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REPORT

Community-based management fails to halt declines of bumphead parrotfish and humphead wrasse in Roviana Lagoon, Solomon Islands

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Abstract Community-based fisheries management that integrates local knowledge and existing user rights is often seen as a solution to the failures of top-down fisheries management in the Pacific. In Roviana Lagoon, Western Solomon Islands, a network of community-based marine protected areas (MPAs) was established in the early 2000s to conserve declining populations of bumphead parrotfish (*Bolbometopon muricatum*) and other locally valuable fish species such as humphead wrasse (*Cheilinus undulatus*). We aimed to evaluate the success of these protected areas at preventing declines of *B. muricatum* and *C. undulatus*. We conducted 27 underwater visual census (UVC) surveys at permanent passage and outer reef monitoring sites in Roviana Lagoon in 2018 and compared our findings with results from 72 UVC surveys that we had conducted at the same sites 18 yrs earlier. We also interviewed Roviana spearfishers about their maximum nightly *B. muricatum* catches from 2018, the early 2000s and the 1980s. Abundances of all *B. muricatum* and *C. undulatus* sighted on UVC surveys declined by 62% and 57%, respectively, between 2000 and 2018, and abundances of adult *B. muricatum* and *C. undulatus* declined by 78% and 72%, respectively, over the same period. Using a joint model of *B. muricatum* abundance and its reported maximum catch, we estimated that in 2018 the population of *B. muricatum* was 8% of its 1980's abundance. By modelling projected rates of decline over three generations, we show that populations of *B. muricatum* and *C. undulatus* in Roviana Lagoon meet the IUCN Red List thresholds for Critically Endangered (CR). The probable causes of these declines are sustained fishing pressure, poor enforcement of community-based management measures and loss of fish nursery habitats due to logging. Our findings suggest urgent co-management of the ridge-to-reef system is needed to prevent further fish population declines in Roviana Lagoon.

Keywords *Bolbometopon muricatum* · *Cheilinus undulatus* · Monitoring · Local knowledge · Coral Triangle · Bayesian generalized linear model · IUCN Red List

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Introduction

The bumphead parrotfish (*Bolbometopon muricatum*) and the humphead wrasse (*Cheilinus undulatus*) are two of the largest bony fishes found on Indo-Pacific coral reefs. Both species are scarine labrids (Westneat and Alfaro 2005) that begin to mature at the age of 6 yrs and grow to over 1 m in length (Choat et al. 2006; Taylor et al. 2018). On many lightly to moderately exploited reefs *B. muricatum* and *C. undulatus* form important components of subsistence and small-scale commercial fisheries (e.g. Hamilton et al. 2012a; Rhodes et al. 2018). However, there is widespread concern over the status of both species (Fenner 2014), with population declines reported across their ranges (Sadovy et al. 2003; Bellwood et al. 2003; Donaldson and Dulvy 2004; Dulvy and Polunin 2004; Hamilton and Choat 2012). These declines have been attributed to commercial fishing pressure to supply local, national and international markets (Sadovy et al. 2003; Hamilton and Choat 2012) and the loss of inshore recruitment habitat (Hamilton et al. 2017). The predictable nocturnal aggregating behaviour of *B. muricatum* makes this species vulnerable to night spearfishing (Hamilton et al. 2016), with *C. undulatus* susceptible to a range of fishing gears including hook and line, spearfishing and traps (Colin and de Mitcheson 2012; Lindfield et al. 2014). *C. undulatus* is also a prime target of the live-reef food-fish trade (LRFFT) (Sadovy et al. 2003).

Once overfished both species have low recovery potential due to life-history traits that include late maturation and long-life span (Choat et al. 2006; Andrews et al. 2015; Taylor et al. 2018). *B. muricatum* is listed as Vulnerable (VU) and *C. undulatus* is listed as Endangered (EN) on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Russell 2004; Chan et al. 2012). *C. undulatus* is also listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Vincent et al. 2014). Despite these listings, there remains a scarcity of long-term empirical data upon which temporal trends in *B. muricatum* and *C. undulatus* populations can be examined. This data gap hinders evaluating the effectiveness of local management actions and the status of these fish species on the IUCN Red List. Typically, population declines in these species have been inferred from spatial comparisons or local knowledge surveys. For example, Sadovy et al. (2003) collected abundance data of *C. undulatus* across its geographic range and found a tenfold decreases in *C. undulatus* in fished areas compared to unfished areas. While Lavides et al. (2016) used local knowledge surveys to conclude that the mean perceived biomass of *B. muricatum* and *C. undulatus* declined by 82% and 88%, respectively, between the 1950s and 2014 in five regions of the Philippines.

Here we report on changes in abundance of *B. muricatum* and *C. undulatus* over 18 yrs from surveys in Roviana Lagoon, Western Province, Solomon Islands. Roviana fishers developed traditional fishing methods and detailed local knowledge about *B. muricatum* (known as “Topa” in the local language) and *C. undulatus* (“Habili”) generations ago (Aswani 1997; Hamilton 2003), and both species remain highly valued in contemporary Roviana culture. In the early 1980s, a commercial night spear fishery for *B. muricatum* developed in Roviana Lagoon (Hamilton 2003), and in the mid-1990s *C. undulatus* were targeted to supply LRFFT operations (Johannes and Lam 1999). The ecological impacts of the commercial *B. muricatum* fishery that operated from 1980 to 2000 have been inferred from local knowledge surveys (Hamilton 2003, 2005). In the early 1980s night spearfishers reported very high catches of *B. muricatum*, with catch rates having declined rapidly by 2000 (Hamilton 2005). Concern over the perceived declines in commercially valuable fish stocks in Roviana Lagoon resulted in efforts to manage the lagoon’s fisheries through the establishment of a network of small community-based marine protected areas (MPAs) (e.g. Aswani and Hamilton 2004a, b; Weiant and Aswani 2006; Aswani et al. 2007).

One of the primary objectives of establishing this network of MPAs was to conserve populations of *B. muricatum* in Roviana Lagoon (Olds et al. 2014). Despite these efforts, some Roviana fishers and scientists are of the view that valuable finfish resources in Roviana Lagoon are continuing to decline (Hughes, personal communications, 2018; Ensor et al. 2018). To evaluate these perceptions, we conducted underwater visual census (UVC) and local knowledge surveys in Roviana Lagoon in 2018 and compared our findings with UVC and local knowledge surveys that we had conducted in Roviana Lagoon 18 yrs earlier. We developed Bayesian generalised linear mixed models (GLMMs) to assess the changes in the abundance and size structure of *B. muricatum* and *C. undulatus* that were sighted at permanent UVC sites during these two distinct time periods. For *B. muricatum,* we also developed a joint model that integrated UVC and local knowledge and allowed us to estimate change in abundance since the 1980s. We apply the model to project declines in adult populations over three generations, allowing us to assess declines relative to IUCN Red List Criteria A for population decline (past, present and/or projected).

Methods

Local knowledge surveys

In 2000 we conducted detailed interviews with fifteen active and six retired *B. muricatum* spearfishermen. These interviews were undertaken to document local knowledge on *B. muricatum* ecology and to build a picture of technological, ecological and economic changes that had occurred in this fishery since the 1940s (Hamilton 2005). Interviews were carried out with spearfishermen from the communities of Dunde, Nusa Roviana, Nusabanga, Sasavele, Baraulu, Bula Lavata and Nusa Hope in Roviana

Lagoon. These interviews revealed that large catches commenced in the 1980s, which coincided with the introduction of underwater flashlights and the establishment of fisheries centres at the provincial headquarters of Munda. The interview questions that were asked to night spearfishermen in 2000 that are relevant to this study were: Question 1: "What was the most Topa you ever caught in a single night when you first started spearfishing?" and Question 2: "What is the most Topa you have caught in a single night in the last 2 yrs?". In 2018 we discussed the purpose of this study with eight active night spearfishers from the communities of Dunde, Nusabanga, Sasavele and Nusa Hope and asked them Question 2. We focused on questions that relate to maximum catch since memory that is related to self-esteem can be positively biased (Thompson et al. 1996), hence maximum catches may be more memorable than "average" catches (Hamilton et al. 2012b). In both time periods, the only fishers in Roviana Lagoon that targeted *B. muricatum* were night spearfishermen. Interviewees were selected based on authors' prior knowledge of night spearfishermen and through peer recommendation (Davis and Wagner 2003).

UVC surveys

We conducted repeated underwater visual census (UVC) surveys at four permanent monitoring sites located in passage and outer reef environments in Roviana Lagoon during daylight hours (Fig. 1). Sites were randomly selected to reflect typical passage and outer reef environments, which is where subadults and adults of both species are found (Hamilton et al. 2016). UVC surveys were done by two SCUBA divers and consisted of 500-m-long swims along passage and outer reef slopes at a depth of 10 m. UVC surveys took approximately 20 min. Initially the exact length of the transects was determined by laying out a 50-m transect ten times, with GPS readings taken at the transect start points. On each survey one diver recorded the size of each *B. muricatum* and *C. undulatus* observed within a 20-m-wide band, 10 m either side of the diver. Hence each UVC survey covered one hectare of reef. Long UVC surveys were used since this is the most suitable method for surveying populations of naturally rare species such as *B. muricatum* and *C. undulatus* (Choat and Pears 2003). The permanent UVC sites were surveyed 72 times between October 2000 and June 2001 on new and full moon phases, and 27 times between March and October 2018 on new, full and last quarter lunar phases

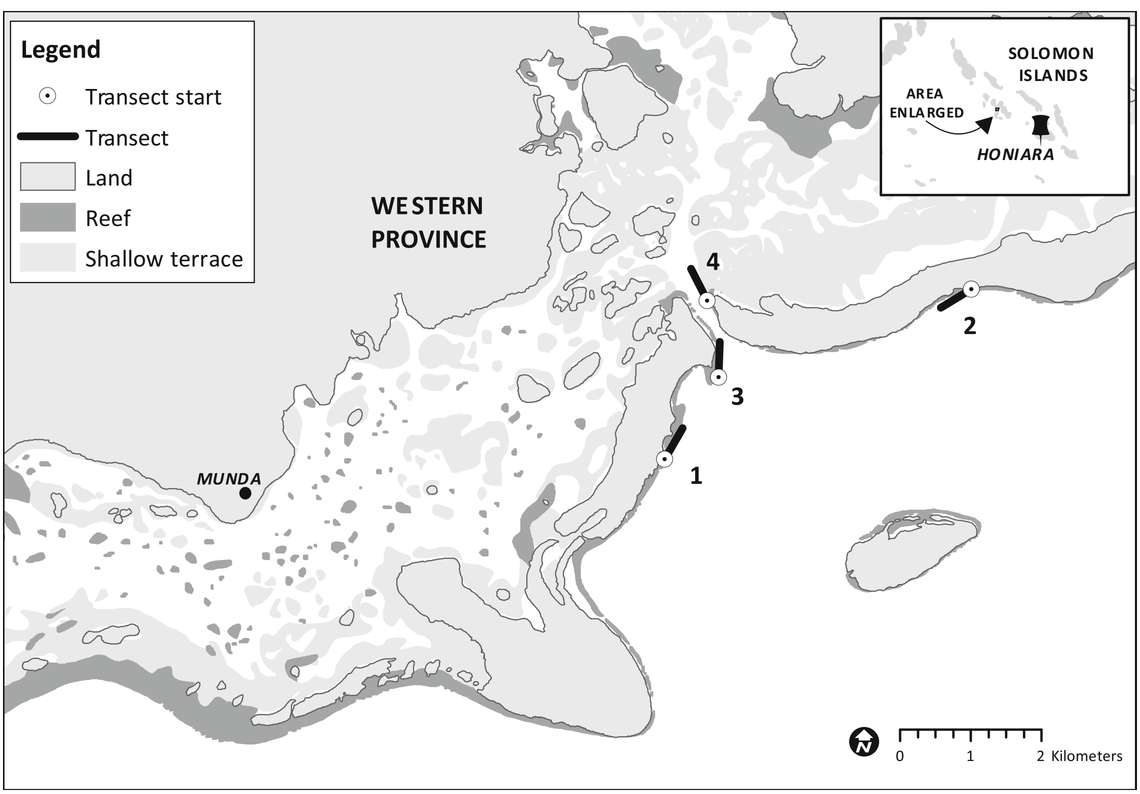


Fig. 1 Location of the four permanent UVC sites. Sites 1 and 2 are located on outer reef slopes, and sites 3 and 4 are located in passage slopes. The location of Munda township is also shown

(Electronic supplementary material, Table S1, Table S2 and Table S3).

Statistical analysis

Change in abundance

We developed two Bayesian GLMMs for change in abundance between the UVC surveys in the 2000s to the surveys in 2018. The first model was applied to UVC counts for *B. muricatum* and *C. undulatus*. This model used a log link with a Poisson distribution for *C. undulatus* counts and a negative binomial distribution for *B. muricatum* counts. The choice of distributions was made on the basis of exploratory analysis that suggested counts were overdispersed relative to a Poisson for *B. muricatum* but not *C. undulatus*. The log link meant that change in abundance over the 18-yr time period was modelled as a multiplicative (exponential) change. We included an additive random effect for sites.

We did not include an effect of lunar period, because it has previously been shown not to affect abundance counts in UVC analysis (Hamilton 2005). We repeated that analysis here using Bayesian methodology once again finding that moon phase had no impact on abundance (Electronic supplementary material, Table S4).

The model for abundance was thus specified:

$$\ln(y_{i,j,t}) \sim Poisson(\mu_{j,t})$$

$$\mu_{j,t} = a_n + \beta_n x_t + s_j$$

where $y_{i,j,t}$ are the UVC counts for survey i at site j at time period t, $\mu_{j,t}$ is the linear predictor for the Poisson (or negative binomial for *B. muricatum*) distribution, a_n is the intercept, β_n is the log magnitude of decline, x_t is an indicator for 2000s (= 0) or 2018 (= 1) and s_j are the site random effects.

The second model was applied only to the data for *B. muricatum*, for which we had information on historical maximum nightly catch rates. We aimed to estimate the magnitude of the bias between maximum catch and UVC abundance based on the 2000 and 2018 data. We then used the estimated bias to correct the 1980s maximum catch data and infer on what UVC abundances would have been in the 1980s. We assumed that UVC abundance measures were an unbiased sample of population density, whereas maximum catch was a biased measure. We treated maximum catch as biased because we expected catch records to be hyper-stable relative to abundance (Hamilton et al. 2016).

We jointly modelled changes in abundance in the UVC and changes in historical catch rates to estimate the relationship between catch rates and UVC abundance. We modelled maximum catch as Poisson distributed:

$$c_i \sim \text{Poisson}(v_i)$$

$$v_i = a_c + \beta_c x_i + \beta_{dh} z_i$$

where a_c is the expectation for catch in 2000s (logged), β_c is the difference in logged mean catch from the 2000s to 2018 and β_{dh} is the difference in logged mean catch from 2000s to 1980s. x_i and z_i are indicator variables for the time period of the observation.

To link maximum catch to UVC abundance we further required that the difference in logged maximum catch was the sum of the difference in UVC abundance and a bias correction factor:

$$\beta_c = \beta_n + \beta_m$$

where β_m had a weakly informative normal prior (mean = 0, sd = 3). Thus β_m represents a multiplicative correction factor for the difference between the UVC change in density (β_n) and the change in density as estimated by maximum catch.

We then estimated the change in maximum catch from 2000s to 1980s as:

$$\beta_{dh} = \left(\beta_m * \frac{15}{18}\right) + \beta_h$$

So the change in maximum catch was calculated as the sum of β_m (with a correction factor = 15/18 for the difference in time-scale of 15 yrs from mid-1980s to 2000) and the latent variable β_h which represents the theoretical change in UVC counts between the 1980s and 2000s. β_h had the same prior as β_n. Thus, from β_h we could directly calculate the expected change in UVC abundance since the 1980s.

We calculate % change as 100—A2018/A2000 where A2018 was estimated abundance in 2018, with 89% credible intervals (89% was chosen consistent with advice from McElreath 2016). Prior choice for both models followed standard practice for Bayesian GLMMs. We used a weakly informative normal prior (mean = 0, sd = 10) for change in abundance, a broad normal (0, 100) for the intercept, a weakly informative exponential prior (rate = 1) for the variance of the random effect and a Cauchy prior (0, 2) for the negative binomial scale parameter. The weakly informative priors were chosen to avoid over-fitting and will shrink the model's predictions towards no change if the data are not informative. We used the Stan program (Stan Development Team 2018) for estimation with 5000 samples from 3 chains for each model and confirmed convergence diagnostics reached appropriate values for all parameter estimates.

Changes in size and maturity

We used a Bayesian mixed effects model to estimate changes in size of surveyed fish for *B. muricatum* and *C. undulatus* over 2000–2018. We modelled the data with a log-normal distribution (and assumption checks confirmed this assumption was adequate). We included a fixed effect for time period and additive random effect for surveys and sites. Model fitting, priors and intervals were calculated as above for abundances. We also estimated the change in the proportion of individuals presumed to be mature, where mature fish were taken to be individuals over 650 mm and 550 mm for *B. muricatum* and *C. undulatus,* respectively (Choat et al. 2006; Hamilton et al. 2008; Taylor et al. 2018). We then generated posterior predictive estimates of fish sizes and calculated the probability that size was above the maturity thresholds in each time period.

IUCN thresholds

To evaluate the status of *B. muricatum* and *C. undulatus* populations in Roviana Lagoon relative to their current IUCN Red List categories, we modelled the projected rates of decline for each species over three generations. Following IUCN Red List criteria, only adult populations were considered (IUCN Standards and Petitions Subcommittee 2017). For *B. muricatum,* we estimated two different generation times using established IUCN methods. First, we calculated a generation time of 13 yrs by determining the mean age of 166 adult male and female *B. muricatum* (> 650 mm) that had been sampled and aged from the lightly exploited region of Kia, Isabel Province, Solomon Islands (Taylor et al. 2018). Secondly, we calculated a generation time of 8 yrs based on age at 50% sexual maturity for *B. muricatum* (Hamilton et al. 2008; Taylor et al. 2018). This second method is likely to underestimate generation time in long-lived species such as *B. muricatum* and *C. undulatus*, but provides a useful proxy of the lower estimate of generation time. There is limited demographic data for *C. undulatus* populations in Solomon Islands, so we used the *B. muricatum* generation times of 8 and 13 yrs as proxies (IUCN Standards and Petitions Subcommittee 2017) and considered any *C. undulatus* over 550 mm to represent an adult (Choat et al. 2006). These upper and lower proxies for *C. undulatus* generation times seem reasonable as the current estimate for *C. undulatus* generation time on the IUCN Red list is approximately 10 yrs (Russell 2004) and *B. muricatum* and *C. undulatus* are both scarine labrids that obtain similar maximum size and ages (Andrews et al. 2015).

We used the same Bayesian GLMMs as above to estimate changes in adult abundance, assuming a Poisson distribution for adult UVC counts. We then projected declines over three generations from the early 2000s onwards, where generation time equalled 13 yrs (i.e. from 2000 to 2039) and 8 yrs (i.e. from 2000 to 2024). Given that the threats to these populations in Roviana Lagoon are ongoing, we assumed that future rates of decline would mirror the rates of decline observed between 2000 and 2018.

Results

Local knowledge

The commercialisation of the night spear fishery for *B. muricatum* in the 1980s initially enabled extraordinarily high catches, as one of our interviews with a Roviana spear fishermen demonstrates:

> "*I remember a spear fishing trip in 1985, not long after I had learned to use fins, when we were asked to spear Topa for an upcoming wedding. I wanted to go and spear Topa out at Isuna (outer Munda reefs) but no one would come with me as they were too scared of the big sharks, so I went by myself. My small boy minded the canoe, and I speared 74 big Topa that night. I could have speared many more, but our canoe began to sink from the weight of all the Topa*" (Hamilton 2005, p 66).

Reported maximum catches had declined notably by 2000, with many spearfishermen turning their attention to juvenile *B. muricatum* populations within the inner lagoon as adult populations on the outer reefs and passage environments were fished out (Hamilton 2005). By 2018 maximum catch rates were even lower, with three of the eight spearfishers interviewed in 2018 reporting that they had not speared any *B. muricatum* in the past 2 yrs (Table 1).

Change in abundance

Analysis of all UVC data (juveniles and adults) indicated that *B muricatum* abundance in 2018 was 62% lower than in the 2000s (47–72%, 89% CIs), and *C. undulatus* abundance in 2018 was 57% lower than in the 2000s (43–68%, 89% CIs). From our model that incorporated maximum nightly catch rates, we estimated that *B. muricatum* abundance in 2018 was 8% of its likely abundance in the 1980s (Fig. 2). The probability of this observed decline in *B. muricatum* being > 50% or > 30% was 0.91 and 1, respectively. The probability of this observed decline in *C. undulatus* being > 50% or > 30% was 0.79 and 1, respectively. Both species had zero probabilities of a population increase. When analysis of the UVC data was limited to adults, adult *B muricatum* abundance in 2018

Table 1 Maximum nightly catches of *B. muricatum* by time period

Reported maximum catches	1980s (*n* = 7)	2000 (*n* = 15)	2018 (*n* = 8)
	74[a]	15[a]	17
	60	16	12
	50[b]	10[b]	4[b]
	50	14	2
	50	11	2
	40	10	1
	30	10	0
		10	0
		9	0
		8	
		8	
		7	
		6	
		5	
		5	
Mean maximum catch	50.6	9.6	4.8

[a]Individual spear fisherman's maximum catches in 1980s and 2000

[b]Individual spear fisherman's maximum catches in 1980s, 2000 and 2018

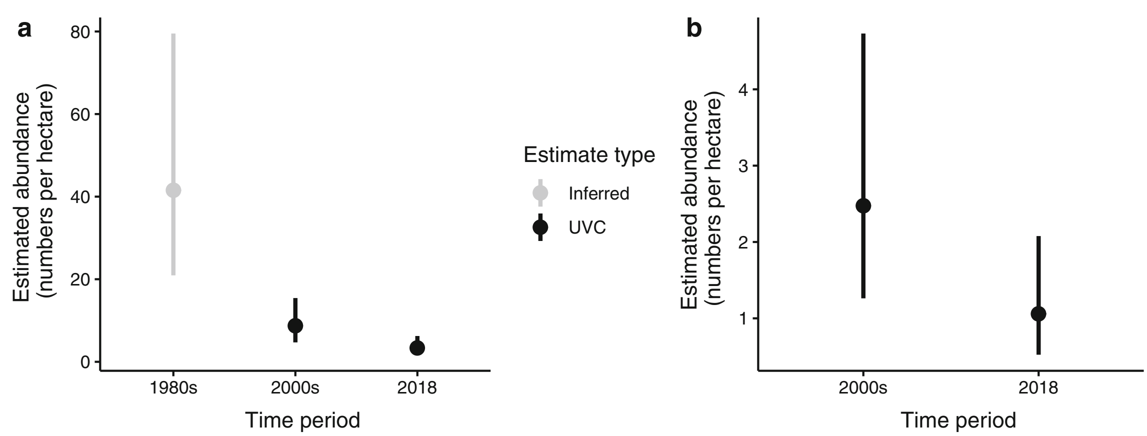


Fig. 2 UVC abundance estimates for **a** all *B. muricatum* and **b** all *C. undulatus*. Points show median estimate and error bars with 89% credible intervals. Note that y-axis scale varies between plots

was 78% (64–88%, 89% CIs) lower than in the 2000s, and adult *C. undulatus* abundance in 2018 was 72% (41–89%, 89% CIs) lower than in the 2000s.

Change in size and maturity

Bayesian GLMMs revealed that between the 2000s and 2018 the mean total length of *B. muricatum* dropped from 716 mm to 563 mm (multiples of 0.73, 0.79, 0.85 median and 89% CIs), whereas the mean total length of *C. undulatus* dropped from 746 to 468 mm (multiples of 0.54, 0.62, 0.72 median and 89% CIs) (Fig. 3). Over the same time the probability that *B. muricatum* individuals were mature fell from 0.28 to 0.08, and the probability that *C. undulatus* individuals were mature fell from 0.44 to 0.1.

IUCN thresholds

The projected decline assuming a generation time of 8 yrs gave probabilities of *B. muricatum* adult populations in Roviana Lagoon declining by > 80% or > 50% over three generations of 0.84 and 0.99, respectively. When a generation time of 13 yrs was used, the probabilities of *B. muricatum* adult populations in Roviana Lagoon declining by > 80% or > 50% over three generations were 0.99 and 1, respectively, (89% CI) (Fig. 4). When a generation time of 8 yrs was used for *C. undulatus*, the probabilities of *C.*

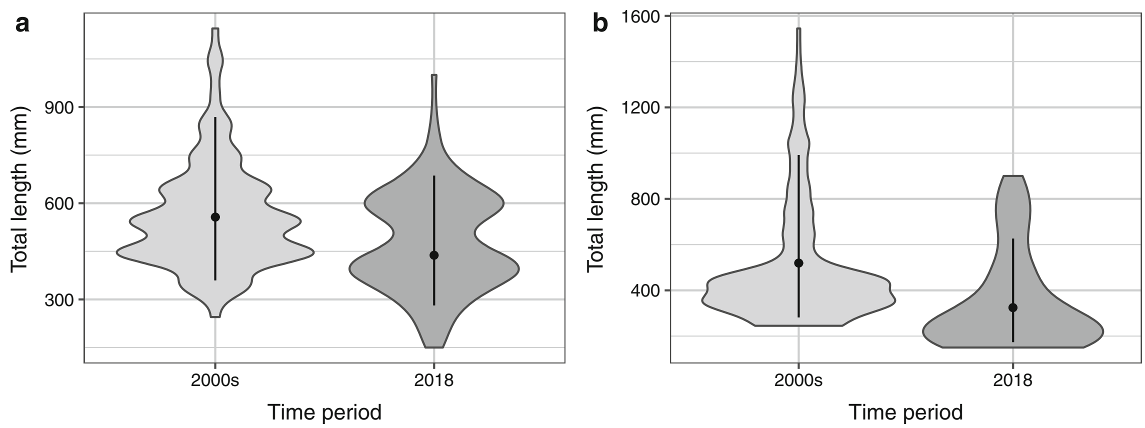
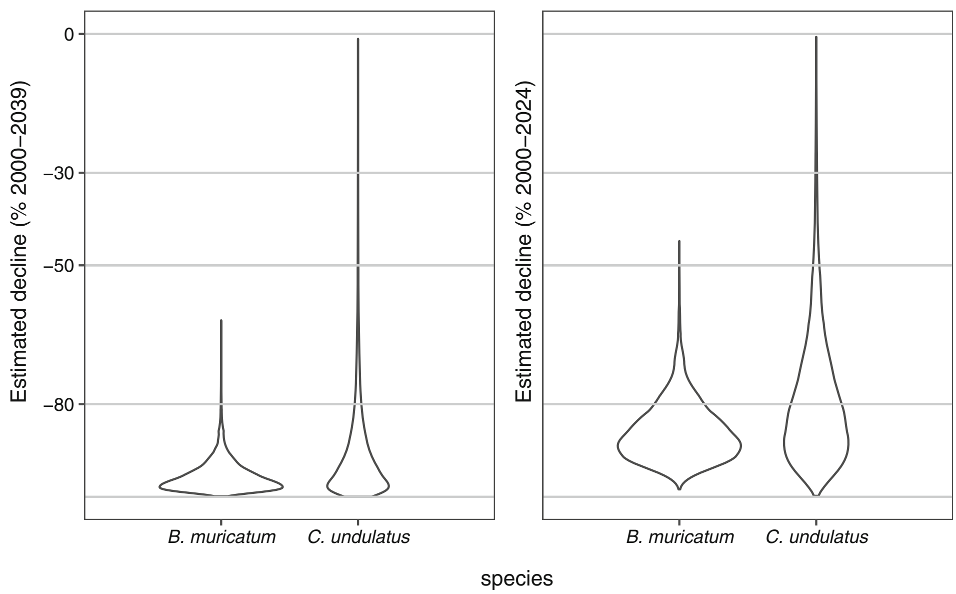


Fig. 3 Size-frequency distributions of **a** all *B. muricatum* and **b** all *C. undulatus* sighted in passage and outer reef environments in Roviana Lagoon in the 2000s and 2018. Points with error bars show estimated mean total lengths with 89% credible intervals. Note that y-axis scale varies between plots

Fig. 4 Posterior distributions for estimated decline in adult *B. muricatum* and adult *C. undulatus* populations in Roviana Lagoon over three generations. Panel on left assumes a generation time of 13 yrs whereas panel on right assumes a generation time of 8 yrs



undulatus adult populations in Roviana Lagoon declining by > 80% or > 50% over three generations were 0.57 and 0.95, respectively. When a generation time of 13 yrs was used, the probabilities of *C. undulatus* adult populations in Roviana Lagoon declining by > 80% or > 50% over three generations were 0.87 and 0.98, respectively (Fig. 4).

Discussion

Over the past two decades Roviana communities, academics and non-government organisations have invested a significant amount of time and resources into improving the management of valuable fish stocks in Roviana Lagoon (e.g. Aswani and Hamilton 2004a, b; Aswani et al. 2007; Hamilton et al. 2012a). Reports on these community-based initiatives have described a mix of successes and failures (e.g. Aswani and Sabetian 2010; Halpern et al. 2013; Olds et al. 2014; Aswani et al. 2015, 2017). We found that these management efforts have been unsuccessful in conserving two of the largest and most culturally significant fishes in Roviana Lagoon. Adult populations of *B. muricatum* and *C. undulatus* in Roviana Lagoon declined by 78% and 72%, respectively, between 2000 and 2018, with these reductions in abundance accompanied by significant declines in the mean total length of each species. Our joint model that incorporated local knowledge and UVC data also indicated that by 2018 the population of *B. muricatum* in Roviana Lagoon had been reduced to 8% of its 1980's abundance, a level that indicates fishery collapse by standard measures (e.g. Pauly et al. 2013).

In Roviana Lagoon we estimated that over three generations the declines in adult *B. muricatum* and *C. undulatus* populations will be greater than 80%, which indicates that if the populations of *B. muricatum* and *C. undulatus* in Roviana Lagoon are considered in isolation, they would both meet the IUCN Red List criteria for Critically Endangered (CR). While it is unlikely that the trends observed in Roviana Lagoon are representative of population trends across both species' entire geographical range (IUCN 2012), it is plausible that they are indicative of what is occurring across much of the Pacific where targeted fisheries exist for both species (Sadovy et al. 2003; Hamilton and Choat 2012). Anecdotal accounts from fishers in other Pacific countries certainly indicate this for *B. muricatum*. For example, in February 2018 one of the authors (RH) visited remote reefs to the north-west of Pere, Manus Province, Papua New Guinea. He was travelling with fishermen from the Pere community who stated that in the 1990s they began to make the trip from Pere to these reefs to spear fish at night, a round trip of over 60 km. When asked if they caught many *B. muricatum* on these reefs Pere fishermen's response was: "Back in the 1990s when the reef was good we would catch 20–30 adult *B. muricatum* in a night. Now we rarely catch any". Anecdotal observations such as this highlight the value of documenting fisher's local knowledge to infer recent ecological changes, a methodology that is increasingly used in countries throughout the Coral Triangle (Hamilton et al. 2012b; Lavides et al. 2016; Larsen et al. 2018).

In Roviana Lagoon, the magnitude of decline in abundances of *B. muricatum* and *C. undulatus* from the 2000s to 2018 was similar. This consistent decline across species contrasts with a recent study on the lightly exploited Kia fishing grounds in Isabel Province, where *B. muricatum* populations declined in response to night spearfishing, whereas *C. undulatus* populations did not (Pearse et al. 2018). A likely explanation for the difference between Kia and Roviana is that Roviana spearfishers changed their fishing practices as resources became scarcer. The predictable aggregating behaviour of *B. muricatum* coupled with the relatively high abundances of *B. muricatum* in the Kia fishing grounds enabled Kia spearfishers to routinely obtain high catches through a method known as spot checking (Hamilton et al. 2016). With spot checking, spearfishers will spend 10–15 min snorkeling on the surface at a known resting site searching for a school of *B. muricatum*. If none are sighted, they will get back in their boat and travel to another resting site and repeat this practice. This spot checking method minimizes the amount free-diving effort that is required, hence affording a degree of protection to more nocturnally cryptic species such as *C. undulatus* (Pearse et al. 2018). Declining catches of *B. muricatum* in the Roviana night spear fishery would have made this spot checking strategy increasingly unsuccessful, forcing free-divers to adopt an intensive free-diving strategy that increases the likelihood of capturing cryptic species such as *C. undulatus*.

While the findings of this study cast doubt over the suitability of community-based fisheries management for *B. muricatum* and *C. undulatus*, it is worth highlighting that the declines documented here appear to relate to a combination of factors. Several of these factors cannot be mitigated against through the establishment of small community-based marine protected areas. One of the most plausible reasons for the ongoing declines is commercial logging. *B. muricatum* juveniles are restricted to shallow lagoonal reefs that have a high proportion of live branching corals, and these inshore nursery reefs also support very high densities of juvenile *C. undulatus* (Hamilton et al. 2017). In the Kia region of Isabel Province, which is located approximately 130 km north east of Roviana Lagoon, sediment run off from logging operations dramatically reduced juvenile habitat and populations of juvenile *B. muricatum* on inner lagoon reefs (Hamilton et al. 2017; Brown and Hamilton 2018), with similar magnitudes of decline observed for populations of juvenile *C. undulatus* (Hamilton and Brown, unpublished data). The watersheds on the New Georgia mainland that drain into Roviana Lagoon have been heavily logged over the past three decades, with corresponding declines in water quality in the inner lagoon (Halpern et al. 2013). It is therefore conceivable that the declining abundances of *B. muricatum* and *C. undulatus* in passage and outer reef environments reflect the flow on effects of reduced recruitment into the Roviana fishery due to logging. Land conversion and climate-induced thermal stress is escalating the degradation of nursery habitats on a global scale, impacting adult fish populations and the livelihoods of fishers (McMahon et al. 2011; Zilio et al. 2013; Brown et al. 2019a, b; McClure et al. 2019).

The inability of community-based MPAs to conserve subadult and adult populations of *B. muricatum* and *C. undulatus* in passage and outer reef environments in Roviana Lagoon is also likely a function of MPA sizes and their placement. MPAs should cover 5–10 km of linear reef to effectively conserve *B. muricatum* and *C. undulatus* populations (Green et al. 2015), but MPAs in Roviana Lagoon are much smaller than this (Aswani and Hamilton 2004b; Olds et al. 2014), and predominantly located in lagoon environments. Indeed, the establishment of small MPAs is the norm throughout the Coral Triangle (Govan et al. 2009; Mills et al. 2010; Weeks et al. 2010). While small lagoonal MPAs in Roviana Lagoon may provide some protection for *B. muricatum* and *C. undulatus* during their first years of life (Olds et al. 2014), ontogenetic migration out of nursery MPAs has clearly not been sufficient to halt ongoing declines in subadult and adult populations in Roviana Lagoon. Poor compliance with fisheries regulations within many of the MPAs in Roviana Lagoon (Halpern et al. 2013; Aswani et al. 2017), and sustained fishing pressure across the entire lagoon system is also likely to be hindering population recovery.

While community-based fisheries management strategies have proven successful in some instances (Cinner et al. 2005; Hamilton et al. 2011; Cohen and Alexander 2013: Albert et al. 2014; Aswani et al. 2015), this study adds to earlier research that has demonstrated that this is by no means always the case (e.g. Foale 1998; Foale et al. 2011; Jupiter 2017). It is also worth considering that success may often be time bound, with interest and compliance in community-based management measures likely to wax and wane over time (Aswani et al. 2017). A growing volume of literature is calling for "ridge-to-reef" co-management, where the impacts of land-based practices on coastal fisheries are considered (Brown et al. 2019a, b) and communities, NGOs and governments are involved in management decisions (Aswani et al. 2017; Jupiter 2017). In a recent attempt to manage *B. muricatum* and *C. undulatus* fisheries at a national scale, the Solomon Islands Ministry of Fisheries and Marine Resources passed regulations under the 2015 Fisheries Act that bans the sale of any *B. muricatum* or *C. undulatus* below 650 mm total length.

These regulations came into effect in August 2018, and the fine for being caught selling undersized *B. muricatum* or *C. undulatus* is "30,000 penalty units or 3 months imprisonment or both" (Fisheries Management Prohibited Activates 2018). The rationale behind these size limits were twofold. First, they would give both species the chance to reach sexual maturity before entering the fishery, and second, they would prevent commercial fishers from moving their attention to juvenile populations in the inner lagoons once they had overfished adult stocks on outer reef habitats. If such regulations could be effectively enforced, they would protect over 80% of the *B. muricatum* and *C. undulatus* that were sighted in Roviana Lagoon in 2018. In reality, it is unlikely that the Solomon Islands government currently has the capacity to effectively enforce its regulations (Jupiter et al. 2019), and community-based fisheries management strategies that incorporate the national size regulations may offer a better chance of success.

Finally, while the midterm outlook for *B. muricatum* and *C. undulatus* populations in Roviana Lagoon appears dire, all is not yet lost. Despite decades of overfishing and poor land-based practices, *B. muricatum* and *C. undulatus* can still be found in Roviana Lagoon, and juveniles of varying size and age classes were sighted in 2018, demonstrating ongoing successful recruitment into the Roviana fishery and that there is still some suitable nursery habitat for *B. muricatum* and *C. undulatus* in Roviana Lagoon. The very low abundances of adult *B. muricatum* and adult *C. undulatus* in Roviana Lagoon implies that successful ongoing recruitment may be a result of larval dispersal from adult populations in less heavily exploited regions. One such potential area is a large MPA that is located on the uninhabited island of Tetepare, which lies approximately 40 km to the South of Roviana Lagoon (Read et al. 2010; Moseby et al. 2012). UVC surveys that were undertaken in 2001 revealed that Tetepare had a much higher abundance of adult *B. muricatum* than Roviana Lagoon (Hamilton 2005). This pattern appears to have persisted over the decades, with large schools of adult *B. muricatum* observed within the Tetepare MPA in 2015 (Hughes and Leve, personal observations). If the Roviana system is currently benefiting from larvae supply from upstream regions such as Tetepare, then its long-term resilience is integrally linked to these less exploited areas remaining relatively pristine. In conclusion, the populations of *B. muricatum* and *C. undulatus* in Roviana Lagoon are on a rapidly downward spiral and need urgent management attention. Halting the current rates of decline is likely to require a cessation of commercial logging, ensuring that community commitments are adhered too (Albert et al. 2014) and that national minimum size limits are enforced. To allow stocks the optimum chance of recovery, national wide bans on the harvest and sale of *B. muricatum* and *C. undulatus* should also be considered. A medium-term goal for a community co-management approach in Roviana Lagoon would be to return populations of *B. muricatum* and *C. undulatus* to the abundance levels we observed in the 2000s.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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