

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

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27

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29 Coral Triangle; Bayesian generalized linear model; IUCN Red List

## 30 Abstract

31

32 Community-based fisheries management that integrates local knowledge and existing user  
33 rights is often seen as a solution to the failures of top-down fisheries management in the  
34 Pacific. In Roviana Lagoon, Western Solomon Islands, a network of community-based  
35 marine protected areas (MPAs) was established in the early 2000s to conserve declining  
36 populations of bumphead parrotfish (*Bolbometopon muricatum*) and other locally valuable  
37 fish species such as humphead wrasse (*Cheilinus undulatus*). We aimed to evaluate the  
38 success of these protected areas at preventing declines of *B. muricatum* and *C. undulatus*. We  
39 conducted 27 underwater visual census (UVC) surveys at permanent passage and outer reef  
40 monitoring sites in Roviana Lagoon in 2018 and compared our findings with results from 72  
41 UVC surveys that we had conducted at the same sites 18 years earlier. We also interviewed  
42 Roviana spearfishers about their maximum nightly *B. muricatum* catches from 2018, the early  
43 2000s and the 1980s. Abundances of all *B. muricatum* and *C. undulatus* sighted on UVC  
44 surveys declined by 62% and 57% respectively between 2000 and 2018, and abundances of  
45 adult *B. muricatum* and *C. undulatus* declined by 78% and 72% respectively over the same  
46 period. Using a joint model of *B. muricatum* abundance and its reported maximum catch, we  
47 estimated that in 2018 the population of *B. muricatum* was 8% of its 1980's abundance. By  
48 modelling projected rates of decline over three generations, we show that populations of *B.*

49 *muricatum* and *C. undulatus* in Roviana Lagoon meet the IUCN Red List thresholds for  
50 Critically Endangered (CR). The probable causes of these declines are sustained fishing  
51 pressure, poor enforcement of community-based management measures and loss of fish  
52 nursery habitats due to logging. Our findings suggest urgent co-management of the ridge-to-  
53 reef system is needed to prevent further fish population declines in Roviana Lagoon.

## 54 Introduction

55

56 The bumphead parrotfish (*Bolbometopon muricatum*) and the humphead wrasse (*Cheilinus*  
57 *undulatus*) are two of the largest bony fishes found on Indo-Pacific coral reefs. Both species  
58 are scarine labrids (Westneat and Alfaro 2005) that begin to mature at the age of six years  
59 and grow to over one meter in length (Choat et al. 2006; Taylor et al. 2018). On many lightly  
60 to moderately exploited reefs *B. muricatum* and *C. undulatus* form important components of  
61 subsistence and small-scale commercial fisheries (e.g. Hamilton et al. 2012a; Rhodes et al.  
62 2018). However, there is widespread concern over the status of both species (Fenner 2014),  
63 with population declines reported across their ranges (Sadovy et al. 2003; Bellwood et al.  
64 2003; Dulvy and Polunin 2004; Hamilton and Choat 2012). These declines have been  
65 attributed to commercial fishing pressure to supply local, national and international markets  
66 (Sadovy et al. 2003; Hamilton and Choat 2012) and the loss of inshore recruitment habitat  
67 (Hamilton et al. 2017). The predictable nocturnal aggregating behavior of *B. muricatum*  
68 makes this species vulnerable to night spearfishing (Hamilton et al. 2016), with *C. undulatus*  
69 susceptible to a range of fishing gears including hook and line, spearfishing and traps (Colin  
70 and Sadovy de Mitcheson 2012; Lindfield et al. 2014). *C. undulatus* is also a prime target of  
71 the live-reef food-fish trade (LRFFT) (Sadovy et al. 2003).

72

73 Once overfished both species have low recovery potential due to life-history traits that  
74 include late maturation and long-life span (Choat et al. 2006; Andrews et al. 2015; Taylor et  
75 al. 2018). *B. muricatum* is listed as Vulnerable (VU) and *C. undulatus* is listed as Endangered  
76 (EN) on the International Union for Conservation of Nature (IUCN) Red List of Threatened  
77 Species (Russell 2004; Chan et al. 2012). *C. undulatus* is also listed on Appendix II of the  
78 Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)  
79 (Vincent et al. 2014). Despite these listings there remains a scarcity of long-term empirical  
80 data upon which temporal trends in *B. muricatum* and *C. undulatus* populations can be  
81 examined. This data gap hinders evaluating the effectiveness of local management actions  
82 and the status of these fish species on the IUCN Red List. Typically, population declines in  
83 these species have been inferred from spatial comparisons or local knowledge surveys. For  
84 example, Sadovy et al. (2003) collected abundance data of *C. undulatus* across its geographic  
85 range and found a 10-fold decreases in *C. undulatus* in fished areas compared to unfished  
86 areas. While Lavides et al. (2016) used local knowledge surveys to conclude that the mean  
87 perceived biomass of *B. muricatum* and *C. undulatus* declined by 82% and 88% respectively  
88 between the 1950s and 2014 in five regions of the Philippines.

89

90 Here we report on changes in abundance of *B. muricatum* and *C. undulatus* over 18 years  
91 from surveys in Roviana Lagoon, Western Province, Solomon Islands. Roviana fishers  
92 developed traditional fishing methods and detailed local knowledge about *B. muricatum*  
93 (known as ‘Topa’ in the local language) and *C. undulatus* (‘Habili’) generations ago (Aswani  
94 1997; Hamilton 2003), and both species remain highly valued in contemporary Roviana  
95 culture. In the early 1980s a commercial night spear fishery for *B. muricatum* developed in  
96 Roviana Lagoon (Hamilton 2003), and in the mid-1990s *C. undulatus* were targeted to supply  
97 LRFFT operations (Johannes and Lam 1999). The ecological impacts of the commercial *B.*

98 *muricatum* fishery that operated from 1980-2000 have been inferred from local knowledge  
99 surveys (Hamilton 2003; 2005). In the early 1980s night spearfishers reported very high  
100 catches of *B. muricatum*, with catch rates having declined rapidly by 2000 (Hamilton 2005).  
101 Concern over the perceived declines in commercially valuable fish stocks in Roviana Lagoon  
102 resulted in efforts to manage the lagoon's fisheries through the establishment of a network of  
103 small community-based marine protected areas (MPAs) (e.g. Aswani and Hamilton 2004a;  
104 2004b; Weiant and Aswani, 2006; Aswani et al. 2007).

105

106 One of the primary objectives of establishing this network of MPAs was to conserve  
107 populations of *B. muricatum* in Roviana Lagoon (Olds et al. 2014). Despite these efforts,  
108 some Roviana fishers and scientists are of the view that valuable finfish resources in Roviana  
109 Lagoon are continuing to decline (Hughes, personal communications, 2018; Ensor et al.  
110 2018). To evaluate these perceptions, we conducted underwater visual census (UVC) and  
111 local knowledge surveys in Roviana Lagoon in 2018 and compared our findings with UVC  
112 and local knowledge surveys that we had conducted in Roviana Lagoon 18 years earlier. We  
113 developed Bayesian generalised linear mixed models (GLMMs) to assess the changes in the  
114 abundance and size structure of *B. muricatum* and *C. undulatus* that were sighted at  
115 permanent UVC sites during these two distinct time periods. For *B. muricatum* we also  
116 developed a joint model that integrated UVC and local knowledge and allowed us to estimate  
117 change in abundance since the 1980s. We apply the model to project declines in adult  
118 populations over three generations, allowing us to assess declines relative to IUCN Red List  
119 Criteria A for population decline (past, present and/or projected).

120

## 121 **Methods**

122

## 123 Local knowledge surveys

124

125 In 2000 we conducted detailed interviews with fifteen active and six retired *B. muricatum*  
126 spearfishermen. These interviews were undertaken to document local knowledge on *B.*  
127 *muricatum* ecology and to build a picture of technological, ecological and economic changes  
128 that had occurred in this fishery since the 1940s (Hamilton 2005). Interviews were carried out  
129 with spearfishermen from the communities of Dunde, Nusa Roviana, Nusabanga, Sasavele,  
130 Baraulu, Bula Lavata and Nusa Hope in Roviana Lagoon. These interviews revealed that  
131 large catches commenced in the 1980s, which coincided with the introduction of underwater  
132 flashlights and the establishment of fisheries centres at the provincial headquarters of Munda.  
133 The interview questions that were asked to night spearfishermen in 2000 that are relevant to  
134 this study were: Question 1: “What was the most Topa you ever caught in a single night when  
135 you first started spearfishing? and Question 2: “What is the most Topa you have caught in a  
136 single night in the last 2 years?”. In 2018 we discussed the purpose of this study with eight  
137 active night spearfishers from the communities of Dunde, Nusabanga, Sasavele and Nusa  
138 Hope and asked them Question 2. We focused on questions that relate to maximum catch  
139 since memory that is related to self-esteem can be positively biased (Thompson et al. 1996),  
140 hence maximum catches may be more memorable than ‘average’ catches (Hamilton et al.  
141 2012b). In both time periods the only fishers in Roviana Lagoon that targeted *B. muricatum*  
142 were night spearfishermen. Interviewees were selected based on authors’ prior knowledge of  
143 night spearfishermen and through peer recommendation (Davis and Wagner 2003).

144

## 145 UVC surveys

146

147 We conducted repeated underwater visual census (UVC) surveys at four permanent  
148 monitoring sites located in passage and outer reef environments in Roviana Lagoon during

149 daylight hours (Figure 1). Sites were randomly selected to reflect typical passage and outer  
150 reef environments, which is where subadults and adults of both species are found (Hamilton  
151 et al. 2016). UVC surveys were done by two SCUBA divers and consisted of 500 m long  
152 swims along passage and outer reef slopes at a depth of 10 m. UVC surveys took  
153 approximately 20 minutes. Initially the exact length of the transects were determined by  
154 laying out a 50 m transect ten times, with GPS readings taken at the transect start points. On  
155 each survey one diver recorded the size of each *B. muricatum* and *C. undulatus* observed  
156 within a 20-m-wide band, 10 m either side of the diver. Hence each UVC survey covered one  
157 hectare of reef. Long UVC surveys were used since this is the most suitable method for  
158 surveying populations of naturally rare species such as *B. muricatum* and *C. undulatus* (Choat  
159 and Pears 2003). The permanent UVC sites were surveyed 72 times between October 2000 –  
160 June 2001 on new and full moon phases, and 27 times between March - October 2018 on  
161 new, full and last quarter lunar phases (Electronic supplementary material, Table S1, Table  
162 S2 and Table S3).

163

## 164 Statistical analysis

### 165 Change in abundance

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



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

178 The model for abundance was thus specified:

$$179 \quad \ln(y_{i,j,t}) \sim \text{Poisson}(\mu_{j,t})$$

$$180 \quad \mu_{j,t} = a_n + \beta_n x_t + s_j$$

181 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  
182 predictor for the Poisson (or negative binomial for *B. muricatum*) distribution,  $a_n$  is the  
183 intercept,  $\beta_n$  is the log magnitude of decline,  $x_t$  is an indicator for 2000s (=0) or 2018 (=1)  
184 and  $s_j$  are the site random effects.

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

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

$$196 \quad c_i \sim \text{Poisson}(v_i)$$

197 
$$v_i = a_c + \beta_c x_i + \beta_{dh} z_i$$

198 where  $a_c$  is the expectation for catch in 2000s (logged),  $\beta_c$  is the difference in logged mean  
199 catch from the 2000s to 2018 and  $\beta_{dh}$  is the difference in logged mean catch from 2000s to  
200 1980s.  $x_i$  and  $z_i$  are indicator variables for the time period of the observation.

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

204 
$$\beta_c = \beta_n + \beta_m$$

205 Where  $\beta_m$  had a weakly informative normal prior (mean = 0, sd = 3). Thus  $\beta_m$  represents a  
206 multiplicative correction factor for the difference between the UVC change in density ( $\beta_n$ )  
207 and the change in density as estimated by maximum catch.

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

209 
$$\beta_{dh} = \left(\beta_m * \frac{15}{18}\right) + \beta_n$$

210 So the change in maximum catch was calculated as the sum of  $\beta_m$  (with a correction factor =  
211 15/18 for the difference in time-scale of 15 years from mid-1980s to 2000) and the latent  
212 variable  $\beta_h$  which represents the theoretical change in UVC counts between the 1980s and  
213 2000s.  $\beta_h$  had the same prior as  $\beta_n$ . Thus, from  $\beta_h$  we could directly calculate the expected  
214 change in UVC abundance since the 1980s.

215 We calculate % change as  $100 - A_{2018}/A_{2000}$  where  $A_{2018}$  was estimated abundance in  
216 2018, with 89% credible intervals (89% was chosen consistent with advice from MacElreath,  
217 2016). Prior choice for both models followed standard practice for Bayesian GLMMs. We  
218 used a weakly informative normal prior (mean = 0, sd = 10) for change in abundance, a broad

219 normal (0, 100) for the intercept, a weakly informative exponential prior (rate = 1) for the  
220 variance of the random effect and a Cauchy prior (0, 2) for the negative binomial scale  
221 parameter. The weakly informative priors were chosen to avoid over-fitting and will shrink  
222 the model's predictions towards no change if the data are not informative. We used the Stan  
223 program (Stan Development Team 2018) for estimation with 5000 samples from 3 chains for  
224 each model and confirmed convergence diagnostics reached appropriate values for all  
225 parameter estimates.

226

### 227 **Changes in size and maturity**

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

### 238 **IUCN thresholds**

239 To evaluate the status of *B. muricatum* and *C. undulatus* populations in Roviana Lagoon  
240 relative to their current IUCN Red List categories we modelled the projected rates of decline  
241 for each species over three generations. Following IUCN Red List criteria, only adult  
242 populations were considered (IUCN Standards and Petitions Subcommittee 2017). For *B.*

243 *muricatum* we estimated two different generation times using established IUCN methods.  
244 First, we calculated a generation time of 13 years by determining the mean age of 166 adult  
245 male and female *B. muricatum* (>650 mm) that had been sampled and aged from the lightly  
246 exploited region of Kia, Isabel Province, Solomon Islands (Taylor et al. 2018). Secondly, we  
247 calculated a generation time of 8 years based on age at 50% sexual maturity for *B. muricatum*  
248 (Hamilton et al. 2008; Taylor et al. 2018). This second method is likely to underestimate  
249 generation time in long-lived species such as *B. muricatum* and *C. undulatus*, but provides a  
250 useful proxy of the lower estimate of generation time. There is limited demographic data for  
251 *C. undulatus* populations in Solomon Islands, so we used the *B. muricatum* generation times  
252 of 8 and 13 years as proxies (IUCN Standards and Petitions Subcommittee 2017) and  
253 considered any *C. undulatus* over 550 mm to represent an adult (Choat et al. 2006). These  
254 upper and lower proxies for *C. undulatus* generation times seem reasonable as the current  
255 estimate for *C. undulatus* generation time on the IUCN Red list is approximately 10 years  
256 (Russell 2004) and *B. muricatum* and *C. undulatus* are both are scarine labrids that obtain  
257 similar maximum size and ages (Andrews et al. 2015).

258 We used the same Bayesian GLMMs as above to estimate changes in adult abundance,  
259 assuming a Poisson distribution for adult UVC counts. We then projected declines over three  
260 generations from the early 2000s onwards, where generation time equalled 13 years (i.e. from  
261 2000 to 2039) and 8 years (i.e. from 2000 to 2024). Given that the threats to these populations  
262 in Roviana Lagoon are ongoing, we assumed that future rates of decline would mirror the  
263 rates of decline observed between 2000 and 2018.

264

## 265 Results

### 266 Local knowledge

267

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

271

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

278

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

285

### 286 Change in abundance

287 Analysis of all UVC data (juveniles and adults) indicated that *B. muricatum* abundance in  
288 2018 was 62% lower than in the 2000s (47-72 %, 89% C.I.s), and *C. undulatus* abundance in  
289 2018 was 57% lower than in the 2000s (43-68%, 89% C.I.s). From our model that

290 incorporated maximum nightly catch rates we estimated that *B. muricatum* abundance in  
291 2018 was 8% of its likely abundance in the 1980s (Figure 2). The probability of this observed  
292 decline in *B. muricatum* being >50% or >30% was 0.91 and 1 respectively. The probability of  
293 this observed decline in *C. undulatus* being >50% or >30% was 0.79 and 1 respectively. Both  
294 species had zero probabilities of a population increase. When analysis of the UVC data was  
295 limited to adults, adult *B. muricatum* abundance in 2018 was 78% (64-88%, 89% CIs) lower  
296 than in the 2000s, and adult *C. undulatus* abundance in 2018 was 72% (41-89%, 89% CIs)  
297 lower than in the 2000s.

298

## 299 Change in size and maturity

300

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

## 307 IUCN Thresholds

308 The projected decline assuming a generation time of 8 years gave probabilities of *B.*  
309 *muricatum* adult populations in Roviana Lagoon declining by >80% or >50% over three  
310 generations of 0.84 and 0.99 respectively. When a generation time of 13 years was used, the  
311 probabilities of *B. muricatum* adult populations in Roviana Lagoon declining by >80% or  
312 >50% over three generations was 0.99 and 1 respectively (89% CI) (Figure 4). When a  
313 generation time of 8 years was used for *C. undulatus*, the probabilities of *C. undulatus* adult

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

## 318 Discussion

319

320 Over the past two decades Roviana communities, academics and non-government  
321 organisations have invested a significant amount of time and resources into improving the  
322 management of valuable fish stocks in Roviana Lagoon (e.g. Aswani and Hamilton 2004a;  
323 2004b; Aswani et al. 2007; Hamilton et al. 2012a). Reports on these community-based  
324 initiatives have described a mix of successes and failures (e.g. Aswani and Sabetian 2010;  
325 Halpern et al. 2013; Olds et al. 2014; Aswani et al. 2015; Aswani et al. 2017). We found that  
326 these management efforts have been unsuccessful in conserving two of the largest and most  
327 culturally significant fishes in Roviana Lagoon. Adult populations of *B. muricatum* and *C.*  
328 *undulatus* in Roviana Lagoon declined by 78% and 72% respectively between 2000 and  
329 2018, with these reductions in abundance accompanied by significant declines in the mean  
330 total length of each species. Our joint model that incorporated local knowledge and UVC data  
331 also indicated that by 2018 the population of *B. muricatum* in Roviana Lagoon had been  
332 reduced to 8% of its 1980's abundance, a level that indicates fishery collapse by standard  
333 measures (e.g. Pauly et al. 2013).

334

335 In Roviana Lagoon we estimated that over three generations the declines in adult *B.*  
336 *muricatum* and *C. undulatus* populations will be greater than 80%, which indicates that if the  
337 populations of *B. muricatum* and *C. undulatus* in Roviana Lagoon are considered in isolation,  
338 they would both meet the IUCN Red List criteria for Critically Endangered (CR). While it is

339 unlikely that the trends observed in Roviana Lagoon are representative of population trends  
340 across both species' entire geographical range (IUCN, 2012), it is plausible that they are  
341 indicative of what is occurring across much of the Pacific where targeted fisheries exist for  
342 both species (Sadovy et al. 2003; Hamilton and Choat 2012). Anecdotal accounts from  
343 fishers in other Pacific countries certainly indicate this for *B. muricatum*. For example, in  
344 February 2018 one of the authors (RH) visited remote reefs to the north-west of Pere, Manus  
345 Province, Papua New Guinea. He was travelling with fishermen from the Pere community  
346 who stated that in the 1990s they began to make the trip from Pere to these reefs to spear fish  
347 at night, a round trip of over 60 kilometres. When asked if they caught many *B. muricatum* on  
348 these reefs Pere fishermen's response was: "*Back in the 1990s when the reef was good we*  
349 *would catch 20- 30 adult B. muricatum in a night. Now we rarely catch any*". Anecdotal  
350 observations such as this highlight the value of documenting fisher's local knowledge to infer  
351 recent ecological changes, a methodology that is increasingly used in countries throughout  
352 the Coral Triangle (Hamilton et al. 2012b; Lavides et al. 2016; Larsen et al. 2018).

353

354 In Roviana Lagoon the magnitude of decline in abundances of *B. muricatum* and *C.*  
355 *undulatus* from the 2000s to 2018 were similar. This consistent decline across species  
356 contrasts with a recent study on the lightly exploited Kia fishing grounds in Isabel Province,  
357 where *B. muricatum* populations declined in response to night spearfishing whereas *C.*  
358 *undulatus* populations did not (Pearse et al. 2018). A likely explanation for the difference  
359 between Kia and Roviana is that Roviana spearfishers changed their fishing practices as  
360 resources became scarcer. The predictable aggregating behaviour of *B. muricatum* coupled  
361 with the relatively high abundances of *B. muricatum* in the Kia fishing grounds enabled Kia  
362 spearfishers to routinely obtain high catches through a method known as spot checking  
363 (Hamilton et al. 2016). With spot checking, spearfishers will spend 10-15 minutes snorkeling



364 on the surface at a known resting site searching for a school of *B. muricatum*. If none are  
365 sighted, they will get back in their boat and travel to another resting site and repeat this  
366 practice. This spot checking method minimizes the amount free diving effort that is required;  
367 hence affording a degree of protection to more nocturnally cryptic species such as *C.*  
368 *undulatus* (Pearse et al. 2018). Declining catches of *B. muricatum* in the Roviana night spear  
369 fishery would have made this spot checking strategy increasingly unsuccessful, forcing free-  
370 divers to adopt an intensive free-diving strategy that increases the likelihood of capturing  
371 cryptic species such as *C. undulatus*.

372

373 While the findings of this study cast doubt over the suitability of community-based fisheries  
374 management for *B. muricatum* and *C. undulatus*, it is worth highlighting that the declines  
375 documented here appear to relate to a combination of factors. Several of these factors cannot  
376 be mitigated against through the establishment of small community-based marine protected  
377 areas. One of the most plausible reasons for the ongoing declines is commercial logging. *B.*  
378 *muricatum* juveniles are restricted to shallow lagoonal reefs that have a high proportion of  
379 live branching corals, and these inshore nursery reefs also support very high densities of  
380 juvenile *C. undulatus* (Hamilton et al., 2017). In the Kia region of Isabel Province, which is  
381 located approximately 130 km north east of Roviana Lagoon, sediment run off from logging  
382 operations dramatically reduced juvenile habitat and populations of juvenile *B. muricatum* on  
383 inner lagoon reefs (Hamilton et al. 2017; Brown and Hamilton 2018), with similar  
384 magnitudes of decline observed for populations of juvenile *C. undulatus* (Hamilton and  
385 Brown, unpublished data). The watersheds on the New Georgia mainland that drain into  
386 Roviana Lagoon have been heavily logged over the past three decades, with corresponding  
387 declines in water quality in the inner lagoon (Halpern et al. 2013). It is therefore conceivable  
388 that the declining abundances of *B. muricatum* and *C. undulatus* in passage and outer reef

389 environments reflect the flow on effects of reduced recruitment into the Roviana fishery due  
390 to logging. Land conversion and climate induced thermal stress is escalating the degradation  
391 of nursery habitats on a global scale, impacting adult fish populations and the livelihoods of  
392 fishers (McMahon et al., 2011; Zilio et al., 2013; Brown et al., 2019; McClure et al., 2019).

393

394 The inability of community based MPAs to conserve subadult and adult populations of *B.*  
395 *muricatum* and *C. undulatus* in passage and outer reef environments in Roviana Lagoon is  
396 also likely a function of MPA sizes and their placement. MPAs should cover 5-10 km of  
397 linear reef to effectively conserve *B. muricatum* and *C. undulatus* populations (Green et al.  
398 2015), but MPAs in Roviana Lagoon are much smaller than this (Aswani and  
399 Hamilton,2004b; Olds et al. 2014), and predominantly located in lagoon environments.

400 Indeed, the establishment of small MPAs is the norm throughout the Coral Triangle (Govan  
401 et al. 2009; Mills et al. 2010; Weeks et al. 2010). While small lagoonal MPAs in Roviana  
402 Lagoon may provide some protection for *B. muricatum* and *C. undulatus* during their first  
403 years of life (Olds et al. 2014), ontogenetic migration out of nursery MPAs has clearly not  
404 been sufficient to halt ongoing declines in sub-adult and adult populations in Roviana  
405 Lagoon. Poor compliance with fisheries regulations within many of the MPAs in Roviana  
406 Lagoon (Halpern et al. 2013; Aswani et al. 2017), and sustained fishing pressure across the  
407 entire lagoon system is also likely to be hindering population recovery.

408

409 While community-based fisheries management strategies have proven successful in some  
410 instances (Cinner et al., 2005; Hamilton et al. 2011; Cohen and Alexander, 2013; Albert et  
411 al., 2014; Aswani et al. 2015), this study adds to earlier research that has demonstrated that  
412 this is by no means always the case (e.g. Foale, 1998; Foale et al., 2011; Jupiter, 2017). It is  
413 also worth considering that success may often be time bound, with interest and compliance in

414 community-based management measures likely to wax and wane over time (Aswani et al.,  
415 2017). A growing volume of literature is calling for ‘ridge-to-reef’ co-management, where  
416 the impacts of land-based practices on coastal fisheries are considered (Brown et al. 2019)  
417 and communities, NGOs and governments are involved in management decisions (Aswani et  
418 al. 2017; Jupiter 2017). In a recent attempt to manage *B. muricatum* and *C. undulatus*  
419 fisheries at a national scale, the Solomon Islands Ministry of Fisheries and Marine Resources  
420 passed regulations under the 2015 Fisheries Act that bans the sale of any *B. muricatum* or *C.*  
421 *undulatus* below 650 mm total length.

422

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

435

436 Finally, while the midterm outlook for *B. muricatum* and *C. undulatus* populations in  
437 Roviana Lagoon appears dire, all is not yet lost. Despite decades of overfishing and poor  
438 land-based practices, *B. muricatum* and *C. undulatus* can still be found in Roviana Lagoon,

439 and juveniles of varying size and age classes were sighted in 2018, demonstrating ongoing  
440 successful recruitment into the Roviana fishery and that there is still some suitable nursery  
441 habitat for *B. muricatum* and *C. undulatus* in Roviana Lagoon. The very low abundances of  
442 adult *B. muricatum* and adult *C. undulatus* in Roviana Lagoon implies that successful  
443 ongoing recruitment may be a result of larval dispersal from adult populations in less heavily  
444 exploited regions. One such potential area is a large MPA that is located on the uninhabited  
445 island of Tetepare, which lies approximately 40 km to the South of Roviana Lagoon (Read et  
446 al. 2010; Moseby et al. 2012). UVC surveys that were undertaken in 2001 revealed that  
447 Tetepare had a much higher abundance of adult *B. muricatum* than Roviana Lagoon  
448 (Hamilton 2005). This pattern appears to have persisted over the decades, with large schools  
449 of adult *B. muricatum* observed within the Tetepare MPA in 2015 (Hughes and Leve,  
450 personal observations). If the Roviana system is currently benefiting from larvae supply from  
451 upstream regions such as Tetepare, then its long-term resilience is integrally linked to these  
452 less exploited areas remaining relatively pristine. In conclusion, the populations of *B.*  
453 *muricatum* and *C. undulatus* in Roviana Lagoon are on a rapidly downward spiral and need  
454 urgent management attention. Halting the current rates of decline is likely to require a  
455 cessation of commercial logging, ensuring that community commitments are adhered too  
456 (Albert et al. 2014) and that national minimum size limits are enforced. To allow stocks the  
457 optimum chance of recovery, national wide bans on the harvest and sale of *B. muricatum* and  
458 *C. undulatus* should also be considered. A medium-term goal for a community co-  
459 management approach in Roviana Lagoon would be to return populations of *B. muricatum*  
460 and *C. undulatus* to the abundance levels we observed in the 2000s.

461

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463

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472

## 473 Conflict of interest statement

474

475 On behalf of all authors, the corresponding author states that there is no conflict of interest.

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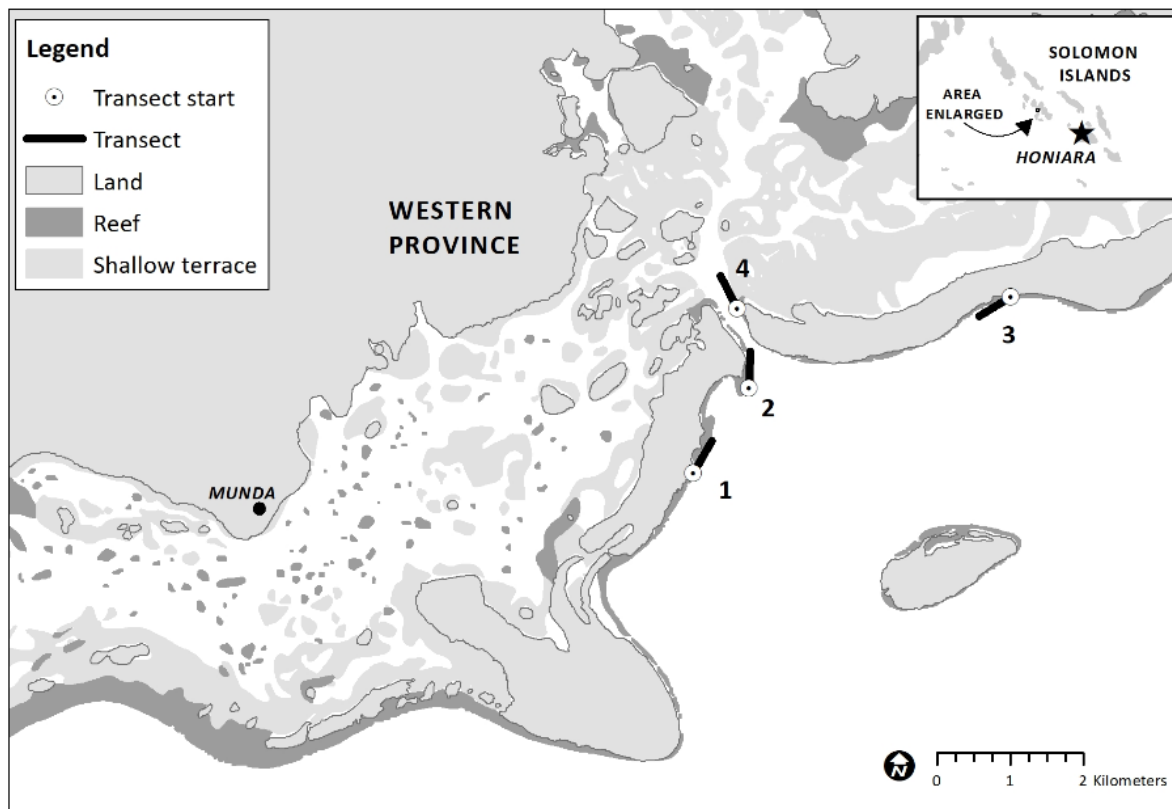
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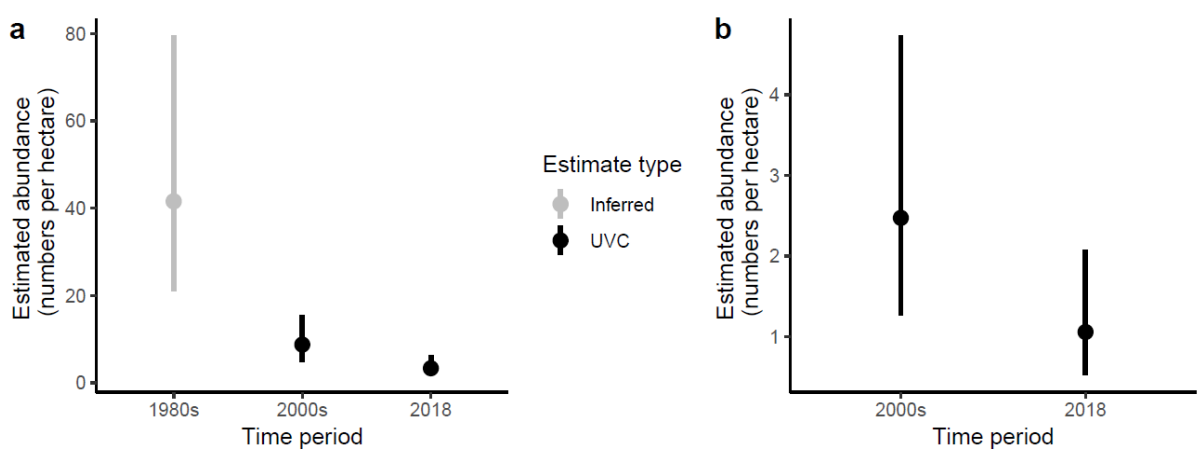
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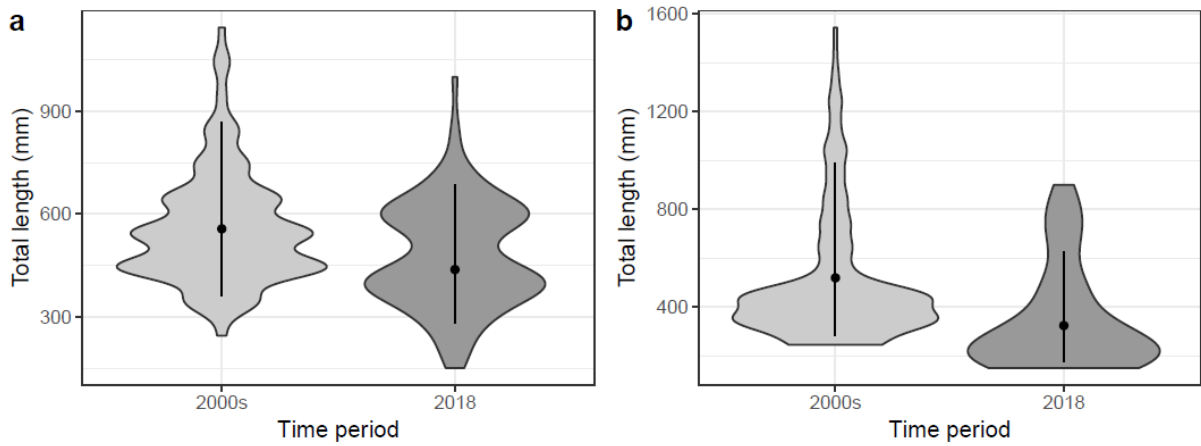
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738



741  
742 Figure 1. Location of the four permanent UVC sites. Sites 1 and 2 are located on outer reef  
743 slopes, and sites 3 and 4 are located in passage slopes. The location of Munda township is  
744 also shown.

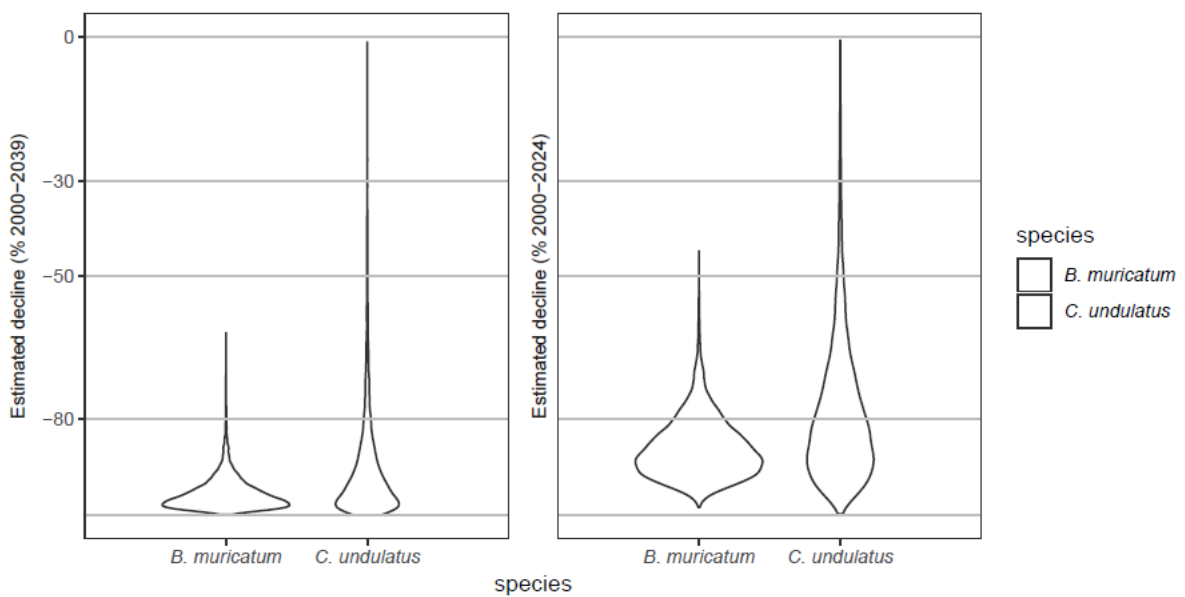


745  
746 Figure 2. UVC abundance estimates for (a) all *B. muricatum* and (b) all *C. undulatus*. Points  
747 show median estimate and error bars with 89% credible intervals. Note that y-axis scale  
748 varies between plots.



749

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



754

755 Figure 4. Estimated decline in adult *B. muricatum* and adult *C. undulatus* populations in  
 756 Roviana Lagoon over three generations. Panel on left assumes a generation time of 13 years  
 757 whereas panel on right assumes a generation time of 8 years.

758