

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

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27 **Social determinants of adaptive and transformative responses to climate**
28 **change**

29

30 **Abstract:** To effectively cope with the impacts of climate change, people will need to adapt
31 and potentially transform. Recent research has highlighted that people's adaptive capacity,
32 which may enable both adaptation and transformation, is comprised of six key domains:
33 assets, flexibility, organization, learning, socio-cognitive constructs, and agency. However,
34 no empirical studies have simultaneously examined how all six adaptive capacity domains
35 are related to both adaptive and transformative actions. Drawing on novel advances in
36 multilevel network modelling, we provide evidence consistent with an influence process in
37 which aspects of social organization (exposure to others in social networks) encourage both
38 adaptive and transformative action among Papua New Guinean islanders experiencing
39 climate change impacts. Adaptive and transformative action are also related to social-
40 ecological network structures between people and ecological resources that enable learning
41 and the internalization of ecological feedbacks. Agency is also key, yet we show that while
42 perceived power may encourage adaptations, it may discourage more transformative
43 actions.

44

45

46 <Introduction>

47 Climate change is already affecting the lives of people across the globe. Even under the
48 most optimistic greenhouse gas emission reduction scenario in the Intergovernmental Panel
49 on Climate Change Fifth Assessment Report ¹, securing biodiversity and ecosystem
50 services, safeguarding food and water security, and protecting the livelihoods and health of
51 future generations presents significant challenges. As sea levels rise and global heating
52 triggers an increase in climate-related disasters, it is imperative that people on the frontlines

53 of climate change have the capacity to effectively respond in ways that reduce their
54 vulnerability ².
55
56 Whether and how people respond to environmental change (adaptive behaviour) is widely
57 recognized to be driven by their adaptive capacity, broadly defined as ‘the underlying
58 conditions that enable people to anticipate and respond to change, to minimize the
59 consequences, to recover, and to take advantage of new opportunities’ ³. Access to capital,
60 such as financial assets, has long been considered a crucial determinant of adaptive
61 capacity ^{3,4}. However, research from across diverse social science disciplines has recently
62 identified a much broader range of determinants that underpin whether and how people
63 adapt to environmental change ⁵⁻⁸. Following this research ^{5,6}, we categorize these
64 determinants into six broad domains: assets, flexibility, organization, learning, socio-
65 cognitive constructs, and agency (Fig. 1). These six domains highlight that in addition to
66 assets, adaptive behaviour can be driven by whether people have the *flexibility* to change
67 strategies ⁶, and the power or *agency* to influence change ⁹ and make their own free choices
68 in determining whether to change or not ¹⁰. *Socio-cognitive* constructs, such as risk attitudes
69 (how people perceive and deal with risk), cognitive biases (e.g., fatalistic attitudes), and
70 personal experience, can also play an important role on people’s adaptive behaviour ^{7,8}. For
71 example, decisions regarding whether and how to respond to changing environmental
72 conditions can be driven by perceptions of the probability and severity of risk associated with
73 change ¹¹ as well as the closeness and intensity of previous related experiences ¹². Finally,
74 adaptive behaviour can be influenced by the social and social-ecological ties binding people
75 to each other and the environment ^{13,14}, as these relationships shape the social and
76 environmental context (*organization*) in which people experience, *learn* to recognize, and
77 respond to climate change (Fig. 1).
78 Together, these emerging insights offer a more comprehensive perspective of a multitude of
79 interrelated factors that may underpin responses to environmental change across diverse
80 contexts. Yet two key gaps remain: first, most studies focus on how people’s adaptive

81 behaviours may be influenced by a single domain of adaptive capacity, rather than
82 simultaneously examining the six domains outlined above. Which domains should be
83 prioritized in policies and programs aimed at reducing climate vulnerabilities ^{7,8} is therefore
84 unclear, despite substantial interest and ongoing investments in building adaptive capacity
85 among local and national governments, non-governmental organizations, and development
86 agencies ^{6,19}. Second, much of the existing work on the relationship between adaptive
87 capacity and adaptive behaviour has relied on hypothetical or intended responses to future
88 impacts, rather than people's actual responses to change ⁷. As a result, our understanding of
89 how diverse domains of adaptive capacity simultaneously interact to shape realized
90 responses to climate change remains limited ⁸.

91

92 Here, we sought to understand how diverse domains of adaptive capacity drive varied
93 household-level (recall) responses to climate change among a population (N = 138 of 140
94 households) on a tropical island in Papua New Guinea (Fig. 2, Methods). Our study context
95 is characteristic of many coastal and island communities across the global tropics in that (a)
96 the majority of households are primarily dependent on fishing and harvesting marine
97 resources (particularly coral reef-associated resources) for livelihoods and food security, and
98 (b) the island is highly vulnerable to, and is indeed already experiencing the impacts of
99 climate change; such as sea-level rise, coastal inundation and erosion ²⁰, and disruptions to
100 reef ecosystems and associated fisheries ²¹. In this context, we integrate a full population
101 census, semi-structured social surveys, key informant and expert interviews, observed fish
102 landings, and published reports to document adaptive behaviours (Fig. 2, Supplementary
103 Table 1) and develop 20 key indicators (Table 1, Supplementary Tables 2-3; Fig. 3)
104 representing the six broad domains of adaptive capacity, i.e., assets, flexibility, learning,
105 organization, socio-cognitive constructs, and agency (Fig. 1). Our indicators included social
106 and economic characteristics, such as wealth and risk perceptions (Table 1, Supplementary
107 Table 2), in addition to a household's position in a complex social-ecological network (Fig 3,
108 Supplementary Table 3). Building on recent advances in network methodology (Autologistic

109 Actor Attribute Models ²²), we then developed a multilevel social-ecological network
110 modelling approach that enabled us to predict adaptive behaviour (Supplementary Table 1)
111 as a function of a household's adaptive capacity (Methods, Supplementary Methods).
112
113 We studied two types of adaptive behaviour, which we classified as (1) adaptive action, and
114 (2) transformative action (Fig. 2). A large body of work describes climate change adaptation
115 as comprising a diversity of responses ranging from minor/moderate or incremental changes
116 to existing practices and behaviours (often referred to as 'incremental adaptation', or simply
117 'adaptation'), to more fundamental changes that have the potential to create a new system
118 or future (often referred to as 'transformational adaptation', or simply 'transformation') ³¹⁻³⁴.
119 Yet debate remains regarding these concepts and when an action should be considered
120 transformative as opposed to adaptive ³². Following recent theoretical and empirical work in
121 this area ^{31,34-36}, we defined *adaptive actions* as changes to existing practices or behaviours
122 which allow existing social-ecological system structures to absorb, accommodate, or
123 embrace change; and *transformative actions* as more fundamental changes that can alter
124 dominant social-ecological relationships and contribute toward the creation of a new system
125 and/or future. Adaptive actions in this case included a range of behaviours such as
126 technological fixes/mitigation (such as building sea walls, which in this case were considered
127 adaptive in nature because the walls were built to protect existing land uses and they did not
128 require major engineering projects), adapting or intensifying fishing practices and effort, and
129 seeking knowledge/creating awareness about climate change (Fig. 2, Methods,
130 Supplementary Table 1). Transformative actions included livelihood diversification that
131 represented a fundamental departure from near complete dependence on traditional marine
132 resource-based activities (i.e., engaging in atoll farming; Fig. 2, Methods, Supplementary
133 Methods), and active engagement in long-term planning specifically aimed at managing
134 climate change impacts on the community (e.g., developing novel community response
135 plans and/or resettlement schemes, which in this case represented a departure from more

136 general community planning which occurs regularly; Supplementary Table 1, Methods). Both
137 adaptive and transformative action are thought to be underpinned by adaptive capacity³¹,
138 yet the majority of the empirical work on adaptive capacity and responses to climate change
139 has focused on adaptive action. Thus, a key unanswered question which we in part aim to
140 address here is whether different (or the same) capacities and domains of adaptive capacity
141 are needed to enable transformative action.

142

143 **Exposure to others in social networks**

144 We found that three key domains of adaptive capacity crosscut both adaptive and
145 transformative action: organization, learning, and agency. First, we found that network
146 exposure – related to the organization domain of adaptive capacity (Table 1, Fig. 3) – played
147 a key role on both adaptive and transformative action (Table 2, Supplementary Table 5).

148 Social networks have long been identified as a source of social capital that can act to
149 support adaptation in the context of climate change (e.g., by providing access to resources
150 and social support¹³), yet existing research has generally not considered the prospect of
151 them having a more direct relationship with adaptive behaviour via network exposure.

152 Interestingly, none of our network measures that are characteristic of social capital were
153 significant in our model (e.g., connectivity, linking ties; Fig. 3); while network exposure was
154 (Table 2, Supplementary Table 5).

155

156 ‘Network exposure’ captures social processes that result in observed ‘homophily’, which is
157 the propensity for like-minded people to be connected³⁷. There are two ways to interpret our
158 network exposure term: (1) social influence, whereby households are influenced by those
159 they are exposed to in their social networks; and (2) social selection (also referred to as
160 ‘choice homophily’), whereby households preferentially choose to interact with households
161 similar to themselves (i.e., like attracts like). An analysis of a subset of the social networks
162 examined here from two distinct time periods shows that some communication partners and
163 key social nodes (i.e., highly connected respondents) in our study community remain stable

164 over time (Supplementary Methods). This suggests that our network exposure effect is likely
165 capturing some degree of social influence (i.e., households are influenced by the adaptive
166 and/or transformative behaviour of their network partners). Yet the full effect is likely a
167 combination of social influence and social selection, which are known to co-occur³⁸. Thus,
168 our result that network exposure is significantly correlated with adaptive and transformative
169 action (Table 2, Supplementary Table 5), indicates that adaptive behaviour is being
170 reinforced, either through the formation of new ties (selection) or the changing attitudes in
171 existing ties (influence). This result represents an example of cultural change^{39,40} in
172 response to climate change. Our results thus lend some weight to recent calls for the
173 development and implementation of social influence approaches that use the power of
174 networks to catalyse action in response to climate change⁸. Such approaches have proven
175 to be successful in reducing bullying in classrooms⁴¹, and our results suggest they may help
176 to encourage adaptive and transformative action among those most vulnerable to the
177 impacts of climate change. Caution is warranted in applying social influence approaches
178 however, as some literature has shown that the co-occurrence of social influence and social
179 selection can lead to segmented networks and polarization^{38,40}, where behaviours and
180 opinions are divided amongst contrasting groups. Importantly, increasing polarization may
181 create challenges for coordinating larger-scale (e.g., community-wide) adaptive and
182 transformative action over time.

183

184 **Social-ecological feedbacks and learning**

185 Our second key result is that social-ecological network structures supporting the learning
186 domain of adaptive capacity played a critical role on both of our studied responses.
187 Specifically, socially linked households with many ties to divergent resources were more
188 likely to have adapted than those linked to interconnected resources (combined effects of
189 open social-ecological square and closed social-ecological square, Fig. 3; Supplementary
190 Methods); whereas households directly linked to interconnected ecological resources

191 (ecological-social triangle) were more likely to have transformed (Fig. 3; Table 2,
192 Supplementary Tables 5 and 6). People are known to learn through different types of
193 interaction and experience, both with the environment and with peers³⁰. Our results indicate
194 that social learning involving many independent resources (in this case households sharing
195 and building knowledge with each other about several different fish species and potentially
196 their different ecosystem functions and/or parts of the ecosystem they inhabit) may
197 contribute understanding about broader ecological trends, thereby prompting households to
198 adapt to changing environmental conditions. In contrast, our results suggest that knowledge
199 built through personal connections with interconnected resources (personal learning about
200 trophically linked fish species in this case) may enable people to internalize ecological
201 feedbacks²⁹, catalysing more transformative action in response to environmental change.
202 Given the complex, micro-level interactions likely to be occurring between two interlinked
203 species, such ecological knowledge is likely gained through personal experience built up
204 over years of observation and reflection²⁸, and people may not be consciously aware of it or
205 how it impacts their behaviour⁸.

206

207 **The role of power**

208 Our third key result provides evidence that perceived power – a key indicator of agency –
209 plays a critical role when it comes to encouraging, or discouraging, adaptive behaviour.
210 Specifically, we found that households that felt they had power or influence over decisions
211 about marine resources (the primary source of income and food) were more likely to adapt,
212 but less likely to transform (Table 2, Supplementary Tables 5 and 6). Moreover, power
213 played a disproportionate role on the adaptive behaviour of households with less exposure
214 to others who had taken action in response to climate change (Fig. 4, Methods,
215 Supplementary Methods). By definition, transformative action supports moves to reorder
216 social-ecological relationships, thereby challenging existing structures^{31,34,36}. Yet people can
217 be resistant to fundamental change, particularly those in powerful positions who may stand
218 to lose from such changes, which often involve shifts in power^{8,36}. Our results thus critically

219 underscore the importance of carefully considering the role of local power dynamics in
220 shaping responses to climate change, as these dynamics can affect the ability of people,
221 communities, and entire social-ecological systems to deal with dramatic change which may
222 require more fundamental action extending beyond what is typically understood as adaptive
223 in order to sustain livelihoods and ecosystems ^{14,36}.

224

225 Surprisingly, we found that none of our indicators of flexibility or financial assets were
226 significantly related to adaptive or transformative action (Table 2, Supplementary Tables 5
227 and 6). In line with recent research highlighting the important, yet often overlooked role of
228 socio-cognitive constructs in supporting adaptive behaviour ^{7,8}, we also found that
229 perceptions of past experience with more severe impacts were significantly related to
230 adaptive action. Yet neither of our indicators of the socio-cognitive domain were significantly
231 related to transformative action. Developing a better understanding of when and how
232 transformative action may be shaped by past experience, and other socio-cognitive factors
233 like risk perception, is an area ripe for future research.

234

235 **Conclusion**

236 Financial assets have long been emphasized as a crucial component of adaptive capacity
237 ^{3,4}. As such, many adaptation programs have focused heavily on building financial assets as
238 well as fostering the flexibility for people, households, and communities to adjust to current
239 and future changes ^{6,42}. By simultaneously examining six domains of adaptive capacity, we
240 show that adaptation programs that focus heavily on building financial assets could benefit
241 extensively if they accounted for the organization, learning, and agency domains of adaptive
242 capacity. Case studies, such as ours of a Papua New Guinean tropical island community,
243 are critical to building the evidence base on complex social-ecological interactions and how
244 they relate to human behaviour ⁴³. We therefore believe our results are likely to be of wide
245 interest and may have relevance to other similar contexts. Indeed, many island communities

246 around the globe, particularly across the tropics, face similar climate change challenges and
247 need the capacity to adapt. In this context, our results suggest that harnessing the influence
248 of networks, facilitating individual and social learning, and carefully considering power
249 dynamics could add considerable value to existing approaches aimed at reducing climate
250 vulnerabilities.

251 **Methods**

252 **Summary of empirical strategy.** This research was conducted in a low-lying coral island in
253 the Manus province of Papua New Guinea. The island is home to a population of
254 approximately 700 people living in 140 households. To understand responses to climate
255 change in this context, we collected a combination of quantitative and qualitative
256 interdisciplinary data including a full population census, semi-structured social surveys with
257 household heads as representatives of their household (N = 138 out of 140 households), key
258 informant interviews (N = 3), and observed fish landings. We also constructed full social-
259 ecological networks akin to Fig. 3A using information from our census, semi-structured
260 surveys, fish landings data, expert knowledge, and published reports. Using this information,
261 we employed novel multilevel network modelling methods in order to simultaneously test
262 how adaptive and transformative action were shaped by twenty key indicators of six broad
263 domains of adaptive capacity, including a household's position in a complex social-
264 ecological network and the behaviour of other households in the network (i.e., network
265 exposure ²⁵). The census, surveys, and interviews were conducted from May – June 2018 in
266 the local language.

267

268 **Responses to climate change.** A broad understanding of responses to climate change
269 among island households was gained via key informant interviews. We captured specific
270 household-level responses in our semi-structured surveys by pooling information from two
271 questions: (1) we directly asked households whether they had made any changes in
272 response to the impacts of climate change; and if so, we asked them to recall what those
273 changes were; and (2) we asked about specific livelihood activities that brought food or
274 money into the household. (2) was included because key informants identified atoll farming
275 as a response to climate change, which was initially introduced on the island by The Nature
276 Conservancy (TNC) in 2017 as an alternate food and income source (see ⁴⁴). Historically
277 there had been little to no engagement in agriculture due to land shortages and poor soil
278 quality, and the island community had been almost entirely dependent on fishing and related

279 activities. Responses were coded as adaptive and/or transformative following the definitions
280 in the main text (see Supplementary Methods and Supplementary Tables 1 and 2 for a
281 summary and descriptive statistics of identified responses). We gathered additional
282 information directly from TNC about how atoll farming was introduced on the island in order
283 to ensure it did not introduce any bias into our results. We found that many who were initially
284 trained in atoll farming methods through the TNC initiative (6 months prior to our fieldwork)
285 either did not adopt and/or continue the practice; yet the activity spread well beyond those
286 initially trained (Supplementary Methods). Importantly, attending a training session was not
287 meaningfully correlated with our transformative action variable ($r = 0.15$) nor was it is
288 significant ($p = 0.12$) in a binary logistic regression on our transformative action variable that
289 included our social and economic indicators of adaptive capacity (Table 1, Supplementary
290 Methods).

291

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

306 as government officials, non-government organizations, and business leaders). Ties to
307 external actors were summed and treated as the node-level attribute 'linking ties' (Fig. 3d).
308
309 The island is primarily a fishing community, with fish comprising the primary source of both
310 income and protein. The ecological network (B , Fig. 3) thus captures trophic interactions (i.e.
311 predator-prey relationships) among target fish species comprising the majority of catch by all
312 fishing gears employed on the island with the exception of gillnets, which were excluded due
313 to strong traditional customs that limit when gillnets can be used and by whom ($N = 60$
314 species, Supplementary Methods). Target species for each gear type were identified using
315 detailed catch surveys collected in the same timeframe the social surveys were performed
316 (Supplementary Methods). Trophic interactions capturing predator-prey relationships among
317 the 60 primary target fish species were estimated based on a combination of diet, relative
318 body size, and habitat use (likelihood of encounter, Supplementary Methods)⁴⁵. The
319 corresponding ecological network was thus undirected, with edges representing trophic
320 interactions between fish species (Supplementary Figure 1). Social-ecological ties (X , Fig. 3)
321 were identified by linking individual fish species to households via the fishing gears they
322 used, as identified in our semi-structured social surveys. In other words, if household A_i
323 used gear type G_t , which targets fish species B_u , a social-ecological link would exist between
324 household A_i and fish species B_u .

325

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

331 (1) Assets. We focused on financial assets by measuring wealth, access to credit, and
332 remittances. We used a material style of life index for *wealth*⁴⁶ that included

333 measurements of housing materials (e.g., types of roofing, walls, and floors) and
334 material assets (e.g., boats, generators, solar panels, and agricultural assets like
335 chickens⁴⁷). *Access to credit* was a binary variable measuring whether households
336 had access to credit through formal (i.e. banks and financial institutions) or informal
337 (e.g. friends and family) means. *Remittances* was a binary variable measuring
338 whether the household receives remittance (cash) payments from family off-island, of
339 any amount or frequency.

340 (2) Flexibility. We measured technological diversity (i.e. flexibility within fishing
341 livelihoods), occupational multiplicity (i.e. having two or more livelihood options), and
342 the *age* of household heads. Age of primary decision-makers was included because
343 it has been shown to influence planning horizons, skills, experience^{48,49}, behavioural
344 barriers⁵⁰, and the propensity to adopt innovations⁵¹ in ways that influence adaptive
345 strategies³⁵. *Technological diversity* measured the number of different types of
346 fishing gears (e.g. spear gun, net) owned by a household¹⁵. *Occupational multiplicity*
347 was the total number of livelihood activities that brought food or money into the
348 household (with the exception of atoll farming, which was captured as one of our
349 transformative responses).

350 (3) Social organization. We measured levels of trust in institutions. We also used four
351 network configurations capturing aspects of social capital (defined here as including
352 networks, norms, and trust^{16,17}) and key social relationships: i. social connectivity
353 (how well connected households were in the social network, which can provide
354 access to information and resources²⁴; Fig. 3b); ii. social-ecological connectivity
355 (which extends the idea of social connectivity to the ecological system¹⁴; Fig. 3e); iii.
356 linking ties (ties to external actors, which can provide access to a diversity of
357 information and support²⁴; Fig. 3d), and iv. exposure via network contacts ('network
358 exposure', which can capture effects of social influence²⁵ and social selection; Fig.
359 3c). For *trust in institutions*, we calculated a continuous indicator based on the
360 median of three Likert-scale questions that gauged how much household heads

361 trusted locally-relevant institutional actors (i.e., those who would be responsible for
362 supporting and/or safeguarding adaptive and transformative actions); these were
363 community leaders, local government, and police ¹⁵. *Linking ties* was a continuous
364 variable capturing the number of relationships the household had with external
365 actors, such as government officials, non-government organizations, and business
366 leaders (Fig. 3d). We used a continuous indicator because as the number of external
367 ties increase, so too does the potential exposure to outside ideas and influence.
368 *Social connectivity*, *social-ecological connectivity*, and *network exposure* were
369 measured using structural parameters in our multilevel network model (see
370 'Modelling procedure' below).

371 (4) Learning. We measured years of formal schooling of household heads (*education*,
372 which can help train people to learn ^{52,53}); and used four network configurations
373 capturing the manner in which households are connected with ecosystems and each
374 other, which can facilitate social and individual learning about ecological states and
375 trends ¹⁴. These were: i. social-ecological triangle (where households linked to the
376 same resource are socially connected, which may facilitate social learning about
377 shared ecological resources ^{14,26}; Fig. 3f), ii. ecological-social triangle (where a
378 household is connected to two interdependent resources), which may help to build
379 knowledge about interconnected resources and provide the necessary structural
380 foundation for households to internalize ecological feedbacks ²⁹, Fig. 3g), iii. social-
381 ecological square (where socially connected households are connected to
382 interdependent resources, which may enable social learning about interconnected
383 resources and provide the necessary structural foundation for the internalization of
384 ecological feedbacks ^{14,29}; Fig. 3h), and iv. open social-ecological square (which
385 captures linked households with many ties to divergent resources which may
386 facilitate social learning about broader ecological trends ^{24,30}; Fig. 3i). These
387 hypothesized configurations were identified in existing literature (e.g., ^{6,14}) and further
388 developed through a workshop conducted in 2018. We measured them using

389 structural parameters in our multilevel network model (see 'Modelling procedure'
390 below).

391 (5) Socio-cognitive constructs. We measured both past experience and future risk
392 perceptions because existing research has demonstrated that adaptive behaviour is
393 often positively correlated with the physical closeness and/or intensity of previous
394 related experiences ¹² and the perceived severity of future impacts (risk appraisal)
395 ^{11,54}. *Past experience* was a binary indicator of previous experience with severe
396 climate change impacts. We used a relative measure based on whether household
397 heads (as representatives of their household) felt they had been impacted by climate
398 change worse than most others in the community (1), compared to whether they felt
399 they had been impacted the same or less than others (0). A relative measure for past
400 impacts was used because research in psychology on risk and social comparison
401 suggests that people often compare their relative standing to others in order to form
402 judgements ⁵⁵, and the manner in which people view the impacts of climate change
403 are often socially mediated ⁵⁶. *Future risk perception* was a binary indicator
404 measuring whether households felt that climate change impacts were getting worse
405 (1), compared to staying the same or improving (0).

406 (6) Agency. We measured active (involvement) in decision-making and perceived
407 power/influence over decision-making ⁵⁷. *Active in decision-making* was a binary
408 variable measuring whether household heads were actively involved in decisions
409 about marine resources (1), as opposed to only being passively involved (e.g.
410 attended meetings but did not speak) or not involved at all (0). *Power/influence* was a
411 binary indicator that captured whether household heads felt they had some or lots
412 power/influence over decisions about marine resources (1), or little or no
413 power/influence (0).

414

415 **Modelling procedure.** We employed novel multilevel network modelling methods that
416 explicitly account for network dependencies in order to simultaneously test how adaptive and
417 transformative action were shaped by our indicators described above. We took a two-stage
418 approach to our analysis to ensure these models were not overparametrized. Firstly, we ran
419 logistic regression models on adaptive and transformative action including all non-
420 (structural) network indicators of adaptive capacity (indicators 1 – 7, 10, and 16 – 20 in Table
421 1). Structural social and social-ecological network effects (i.e., indicators 8 – 9 and 11 – 15
422 in Table 1, which are depicted as network configurations in Fig. 3b – c and e – i) could not
423 be included at this stage because they can only be modelled using specific network-based
424 models that account for the structure of the multilevel social-ecological network and the
425 interdependencies among the adaptive or transformative actions of networked actors
426 (households in this case). Linking ties (indicator 10 in Table 1 and depicted in Fig. 3d) was
427 included in the initial logistic regressions because it was measured as continuous covariate
428 (and treated as a node-level attribute), as described above. Results of our logistic
429 regressions are included in Supplementary Table 4. All indicators that were significant at the
430 10% level were included as candidate predictors in our final multilevel network models. We
431 choose a significance level of 10% in order to reduce the chance that a potentially important
432 indicator was overlooked in our final models. Following this criteria, the following non-
433 structural network indicators (i.e., node-level attributes) were included in our final multilevel
434 network models: (a) for adaptive action: education, past experience, active in decision-
435 making, and power/influence; (b) for transformative action: remittances, age, linking ties,
436 active in decision-making, power/influence.

437

438 Secondly, in our final models we extended the current functionality of the Autologistic Actor
439 Attribute Model (ALAAM)²² to account for a complex, multilevel (social-ecological) network
440 structure (Supplementary Methods). ALAAMs model the behaviour of network actors as a
441 function of the network structure and other actor (node-level) attributes (or covariates).
442 Compared with traditional logistic regression, ALAAMs explicitly account for network

443 positions as well as how the behaviour of networked partners may be dependent on one
 444 another (i.e., network exposure). For multilevel networks, we used ALAAM to test how the
 445 relationships defined in the social and ecological system affected individual household's
 446 behaviour, with effects represented by network configurations Fig. 3b, d - i. We label the
 447 outcomes or actors who have taken the actions as (Y), the social network as (A), the
 448 ecological network as (B), meso-level social-ecological interactions as (X), and other actor
 449 attributes (i.e., other non-network indicators of adaptive capacity) as (Y^c). The multilevel
 450 ALAAM can thus be expressed as

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

451 where $z_Q(Y, A, B, X, Y^c)$ are graph statistics counting the number of the configurations of type
 452 Q as listed in Figure 2. θ_Q are parameters determining the predominance of various
 453 configurations contributing to the overall outcome (Y). A positive and significant parameter
 454 estimate suggests the corresponding configuration occurs more than we expect by random
 455 conditioning on the rest of the model, whereas negative estimates mean the opposite. κ is a
 456 normalizing constant which allows the ALAAM to follow a proper probability distribution. We
 457 estimated the ALAAM parameters using Markov Chain Monte Carlo (MCMC) maximum
 458 likelihood methods⁵⁸ implemented in the MPNet software⁵⁹. Following^{60,61}, model
 459 convergence and goodness of fit (GOF) tests were assessed using the procedure presented
 460 by Koskinen and Snijders⁶², which compares the observed network statistics with simulated
 461 samples from the converged model using t-ratios as testing statistics, where t-ratios smaller
 462 than 0.1 in scale indicate model convergence. Though this procedure is most commonly
 463 known for its application to exponential random graph models (ERGMs), an ALAAM can be
 464 considered as a special case of a bipartite ERGM for a n (individual) by 1 (outcome) bipartite
 465 network, while using the one-mode n by n network as a covariate²². The definitions of the
 466 various configurations in ALAAMs and ERGMs can be the same, and the estimation and
 467 GOF test techniques applied in ERGMs are equally applicable to ALAAMs⁵⁹, with the

468 implementation in MPNet sharing the same technical approaches⁵⁹. Supplementary Table 5
469 presents full model results for our ALAAMs on adaptive and transformative action.

470

471 **Model interpretation.** The estimated effects in our ALAAMs can be interpreted as the
472 predominance of various attributes and social-ecological network positions affecting
473 individual household's adaptive behaviour. Using the network exposure effect as an
474 example, it has a positive and significant estimate in both of our final models (Table 2,
475 Supplementary Table 5), suggesting a household is more likely than we would expect at
476 random (given the rest of the model) to have taken adaptive and/or transformative action if
477 they are connected to network partners that have taken similar actions. This is a general
478 statement across the overall network. Fig. 4 compared households whom feel they have
479 power or influence over decisions about marine resources verses others in terms of their
480 adaptive and transformative action taking probabilities depending on the number of network
481 partners they have who have taken similar action, given all else being equal, such as
482 average education levels or average numbers of social-ecological squares a household is
483 involved in. The probabilities are calculated by the original likelihood $\Pr(Y_i = 1|X, Y^c) =$
484 $1 / \{1 + \exp\{- (\theta_{density} + \theta_Q z_Q(Y_i, X, Y^c))\}\}$, where $z_Q(Y_i, X, Y^c)$ is the number of configuration
485 of type Q node i is involved. As we can see from Fig. 4, having different numbers of network
486 partners that have taken action will have different associations with the probabilities for a
487 household to have undertaken adaptive and/or transformative action themselves.

488

489

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

492

493 **Data Availability.** Summary data that support the findings of this study are available within
494 the paper and its Supplementary Information file. Raw ecological network data have been

495 deposited in the Tropical Data Hub and can be accessed at {link active upon article
496 acceptance}. Raw social and social network data are available upon request from the
497 corresponding author M.L.B. with reasonable restrictions, as these data contain information
498 that could compromise research participant privacy and consent.

499

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509

510 **Author Contributions.** M.L.B. designed the research. M.L.B., J.E.C., N.A.J.G., J.L., and
511 J.Z.M performed the research. M.L.B. and P.W analysed data. M.L.B., P.W., J.E.C.,
512 N.A.J.G., A.M.G., L.J., J.L., S.S. and J.Z.M. wrote the paper.

513

514 **Competing Interests Statement.** The authors declare no competing interests.

515

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663 Applications*, 141-166 (2013).

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665

666 **Figure legends**

667 **Fig. 1 Six key domains of adaptive capacity.** The assets that people can draw upon to buffer
668 shocks in times of need ⁴; the *flexibility* to change strategies, e.g. to move between livelihoods or
669 between techniques and practices within livelihoods ¹⁵; *social organization*, or the formal and informal
670 relationships that shape processes of social influence and determine whether and how people access
671 information, resources, and support ^{13,14,16,17}; *learning* to recognize change and strategically absorb,
672 process, and synthesize information in order to adapt to shocks and plan for uncertainties ⁶; *socio-
673 cognitive* constructs, such as risk attitudes and cognitive biases, that enable or constrain human
674 behaviour by influencing perceptions regarding the need to adapt to change (or not) and the costs
675 and benefits of adaptation ⁷; and the *agency* or power to determine whether to change or not,
676 including people's belief that they are empowered to manage and influence change ^{10,18}. These six
677 domains are interlinked such that feedbacks and interactions can occur, which are graphically
678 represented by connecting arrows. Note that interactions can occur among any of the domains (not
679 just the neighbouring ones). Adapted from ^{5,6}.

680

681 **Fig. 2 Empirical context and examples of adaptive and transformative action.** (a) An overhead
682 view of the Papua New Guinean island where we conducted this research. (b) Responses to climate
683 change classified as 'adaptive action' included constructing sea walls to protect existing land uses
684 (pictured). (c) Responses to climate change classified as 'transformative action' included engagement
685 in atoll farming (pictured), a form of livelihood diversification which represented a fundamental
686 departure from near complete dependence on traditional marine resource-based activities. Photos by
687 Dean Miller.

688

689 **Fig. 3 The potential role of social-ecological networks on responses to climate change.** (a) A
690 graphical depiction of our social-ecological network capturing trophic interactions among coral reef
691 fish species (ecological network – B, blue); communication relationships between coastal fishing
692 households (social network – A, red); the links households have to specific fish species based on their
693 fishing behaviours (social-ecological ties – X, grey); and the links households have to external actors
694 (green), such as government officials or individuals working with non-governmental organizations. (b-
695 i) Network configurations we hypothesize play a role in driving adaptive and transformative action (Y)
696 in response to climate change by supporting the organization and learning domains of adaptive
697 capacity; where (b) *social connectivity* captures connectivity in the social network which can provide
698 access to information and resources²⁴, (c) *network exposure* captures social processes such as
699 social influence via social network partners or the selection of network partners with the same beliefs
700 or behaviours, both mechanisms which can play a key role in shaping human behaviour²⁵, (d) *linking*
701 *ties* captures ties to external actors (e.g., government officials/NGO representatives/business leaders)
702 which can provide access to a diversity of information and support²⁴, (e) *social-ecological connectivity*
703 accounts for social connectivity that extends to the ecological system, (f) *social-ecological triangle*
704 captures a form of social-ecological alignment^{26,27} which may facilitate social learning about shared
705 ecological resources¹⁴, (g) *ecological-social triangle* captures a form of social-ecological alignment
706 which may help to build knowledge about interconnected resources and enable individuals to
707 internalize ecological feedbacks^{28,29}, (h) *social-ecological square* captures a form of social-ecological
708 alignment which may enable social learning about interconnected resources and the internalization of
709 ecological feedbacks¹⁴, and (i) *open social-ecological square* captures linked households with many
710 ties to divergent resources which may facilitate social learning about broader ecological trends^{24,30}.
711 Dashed lines in (a) represent examples of each of the network configurations (b-i); where two
712 overlapping dashed lines are present, two different configurations are highlighted.

713

714 **Fig. 4 The impact of power and network exposure on adaptive and transformative**
715 **behaviour.** Differences in the probabilities of taking (a) adaptive and (b) transformative actions
716 depending on the number of network contacts a household has that is also engaged in similar
717 action(s), and the perceived power or influence a household has over decisions about marine
718 resource management (Methods, Supplementary Methods). Shaded regions represent 95%
719 confidence intervals calculated based on the estimated standard error for the network exposure
720 effect.

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Tables

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

Domain	Indicators	Description
 Assets ¹	1. Wealth	Total value of household structures and possessions
	2. Access to credit	Access to credit through formal or informal means, e.g., banks/institutions, friends/family
	3. Remittances	Remittance payments from family members living or working off island
 Flexibility	4. Occupational multiplicity	Total number of different livelihood activities that bring food or money into the home
	5. Technological diversity	Total number of different types of fishing gears owned
	6. Age	Age of the primary decision maker in the household
 Organization	7. Trust in institutions	Median of Likert-scale responses regarding trust in community leaders, local government, and police
	8-11. Social networks	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	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)
	16. Education	Years of schooling
 Socio-cognitive	17. Past experience	Perception of severity of past climate change impacts compared to others on the island
	18. Risk perception	Perception that climate change impacts are getting better, worse, or staying the same
 Agency	19. Active in decision-making	Actively involved in decision-making about marine resource management
	20. Power/influence	Perception of power and influence to change or guide the management of marine resources

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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 capital²³) is an indicator of organization.












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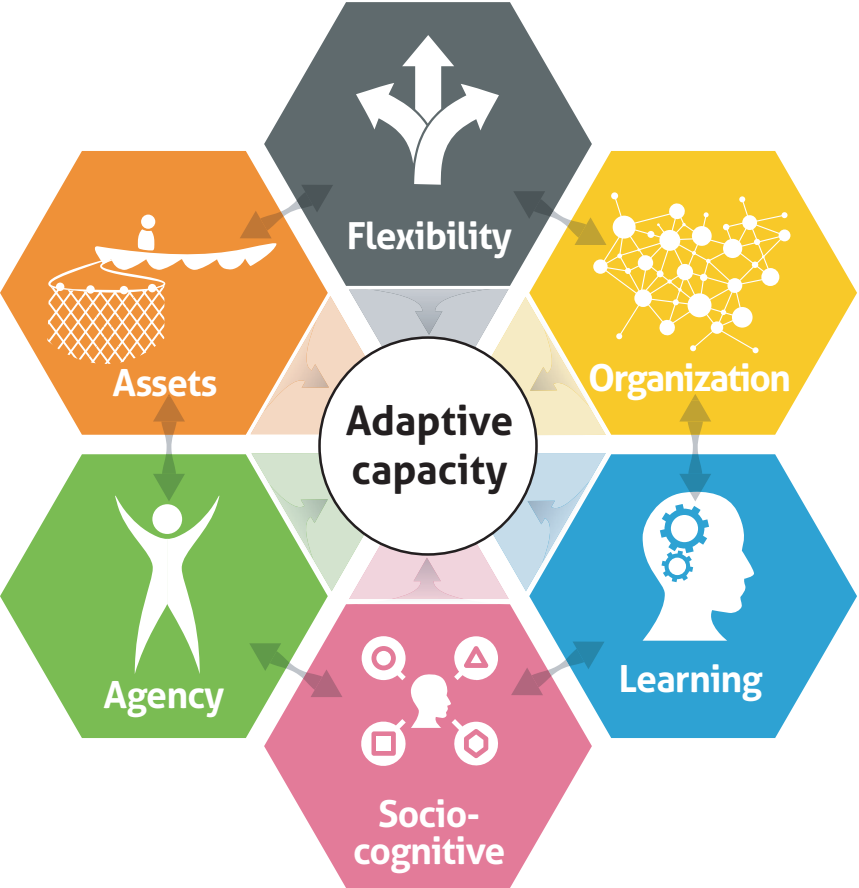
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739 **Table 2. Key factors shaping adaptive and transformative action.** Summary of results from our
 740 Multilevel Autologistic Actor Attribute Models arranged via adaptive capacity domains. All predictors
 741 significant at the 10% level or higher in each model are displayed. The sign (+/-) indicates whether the
 742 effect is positive or negative. Network configuration diagrams and colour coding are akin to those
 743 presented in Fig. 3. Goodness-of-fit tests demonstrate that these models provide a good fit to the
 744 empirical data (Methods, Supplementary Methods). Full model results and conditional log-odds can
 745 be found in Supplementary Tables 5 and 6.

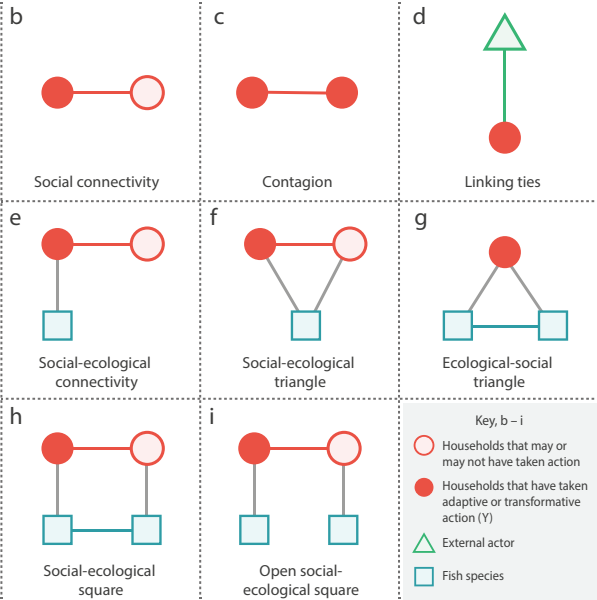
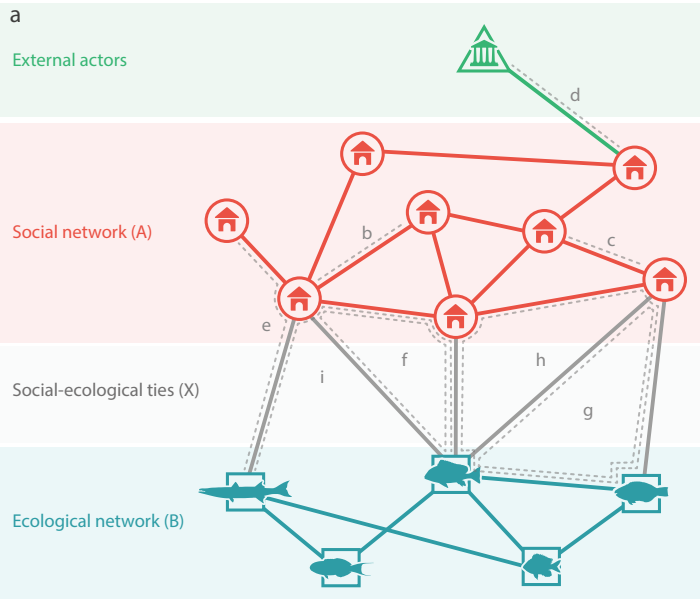
Domain	Adaptive action	Transformative action
 Assets		
 Flexibility		
 Organization	 Network exposure (+)	 Network exposure (+)
 Learning	Education (+)  Open social-ecological square (+)  Closed social-ecological square (-)	 Ecological-social triangle (+)
 Socio-cognitive	Past experience (+)	
 Agency	Power/influence (+)	Power/influence (-)

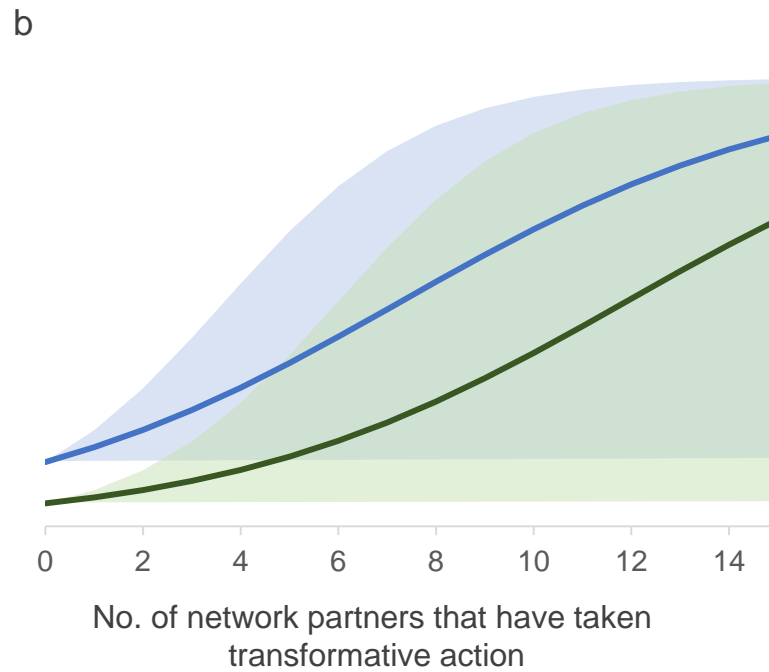
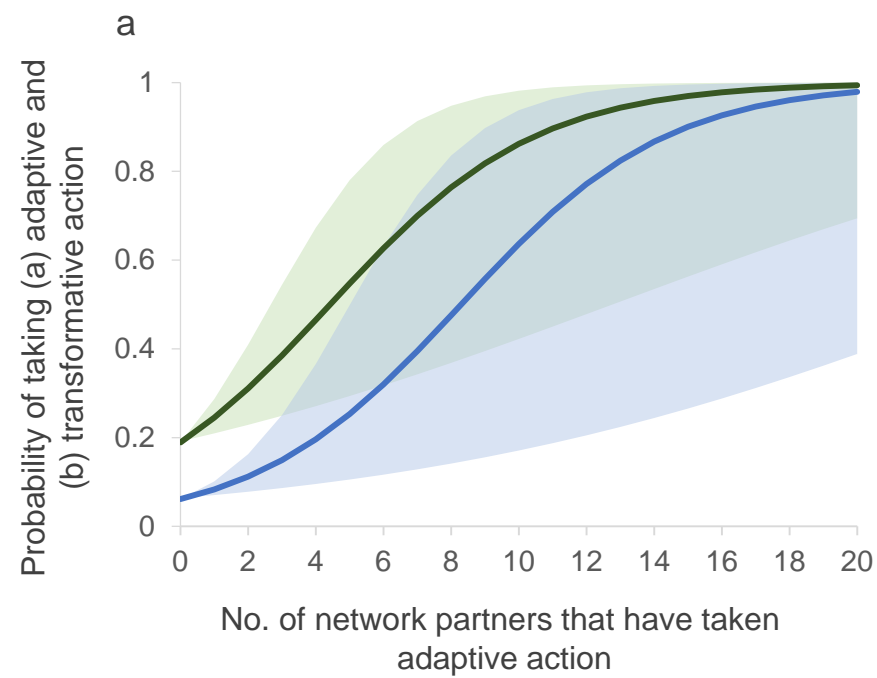
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■ Moderate to high influence/power
■ Little to no influence/power