

Supplementary Information for

Sixteen years of social and ecological dynamics reveal challenges and opportunities for adaptive management in sustaining the commons

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Supplementary text

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SI References

Other supplementary materials for this manuscript include the following:

The dataset includes ecological and social data collected in, and around, two coastal communities (Muluk and Wadau) in Karkar Island (PNG) across five intervals over 16 years. The ecological data contains estimates for structural complexity, coral cover, macro algae, epilithic algal matrix, and biomass estimates for key functional fish feeding groups (scrapers/excavators, grazers, browsers, macro-invertivores, micro-invertivores, piscivore-invertivores, piscivores, planktivores, and detritivores) at multiple sites and depths. The social data contains households responses of livelihood perceptions.

The data is available in James Cook University Tropical Data Hub.

1 **Decision-makers**

2 Decisions about reef closures are made adaptively by clan-chiefs, but with substantial input from
3 community members. For example, before the opening of the reef in 2017, each of the three
4 clans held meetings to not only discuss expected fishing trip contributions from each family to
5 provide fish for the opening ceremony, but also to decide the by-laws to be put in place once the
6 reef was opened. Once these clan meetings were concluded, the clan chiefs came together and
7 discussed their respective plans and proposed by-laws, eventually reaching consensus on the rules
8 for fishing on the reefs when once the reef was open. Although clan chiefs often work together to
9 make decisions about opening and closing reefs, they can make decisions individually about their
10 clan's reef territory. For example, in Muluk, the reef is divided into four clan territories (one clan
11 holds two non-contiguous territories). Each of the three clan chiefs has the right to open or close
12 their section of the reef, but in practice, all three clans tend to agree by consensus to open and
13 close the reef in concert.

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15 **Rationale for reef closure**

16 The reef is generally closed with the explicit purpose of making fish easier to catch in the future,
17 both by allowing them to breed and increase in abundance and also by de-sensitizing them to
18 fishing and thus lowering their wariness of fishers. Fishers explained that when the reef is heavily
19 fished, reef fishes become more wary of fishers (particularly spear-fishers) and kept a greater
20 distance, making them more difficult to catch (1). Fishers perceived that periodically stopping all
21 fishing activity made the fish 'tamer' (2). In addition to the utilitarian rationale for the closure,
22 multiple clan chiefs also described a notion of stewardship/responsibility for looking after
23 (*lukautim* in the lingua franca Tok Pisin) the environment. The rotational closure system is
24 considered a key part of this stewardship practice.

25
26 **Adaptive decisions about reef closure and opening**

27 There is no set period or allocated date for closing and/or opening the reef to fishing. Decisions
28 about when to open and close reefs are generally made such that the system is managed between
29 two dynamic baselines: a low baseline that signals clan leaders to close the reefs and a high
30 baseline that signals clan leaders to open the reef (1). Clan chiefs monitor declining catches and
31 difficulty catching fish from their own fishing experience, reports from fishers in the community,
32 and catches at landing sites. When fish are considered scarce and hard to catch- a low baseline-

33 clan chiefs close the reef to fishing and access for an undefined period. Reefs can also be closed
34 during a mourning period following the death of a chief or other person of high social standing in
35 the community, to provide food for a feast to end the mourning period. In this instance, it may
36 only be a single clan's reef closed. Thus, both social and ecological conditions can trigger a closure.
37 Likewise, clan-chiefs used the perceived 'tameness' of fish (i.e. the ability to swim closer to them
38 than before the closure) and perceived increased numbers of fish as indicators that the reef could
39 be re-opened to fishing- a high baseline. However, the decision to re-open a closed reef was in
40 part also linked to social considerations, such as upcoming celebrations. For instance, one clan-
41 chief suggested that Christmas was a good time to re-open the reef as school children who were
42 attending schools on the other side of the island were home and thus able to enjoy the opening
43 ceremony feast.

44 **Table S1. Broad themes and codes used for coding qualitative interviews**

Theme	Codes
Perceived benefits of adaptive management system	Improved fishing Good fortune and harm Creates identity and connection to ancestors/place Fulfilling customary obligations
Participatory decision-making among community members	Deliberative decision-making Participation in decision-making & customary events
Compliance	Good behaviour rewarded Deviance punished
Leadership & social cohesion	Leadership, obedience, and respect Youth-elder Responsibility Collective identity Caring and sharing Listening to leaders Conflict management

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46 **Table S2. Relationships between reef fish biomass (total and by functional group) and**
 47 **management, depth, and benthos.** Estimates, standard error, and t=values provided for the most
 48 parsimonious model (see methods). Data from 2009, 2012, 2016, 2017, except for browsers and
 49 piscivores, which are only from 2016 (methods).

	Rotational Closure	Depth (3m,7m)	Structural Complexity	% Cover Hard Coral	% Cover Epilithic Algal Matrix	% Macro Algae
Total Biomass	0.52(0.14), t=3.85		0.31(0.07), t=4.7		-0.02(0.008), t=-2.22	
Micro-invertivore	0.35(0.14), t=2.5					
Grazer	0.98(0.2), t=4.9		0.21(0.1), t=2.17			
Excavator/Scraper	0.81(0.26), t=3.12	-0.91(0.27), t=-3.36	0.41(0.16), t=2.43		-0.04(0.02), t=-2.56	
Piscivore- Invertivore	0.52(0.25), t=2.0	1.13(0.2), t=5.97			-0.03(0.01), t=-2.07	
Macro-invertivore	0.76(0.19), t=3.87					
Planktivore		0.8(0.18), t=4.54	0.37(0.12), t=3.34	0.01(0.004), t=2.45		0.03(0.02), t=-2.1
Detritivore		-0.48(0.13), t=-3.61				
Piscivore	0.91(0.49), t=1.84					
Browser	0.59(0.33), t=1.76					

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51 **Table S3. Flight initiation distance models for a) Wadau and b) Muluk**

	Estimate	Std. Error	df	t value	Pr(> t)
a) Wadau					
(Intercept)	416.5	38.3	5.5	10.9	6.29e-05 ***
Closure	-128.7	11.4	371.8	-11.3	< 2e-16 ***
b) Muluk					
(Intercept)	348.4	29.7	5.1	11.7	6.52e-05 ***
Closure	-84.4	10.0	476.6	-8.4	3.96e-16 ***

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53 **Table S4. Illustrative quotes Benefits**

Code	Quote[s]
Improved fishing	<p>Well, closing the sea, we rest it, no one can go into the sea to disturb the reef or disturbing the fish, no one can go and frighten the fish in the reef. It'll be easier in the future... all the fish will grow up and then men and women from the community will find it easier to catch fish. Even close to the beach, and bring them home to eat.</p>
Good fortune and harms	<p>This fulfils us, when we follow custom that the ancestors dictated. We live by the customs and we see the good things that come from following customs, and we know that custom is good.</p> <p>You must follow [the customary law], and you will see that you have plenty of fish and plenty of pigs and plenty of whatever you need. If you don't follow the law, you will lose all these things. This custom, it's so important here in Muluk.</p> <p>You're breaking the custom law. And custom has the power to cause you trouble, and custom has the power to help you live well.</p> <p>If you want to go to the sea, and your wife is menstruating, you cannot go. If you go a fish will shoot you and you will die. You can't eat tallis nut. If you eat tallis nut, then a fish will come and kill you dead. If you eat marita, a fish will kill you. If you eat 'pikpik', a fish will kill you.</p>
Creates identity & connection to ancestors/place	<p>It's something good that we have here; the way that we help other people, and work together and participate in big customary events in the community. Other places don't have this. Other places have gradually lost these ways.</p> <p>In terms of our thinking, practices and customs, we hold these ways strongly because our parents, and grandparents and ancestors taught us these ways.</p>

	<p>It's these things that make us who we are.</p> <p>Our young people see them, respect them, and see the fruits of these practices. We won't forsake them. Our ancestors have blessed these customs, and God has blessed them. And we hold onto them strongly.</p> <p>In terms of our thinking, practices and customs, we hold these ways strongly because our parents, and grandparents and ancestors taught us these ways.</p>
<p>Fulfilling customary obligations</p>	<p>So if there's customary work to be done in the community, everyone comes together to participate and listens and everyone cooperates, even if the call is last minute.</p> <p>These customs are very strong. We have to follow every single one of these. All three clans in Muluk, Boner, GanGan, Marmor – our customs are very strong</p>

55 **Table S5. Illustrative quotes for compliance**

Code	Quote[s]
<p>Good behaviour rewarded</p>	<p>One important thing is, our ancestors, when they wanted to bestow these rights on the young men, they chose the young men who respected their leadership, who obeyed the laws. A respectful man who obeyed the rules. The person's parents, the leaders, all the elders, and all three clans leaders, Boner, Gangan and Marror, they'd all meet and assess the person. And they'd say, this man, he's got good behaviour, ok and in Marror, they'd choose them, and Boner would choose them, and Gangan would choose them, ok and then, they'd all get a number. [bombom license]</p> <p>Not all men get it. Not everyone. All the leaders of the clans, Boner, Gangan, Maror, they choose who gets it. They must see that they're a good man, a respectful man, a law-abiding, obedient man.</p>
<p>Deviance punished</p>	<p>All the young people, they cannot talk back to us. If one is disobedient, then we'll bring him here to talk, and to follow the law of custom. Custom is the same as law. The law of the village. The custom law of this village, you cannot flaunt it. You can't mess with it.</p> <p>No outsiders would mess with it, no one from outside would dare come here and ruin it. The law will get you, the customs... the leaders will get angry. This is the most important custom we have, bombom.</p>

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61 **Table S6. Illustrative quotes for participatory decision-making among community members**

<p>Deliberative decision-making</p>	<p>We will have to have a meeting to discuss it. The practices that the ancestors followed, that continue today, these customs, we follow them. If we don't follow it, then we have to meet and talk about it, about how to do the right thing. It's by respecting custom that we can catch fish, with the net, that we make ourselves.</p> <p>All the leaders meet, and argue about it, and make sure the customs stay strong.</p>
<p>Participation</p>	<p>It's something good that we have here. The way that we help other people, and working together and participating in big customary work in the community. Other places don't have this. Other places have gradually lost these ways.</p>

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63 **Table S7. Illustrative quotes for leadership & social cohesion**

Code	Quote
<p>Leadership, obedience, and respect</p>	<p>The leader is responsible for looking after the reef. The leader is responsible and speaks for all culture and custom... that's what the leaders are for. Clan leaders, community leader, they all look after the people, the young people from here.</p> <p>... we have strong leaders, clan leaders and community leaders, the leaders strengthen the customs. They argue and talk strongly about these things. All the leaders meet, and argue about it, and make sure the customs stay strong</p> <p>When it comes to closing and opening the reef, we have leaders for that, you respect the leader.</p> <p>Like, all my brothers here, they're all talking about the customs and culture of the community... and its very important inside our community. Respecting and leading, that's very important for us.</p>
<p>Social cohesion</p>	<p>It's the way we listen and respect. We can go about our own lives, but when we hear news, then we always come together to help</p> <p>So, in our community, you can see all these kinds of arguments, and people get cross at each other, but something special we have is this way of bringing people together, all the time, and we keep living peacefully, and make sure the peace is maintained.</p> <p>Interviewer: What do you do to resolve conflicts? Interviewee: Well, we... the leaders speak out, we all meet, and sit down to sort it out. And once we've sorted it out, then its peaceful again. Our lives are very good here, before.</p>

Youth-elder ties	<p>Now all the young people, the young boys and girls, mums and dads, everyone knows that underneath the leader, whoever talks, all the young people respect and listen and follow the customs and culture of the community.</p> <p>The leaders, we all sit down and talk with the young people, about respecting the customs and the culture.</p> <p>We here in Muluk, this community, we, all of us young people from here, we've learned how to tambu the reef from the leaders here, and how to tambu the bush from hunting.</p>
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65 **Table S8. Parameter estimates from an exponential random graph model fit to directed**
66 **knowledge sharing ties among fishers in Muluk in 2016 (n = 41).** Structural effects capture self-
67 organizing network processes, such as closure (path closure) and centralization (activity and
68 popularity spread). The arc parameter is akin to the intercept in a linear regression. Clan-based
69 and leader effects are attribute-based, and capture whether leaders or people in particular clans
70 are more or less active in the network (either as a sender or receiver) or whether they
71 preferentially interact with others within their group (interaction). Results show that leaders are
72 significant ‘receivers’ in the network, indicating they are popular sources of information and
73 advice. Results from a goodness-of-fit test (3) indicated all features of the observed network were
74 fit well by the model.

Effects	Lambda	Parameter	Stderr	t-ratio	SACF	
<u>Structural effects</u>						
Arc	2	-4.493	1.167	-0.002	0.053	*
Reciprocity	2	-0.0273	1.13	0.006	-0.027	
Popularity spread (AinS)	2	0.3687	0.343	0	0.04	
Activity spread (AoutS)	2	-0.4583	0.384	-0.007	0.061	
Path closure (AT-T)	2	-0.1088	0.592	-0.04	-0.013	
<u>Clan-based effects</u>						
Clan A_Sender	2	-0.4374	0.662	0.032	-0.008	
Clan A_Receiver	2	0.3561	1.127	0.002	0.021	
Clan A_Interaction	2	1.2875	1.036	-0.023	0.037	
Clan B_Sender	2	-0.518	0.978	-0.05	-0.009	
Clan B_Receiver	2	0.7943	1.105	0.004	0.017	
Clan B_Interaction	2	0.9209	1.021	-0.053	-0.049	
<u>Leader effects</u>						
Traditional leader_Sender	2	-0.1446	0.588	-0.014	-0.03	
Traditional leader_Receiver	2	0.9667	0.416	-0.033	0.016	*
Traditional leader_Interaction	2	0.2953	0.681	-0.045	0.067	

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76 **Table S9. External vs. internal (E-I) knowledge exchange ties within and across age cohorts.** The
77 E-I index is calculated as the number of external group ties minus the number of internal group
78 ties divided by the total number of ties. Values range from -1 to 1, where -1 indicates complete
79 homophily (internal ties only) and 1 indicates complete heterophily (external ties only). The E-I
80 index for elders (shaded in gray) indicates a high level of external group ties.

	Internal	External	Total	E-I Index
Youth (youngest quartile)	12	9	21	-0.143
Middle Age	40	17	57	-0.404
Elders (oldest quartile)	4	20	24	0.667

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Covariate	Description
Closed	Refers to whether closure of reef was in place.
Depth	Reef fish and benthic visual surveys were undertaken within two depths: 3 m (corresponding to the reef flat habitat), 7 m (corresponding to the reef crest habitat).
Site	Seven individual reef sites (each 900 m ²), where reef fish biomass and benthic community structure were estimated.
Structural complexity (SC)	A measure of complexity provided by live corals, the underlying reef matrix and other geological features. Visual estimates of structural complexity were quantified five times along each transect using a 6-point scale: 0 = no vertical relief, flat or rubble areas; 1 = low (<30 cm high) and sparse relief; 2 = low but widespread relief; 3 = widespread moderately complex (30–60 cm high) relief; 4 = widespread very complex (60–100 cm high) relief with numerous fissures and caves; 5 = exceptionally complex (>1 m high) relief with numerous caves and overhangs.
Hard coral (HC)	Percent cover (%) of live scleractinian corals, identified to genera from point-intercept transects.
Macroalgae (MA)	Collective term used for seaweeds and other benthic marine algae >10 mm in height. Percent cover (%) of all macroalgae quantified from point-intercept transects. All macroalgae identified to genera.
Epilithic algal matrix ^L _{SEP} (EAM)	Collective term for epilithic algal communities (i.e. turf forming filamentous algae) and non-living component (i.e. detritus, sediment) ≤ 10 mm in height. Percent cover (%) of EAM quantified from point-intercept transects.

87 **References**

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