such as age, leaders (chiefs or others), or being engaged in an alternative livelihood not dependent on the marine environment (Table S4). An increasing preference for closure across the social-ecological divide is demonstrated by the positive, significant parameter estimate for the 'closed social-ecological square' configuration in our temporal model, compared to an insignificant parameter estimate in our baseline model (Table 3). These results indicate that over our sampling period, households fishing interdependent ecological resources began forming social ties more so than would have been expected by chance. We do not find evidence for this tendency of social-ecological closure in regards to situations where households are fishing the same resources ('social-ecological triangle', Table 3), where there may be more direct competition.

Results from our temporal network model provide little support for our final hypothesis regarding knowledge seeking and learning (H4). Specifically, of all the attributes and configurations tested, we find that only households with newly appointed clan chiefs were significantly more active in the network over time ('new chief activity'; Table 3). It is important to note however that though established chiefs did not become increasingly active over our two sampling periods, they were significantly more active in the network compared to others to begin with (i.e. in 2016, Table S3), and our static model from 2018 (Table S5) shows that the high level of activity around established chiefs remained stable. Households engaged in alternative livelihood options (not dependent on the marine environment), those linked to multiple ecological resources ('social-ecological brokerage', Table 3), and the wealthy were not particularly active in the network compared to others in 2016 (Table S3), and there were no changes in this tendency over time (Tables S4, S5). Although those with linking ties were significantly more active in 2016 according to the results from our baseline model (Table S3), they were not in 2018 (Table S5) and the change process between these two time periods was not significant in our temporal model (Table S4). Importantly, in contrast to our initial expectations described in H4, elders became significantly less active in the network over time ('age activity';

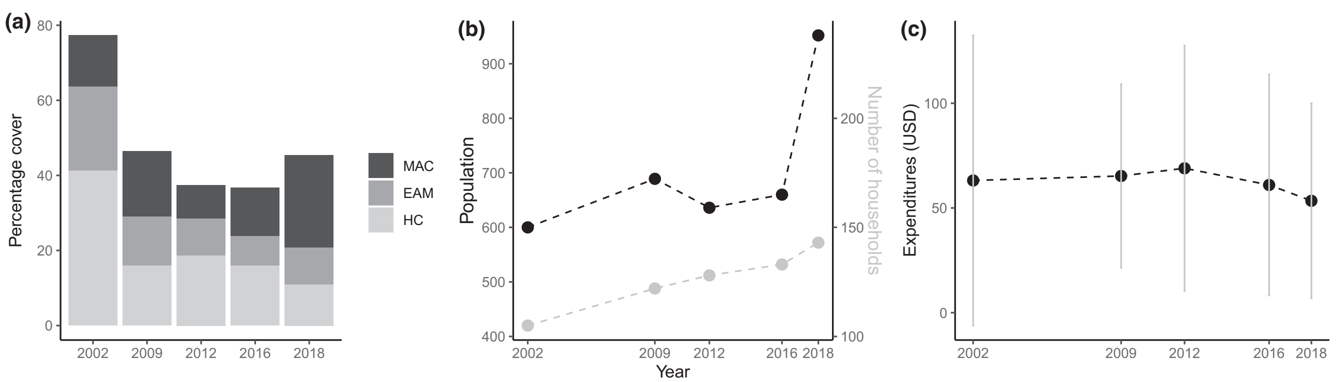
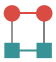


FIGURE 3 Social and ecological changes in a Papua New Guinean island fishing community over a 16 year period (2002–2018). (a) Benthic community structure of the lagoonal reefs: EAM, epilithic algal matrix; HC, hard coral; MAC, macroalgae. (b) Population and number of households in the community. (c) Mean fortnightly expenditures per household (+SD) converted to 2018 $USD.

TABLE 3 Dynamic social-ecological network processes. Parameters estimates and standard errors from our baseline multilevel exponential random graph model (ERGM) of 2016, and our multilevel temporal ERGM (2016/2018) capturing dynamic processes. The fourth column indicates whether the estimates from our temporal model are supportive (or not) of our hypotheses. All parameter estimates relevant to H1 and H3 are presented. As discussed in the text, several different nodal attributes were modelled under H2 and H4 in order to capture homophily and activity associated with different traits (e.g. age, wealth and being engaged in an alternative livelihood not dependent on the marine environment). Here, we only show attribute effects for homophily and activity that were relevant to our hypotheses and significant at $p < 0.05$ (indicated with a *) in our temporal model. Full model results can be found in Tables S3 and S4 in the SI

Network configuration		Model parameter estimate (SE)		Relevant hypothesis, interpretation
		2016 (baseline)	2018/2016 (change)	
	Social network closure	0.36 (0.17)*	0.48 (0.14)*	H1, supportive
	Social network centralization	−0.10 (0.23)	0.40 (0.21)	H1, supportive
	Clan b, c & d homophily	0.84 (0.75) 1.33 (0.59)* 0.84 (0.97)	1.99 (0.86)* 1.55 (0.53)* 1.47 (0.58)*	H2, supportive
	Social-ecological triangle	0.05 (0.04)	0.00 (0.03)	H3, not supportive
	Social-ecological square	−0.01 (0.01)	0.02 (0.01)*	H3, supportive
	Age activity	−0.02 (0.01)	−0.02 (0.01)*	H4, not supportive
	New chief activity[a]	–	0.84 (0.30)*	H4, supportive
	Social-ecological brokerage	−0.05 (0.03)	0.00 (0.04)	H4, not supportive
	Open social-ecological square	−0.01 (0.00)*	−0.02 (0.01)*	H4, not supportive

*Indicates significance at $p < 0.05$.

[a]Parameters denoted 'new' refer to attributes which changed between the two sampling periods, and thus, they can only be estimated in temporal models; for example, a positive 'New chief activity' parameter indicates that individuals whose status changed to 'chief' between our sampling periods were significantly more active than others in 2018.

Table 3). Moreover, our results show that actors linked to different, independent resources were actually less likely to form ties with each other over time ('open social-ecological square', Table 3), rather than more likely, as we had hypothesized.

5 | DISCUSSION

5.1 | Increasing risks to resource-dependent livelihoods

Our results are suggestive of a community grappling with increasing risk to resource-dependent livelihoods driven by escalating social and ecological change. The island's population has increased substantially and the benthic structure is transitioning from coral to algae dominated (Figure 3), which does not support the same level of biodiversity in terms of the assemblage of reef fish. Together these changes add pressure to a fishery that is already severely depleted (MacNeil et al., 2015). Previous studies suggest the island has experienced gradual sociocultural changes as well, including declines in respect for leadership and reduced legitimacy of customary reef management systems (Lau et al., 2020, 2021). Meanwhile, the island is facing mounting pressures associated with being integrated with the global economy (e.g. transition to a cash-based economy, introduction of smart phones, etc.) and is highly vulnerable to, and already experiencing impacts from climate change (e.g. sea-level rise, coastal inundation and erosion, and disruptions to reef ecosystems and associated fisheries; Barnes et al., 2020).

5.2 | Increasing bonding social-ecological network structures

Although we did not measure people's social networks prior to 2016, our results from both our baseline model in 2016 and our temporal model [2016/2018 (change)] are consistent with a society already responding to a state of risk (Table 3), and in a relatively short period of time (i.e. between 2016 and 2018) continuing to adapt their social interactions to account for this risk. Specifically, our results in support of our first hypotheses confirm the basic expectations of the risk hypothesis, which argues that actors will form closed, bonding social network structures when faced with cooperation problems in order to prevent defection and discourage free-riding (Berardo & Scholz, 2010). This proposition rests on the notion of bonding social capital (Putnam, 2000; Woolcock, 1998), which is argued to decrease the risk associated with unmonitored behaviour and help to build trust, thereby increasing the probability of sustaining cooperation over time (Berardo, 2014a).

Our findings in support of our third hypothesis extend these ideas to account for how complex social-ecological systems evolve in the presence of uncertainty and collective action problems involving not only the human elements in the system but also the ecological resources on which humans depend for their livelihood. Because we conditioned our models on the social-ecological ties present in 2016 (i.e. ties that linked fishing households with specific fish species), our findings regarding H3 in regards to 'social-ecological square' (Table 3) indicate that more communicative ties were created between households to form bonding social-ecological structures over time. Extending the risk hypothesis, this indicates that when faced with a cooperation problem, individuals connected to interdependent resources are likely to increasingly seek out and form social relationships. Such relationships may offer a foundation for gaining additional ecological information (Bodin et al., 2014) and encouraging cooperation over interdependent resources (Barnes, Bodin, et al., 2019), thereby helping to avoid potentially negative feedbacks associated with resource use and/or punishing defection in line with the original spirit of the risk hypothesis (Berardo & Scholz, 2010). Support for both H1 and H3 indicate that the potential for cooperation extends beyond the simple structures that the original risk hypothesis envisioned as forming only among actors in the same level.

Importantly, support of the risk hypothesis has not been consistent across the literature (Berardo & Lubell, 2016; McAllister et al., 2017; Nyantakyi-Frimpong et al., 2019), suggesting that the context of the collective action problem matters. For example, it has been suggested that in contexts that have remained stable over time, bridging social network structures are sometimes favoured (even in the presence of risk), whereas contexts experiencing change favour bonding structures (Bodin et al., 2020). In line with this argument, in our case the contextual data we collected over a 16-year period coupled with insight from existing research points to an acute cooperation problem underpinned by dramatic social and ecological change that poses substantial risk to the livelihoods and wellbeing of community members (Cinner et al., 2005; Lau et al., 2020, 2021). Additional case studies and comparative work are necessary to determine whether our findings in support of the risk hypothesis demonstrating an increasing tendency for bonding social-ecological network structures are indeed related to this context of change and the inherent risk these changes pose to the current structures and processes in the social-ecological system, as we suspect.

5.3 | Increasing ingroup ties

Our second hypothesis, which extended the original risk hypothesis to account for homophily, was partially supported, providing evidence that when ecological resources are scarce and increasingly threatened and social actors that depend on them face a cooperation problem, they will increasingly form tight-knit homophilous ties. Homophily is ubiquitous in shaping social interaction (McPherson et al., 2001). The preference to form ties with similar others (thus leading to observed homophily) can be explained by the social identity theory (Tajfel & Turner, 1979), which describes that social actors tend to prefer within-group ties because they bring a sense of belonging with respect to cultural norms, values, and traditions. We argue that the strong tendency for clan-based homophily observed here extends beyond the underlying, baseline-levels of homophily that we would generally expect to observe in social networks in less risk-prone settings. Though similarity in underlying characteristics, particularly those associated with sociocultural background, can be important for structuring ties across many different contexts (McPherson et al., 2001), it has been shown to be especially important under conditions of risk and uncertainty (Coleman, 1990; Melamed et al., 2020). This is because identities tend to be associated with expectations about how people are likely to treat fellow 'ingroup' members (i.e. others like them), leading people with similar social identities to have higher levels of inherent trust among themselves (Brewer, 2007, 2008). When faced with social dilemmas (such as a cooperation problem) riddled with risk and uncertainty, trust can be crucial for determining whether people decide to cooperate or defect (Balliet et al., 2014; Kollock, 1998; Kramer & Brewer, 1984).

5.4 | Leaning on traditional leaders

Theoretical and empirical work from across a wide range of disciplines shows that connections with diverse actors can promote learning (Matous & Wang, 2019; Stovel & Shaw, 2012), which is increasingly recognized as an essential factor underpinning the capacity to adapt in the face of social-ecological change (Cinner et al., 2018; Cinner & Barnes, 2019). Yet, while our results show that households with established clan chiefs retained a high level of activity in the network and newly appointed clan chiefs became even more active by our final sampling period in 2018, this is not the case for other types of actors that may have access to novel information and ideas (i.e. other community leaders, elders, the wealthy, those with alternative livelihood sources, those with linking ties to actors outside the community, those connected to many and/or different ecological resources). Our results thus demonstrate that under conditions of a cooperation problem where resources that people depend on are increasingly threatened, the community is increasingly turning to cultural leaders for information and advice, rather than others who may have a diverse knowledge base. Formal and traditional leaders have been consistently shown to act as hubs of communication activity in small-scale fishing communities (Alexander et al., 2018; Barnes, Mbaru, & Muthiga, 2019; Mbaru & Barnes, 2017). This may be due, at least in part, to views of leaders as being resourceful and knowledgeable, underlying levels of trust in leaders, and socio-cultural expectations about the role of leaders in sharing information.

5.5 | Long-term outlook: The benefits and pitfalls of 'bunkering down' in response to change

Taken together, our results suggest a community that is largely 'bunkering down' (Putnam, 2000) and looking inward in response to increasing risk to resource-dependent livelihoods and a breakdown in the collaborative processes that traditionally sustained them. Specifically, community members are increasingly choosing to interact with others more like themselves, with friends of friends, and with those connected to interdependent ecological resources—in other words, they are showing a strong, increasing preference for forming bonding ties with like-minded, similar others. Derived from the theory of embeddedness (Granovetter, 1985), cohesive bonding social ties are argued to reflect a type of social capital lubricated by reciprocal interactions, bounded solidarity, and trust; in which rules, norms, and sanctions are more likely to be established and upheld (Portes & Sensenbrenner, 1993). These types of bonding network structures can be beneficial for adaptation and for sustaining cooperation among small groups, having potential positive net effects on ecological sustainability (Baggio & Hillis, 2018; Barfuss et al., 2017; Barnes, Bodin, et al., 2019). Among the broader collective breakdown, it is therefore possible that this is an effective adaptive strategy for maintaining some level of pro-social behaviour in the short-term. However, the presence of an overabundance of bonding ties at the social-ecological network level may pose significant long-term risks (Baggio & Hillis, 2018; Bodin et al., 2006). Bonding ties lead to clustering in networks, creating groups of actors that can end up relatively isolated from each other socially, even when they are in close proximity. Though homophily has been argued to enhance cooperation within groups (Melamed et al., 2020), the segregation it leads to between groups can present significant challenges when collaboration and cooperation is needed at a larger scale, such as the scale of the island in which we conducted our research.

The rather extreme levels of increasing homophily observed in our study community around clan lines are particularly likely to have important implications for the trajectory of this social-ecological system. Although we did not measure people's social or ecological networks prior to 2016, our knowledge of this community built up over the 16-year period we have been working there leads us to believe that the structural changes we observe in the social-ecological network between 2016 and 2018 reflect a continuation of changes which likely began sometime after 2012. Traditionally, the island's reefs were governed by a complex set of tenure and ownership rights whereby clans worked collaboratively to decide on, uphold, and enforce rules about reef areas, gears used, and times that people could fish (Cinner et al., 2005; Lau et al., 2020). Indeed, when we first began working there in 2002, anecdotal observations suggest that there was considerably more inter-clan interaction as compared to 2016. For example, community meetings where clans came together were consistently held to discuss and decide on rules guiding resource use. However, this customary management system began breaking down in 2009 and was largely abandoned by 2012. Following the breakdown of this system, associated community meetings and inter-clan cooperation for harvesting has waned, and compliance with rules regarding reef resources has been dwindling (e.g. bans on intensive fishing methods; Lau et al., 2020). These are critical developments because a lack of cohesion and trust across clans can reduce the ability of the community to mobilize and agree on and enforce rules and norms (Carrillo et al., 2019; Ostrom & Ahn, 2009), and group identities can cause individuals to accentuate their differences with others rather than their similarities, which can augment any underlying conflicts (Baerveldt et al., 2004). Together, these changes have gradually eroded the legitimacy of community leadership and led to the breakdown of the collaborative processes underpinning customary management of the reef (Lau et al., 2020), which we argue may be reflected in, and partly responsible for the continuing breakdown of inter-clan ties.

Whilst bonding ties are often critical for recovery after extreme events (Karunarathne & Lee, 2020; Pelling, 2003), existing research shows that densely structured, segregated networks also struggle to deal with more fundamental changes (Calliari et al., 2019; Newman & Dale, 2004). Fault lines often emerge between different network subgroups in societies, which can stifle social learning, limit the spread of innovations, and lead to inequalities associated with unequal access to information and resources (Barnes, Mbaru, & Muthiga, 2019). Ties linking diverse actors form a critical foundation for overcoming these limitations, thereby spurring more fundamental, transformative responses to social and ecological change; that is, responses that can alter dominant social-ecological relationships and work to create a new system or future whereby community-level vulnerabilities are reduced over the long term (Barnes et al., 2017). Yet in our case, we found that resourceful actors with diverse or specialized knowledge bases; such as elders, the wealthy, and those with ties to multiple, independent ecological resources; were not particularly active communicators—potentially putting at risk the community's capacity for developing transformative responses to deteriorating social and ecological conditions. In addition, while decisions about the reef used to be made collaboratively at community and clan meetings led by clan chiefs and other community leaders, other research by our team shows that alongside fewer community meetings there has also been more disrespect toward leaders (Lau et al., 2021). Despite this, we found that clan chiefs remained a significant source of information and advice for many people in the community over time, and newly appointed chiefs became even more active by our final sampling period. As trusted information sources, clan chiefs may have an opportunity to exert transformational leadership (Westley et al., 2013) that helps to steer the social-ecological trajectory away from a precarious position of non-cooperation and degradation. In this context of entrenched homophily, this will require fostering trust and greater inter-clan cooperation, facilitating innovation and supporting the joint development of a common vision that the community could strive toward (Scoones et al., 2020; Westley et al., 2011, 2013).

As societies around the globe grapple with unprecedented social and ecological change, our findings are likely relevant and potentially shared by communities who depend on and manage common-pool resources in other contexts with little top-down governance, such as other small-scale fishing, pastoralist, and forest communities, or agricultural communities managing shared irrigation systems. Our study also raises the important question of how common 'bunkering down', as described here, might be in response to change more broadly. Although increased in-group cooperation may be crucial in the short-term or for overcoming certain types of change, it may be maladaptive for confronting grand challenges such as climate change and pandemics. Indeed, in some places, the response to COVID-19 has been increasing alignment with in-groups, and resultant rejection of key solutions perceived to be viewed as out-group in origin (e.g. vaccines, physical distancing, mask wearing; Druckman et al., 2021; Gollwitzer et al., 2020; Khubchandani et al., 2021). Future research should seek to understand if bunkering down is a common response in other communities that are grappling with unprecedented global change and depend on common-pool resources, the extent to which this process may also be occurring in other contexts and in response to different types of change (i.e. shocks vs. gradual change), and whether this represents an intended adaptive strategy. Research that focuses on the psychological dimensions underpinning strategies to adapt social and ecological ties in the context of both episodic shocks and more gradual change would likely be particularly useful. Perceptions and cognitions are often strongly linked to adaptive behaviour (Clayton et al., 2015; Grothmann & Patt, 2005), and recent research argues that the interplay between social-ecological networks and human cognition can help to drive the cultural change needed to initiate large-scale transformations toward sustainability (Kashima, 2020).

6 | CONCLUSIONS

Social-ecological networks are not static, especially in the context of global environmental change. Yet, we have limited information on network dynamics, which are important because changing structures can reflect underlying capacities that are important for dealing with and adapting to change (Adger, 2003; Barnes et al., 2020). We quantified the temporal dynamics of a social-ecological network over two time periods in a Papua New Guinean fishing community to test a series of risk-based hypotheses (Berardo, 2014b; Berardo & Scholz, 2010). We found that as social and environmental change increasingly threatened resource-dependent livelihoods, there was a growing tendency for people to 'bunker down' by forming closed, bonding social-ecological network structures and by preferentially interacting with those most similar to themselves along clan lines (homophily). While this bunkering down may help promote in-group cooperation, it may be somewhat maladaptive by stymieing the larger-scale cooperation required to counteract the degrading marine environment upon which the community is heavily dependent. Indeed, this tendency toward bunkering down may create a negative feedback cycle whereby change promotes people bunkering down, which then reinforces environmental degradation through reduced larger-scale cooperation, which further entrenches bunkering down. This would likely reduce the community's ability to 'break loose' from the current trajectory, thereby inhibiting attempts to initiate more fundamental transformational changes that could help them to maintain their current or alternative livelihoods in spite of ongoing global change. In our case, clan chiefs—who appear to remain trusted information sources—may have an opportunity to foster the transformational leadership needed to promote larger-scale cooperation and transformative innovation (Westley et al., 2013). Whether this opportunity is realized will, at least in part, ultimately depend on the intent and capacity of these traditional leaders, as well as their will to potentially challenge the dominant structures and processes that comprise the current social-ecological system (Blythe et al., 2018; Crona & Bodin, 2010; Westley et al., 2011).

AUTHORS' CONTRIBUTIONS

M.L.B.: Conceptualization, funding acquisition, resources, methodology, investigation, data curation, formal Analysis, visualization, writing—original draft, writing—review and editing, validation, supervision and project administration. L.J.: Conceptualization, writing—original draft and writing—review and editing. A.B.: Investigation, data curation and writing—review and editing. J.B.: Investigation, validation and Writing—review and editing. R.B.: Conceptualization, writing—original draft and writing—review and editing. Ö.B.: Conceptualization, writing—original draft and writing—review and editing. J.C.: Investigation, data curation, writing—review and editing and funding acquisition. D.A.F.: Investigation, data curation and riting—review and editing. A.M.G.: Conceptualization, data curation, writing—original draft and writing—review and editing. F.A.J.-H.: Investigation, formal analysis, visualization and riting—review and editing. J.T.K.: Investigation, validation and writing—review and editing. J.D.L.: Investigation, writing—original draft and writing—review and editing. P.W.: Conceptualization, methodology, software, formal analysis, writing—original draft and writing—review & editing. J.Z.-M.: Resources, investigation, data curation and writing—review and editing.

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CONFLICT OF INTEREST

The authors have no conflict of interest, including but not limited to commercial affiliations, to declare.

DATA AVAILABILITY STATEMENT

Summary social and ecological change data that support the findings of this study are available in the Supplementary Information files. Raw ecological network data has been deposited in Research Data JCU and can be accessed at: https://doi.org/10.25903/5ecf39990a0bb. Social network data are available upon request from the corresponding author with reasonable restrictions, as these data contain information that could compromise research participant privacy and consent.

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ENDNOTE

1 Conditioning on none of the other model terms being applicable.

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