Vol. 508: 163–176, 2014
doi: 10.3354/meps10865

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published August 4

Long-term effects of marine park zoning on giant mud crab *Scylla serrata* populations in three Australian estuaries

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ABSTRACT: Multiple-use marine parks are a powerful management tool to help protect marine biodiversity and sustain wild fisheries while allowing some access to recreational and commercial activities using zoning arrangements. Research has focused on fish but far less is known about the effectiveness of zoning for other groups, such as exploited crustaceans, especially in estuaries. In this 8 yr study, we tested the hypotheses that unfished zones, which had been closed to fishing since 1991, would have higher abundances (catch per unit effort) of the giant mud crab *Scylla serrata* in 3 estuaries (Wooli, Corindi and Sandon) of the Solitary Islands Marine Park (SIMP) in New South Wales, Australia, and that recovery after fishing closure would be rapid. Replicate fished and unfished zones were sampled from December 1998 (Wooli) and July 2000 (Corindi and Sandon) until April 2007. In August 2002, re-zoning occurred with some estuarine sections re-opened to trapping, some newly closed and others either remaining closed or open. This enabled Before-After-Control-Impact analyses to test our hypotheses. Crab numbers increased rapidly after zone closure and unfished zones protected giant mud crabs from exploitation with catches 2 to 3 times greater than in fished zones. Although there was substantial temporal variation in crab abundance within and among the 3 estuaries, responses to zoning were consistent and spatial protection in estuaries in the SIMP proved effective for sustaining giant mud crab populations. This type of management shows promise for protecting or replenishing stocks of other species of crabs worldwide.

KEY WORDS: Marine parks · Giant mud crab · *Scylla serrata* · No-take zones · CPUE

INTRODUCTION

Marine Protected Areas (MPAs) can benefit marine biodiversity through increased abundance, growth rates, average size, and recruitment of fish, as well as reduced disturbance to habitats (Pillans et al. 2005, Watson et al. 2009, Sciberras et al. 2013). However, effective design, implementation and ongoing management of MPAs are essential if they are to achieve their conservation objectives (Stewart et al. 2003, McCook et al. 2009, Fox et al. 2012). As community support is integral to effective MPA management, providing scientific evidence to demonstrate the efficacy of park management is crucial in generating and maintaining this support (Kelleher 1999, Banks & Skilleter 2010). In particular, local communities want scientific evidence within a local context (Banks & Skilleter 2010) and regular evaluations of zoning

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arrangements can provide models of the changing conditions and help direct and justify future management decisions (Dahl-Tacconi 2003).

Measures of effectiveness can be derived by comparing differences in abundance, size class, sex ratio, and spill-over of 'indicator' species between areas with different zoning arrangements (Russ & Alcala 2004, Pillans et al. 2005). Ideally, indicator species should be readily caught or easily surveyed, taxonomically distinct, relatively abundant, representative of other taxa, ecologically significant, and, preferably, of direct recreational and commercial importance (Gladstone 2002, Shokri et al. 2009). The abundance and mean size of commercial species are generally greater in protected than in adjacent fished areas (Babcock et al. 2010, Cariglia et al. 2013, Sciberras et al. 2013) but far less is known about crustaceans and other invertebrates (Kelly et al. 2000, Iacchei et al. 2005, Pillans et al. 2005). However, effectiveness of protected areas is not guaranteed and depends on their individual management arrangements (Stewart et al. 2003, Nardi et al. 2004, Russ & Alcala 2004). Few studies have examined the influence of protected areas within estuaries (Pillans et al. 2005) or examined the influence of re-opening closed areas (Mapstone et al. 2004) although some have demonstrated rapid depletion in the abundance of targeted reef fish following reopening to fishing (Ayling & Ayling 1998, Russell 1998, Mapstone et al. 2004).

The Solitary Islands Marine Park (SIMP) in northern New South Wales (NSW), Australia, was the first multiple-use marine park in NSW (established in 1991) and covers 72000 hectares along 80 km of coast-line, spanning several estuaries. Estuaries within the SIMP are managed under estuary-specific spatial zoning schemes that involve complete, partial or no closure to commercial and/or recreational fishing (i.e. line-fishing, trapping, netting and hand collection of fish and all invertebrates) in various sections of each estuary (www.mpa.nsw.gov.au/simp.html). Rezoning of the SIMP in August 2002 changed fishing pressure in some of the estuaries. These included re-zoning areas in which commercial and recreational fishing had previously been allowed into 'sanctuary zones' (i.e. targeting any individuals is prohibited), and vice versa. These zoning schemes were implemented based on the best available information at the time but lacked local monitoring programs that demonstrated their efficacy. To investigate the effectiveness of these zones in each estuary, the giant mud crab *Scylla serrata* Forskal, 1775 (Portunidae) was identified as a potential 'condition' indicator species (Butcher et al. 2003) as it is abundant, targeted by commercial and recreational fishers, and has a short lifecycle, making it responsive to overfishing and/or recovery.

The giant mud crab inhabits much of the inshore regions of the tropical Indo-Pacific (Kailola et al. 1993). In Australia, its distribution extends from the Bega River on the eastern seaboard, across northern Australia to the Exmouth Gulf (Fig. 1; Kailola et al. 1993) where it inhabits a range of estuarine, bay and mangrove habitats (Hill et al. 1982, Hyland et al. 1984). In subtropical eastern Australia, giant mud crab is fished by both commercial and recreational sectors primarily from late spring to early autumn (November to April) (Bartleet et al. 1993). In NSW, the fishery is managed by controls on input (e.g.

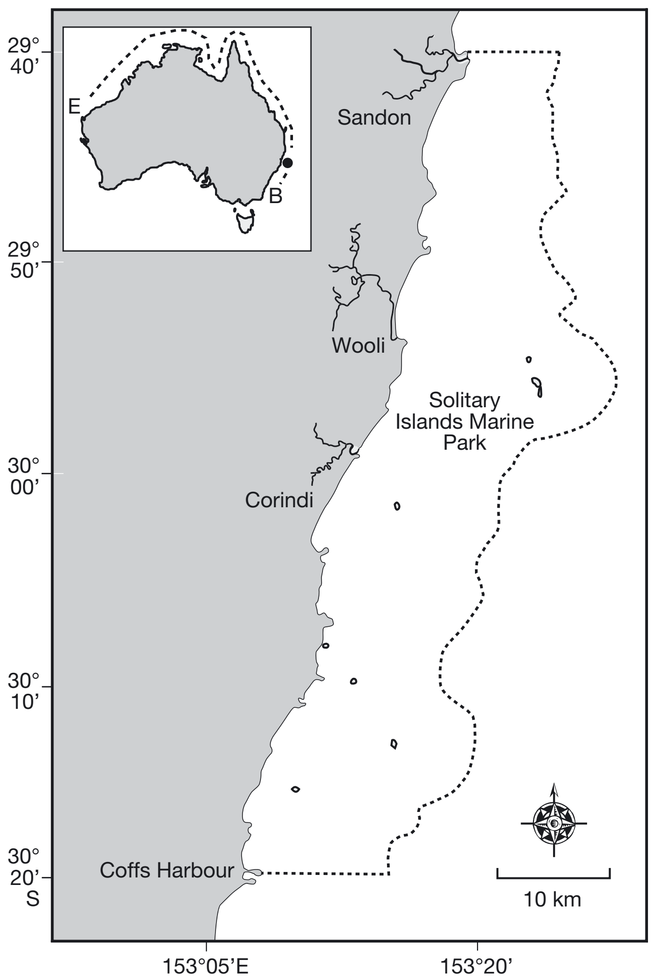

Fig. 1. Solitary Islands Marine Park, NSW, Australia (dashed line, ● in insert), showing locations of the Sandon, Wooli and Corindi estuaries. Insert shows distribution range of the giant mud crab *Scylla serrata* across northern Australia between Bega River, New South Wales (B) and Exmouth Gulf, Western Australia (E)

number and size of traps) and output (size and bag limits; sex-based restrictions: taking of gravid females prohibited). Additionally, spatial management through marine park zoning may aid this fishery. Improved understanding of *S. serrata* population demographics in response to such spatial management will assist planning and improve the effectiveness of this management.

To assess how marine park zones might influence giant mud crab populations, an 8 yr sampling program was implemented in the SIMP. The primary objective of this study was to evaluate the effectiveness of spatial management arrangements in estuaries by comparing the abundance of giant mud crab in samples taken from adjacent fished and unfished zones in the 3 largest estuaries within the SIMP. Specific hypotheses addressed involved comparisons of catch rates (1) between zones open and closed to fishing, (2) in areas reopened to fishing and (3) in previously fished sites that were closed to fishing; these are outlined in detail below.

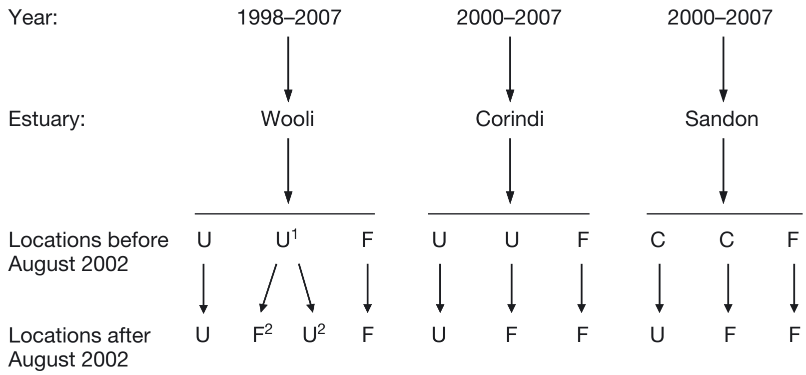

Fig. 2. Schematic representation of the experimental design used in the Wooli, Corindi and Sandon estuaries. Each estuary was represented by an unfished (U) and fished (F) location and for the Sandon estuary a commercial-trapped only (C) location prior to the 2002 August zoning change. Each location within each estuary was represented by 3 sites, which contained 3 traps that we deployed and hauled every 24 h for 3 consecutive days during December (early season) and April (late season) between 1998 and 2007. Note that one of the unfished locations in Wooli (U^1) was split in 2 during the August 2002 zoning change. Within this location, 2 sites became fished and the other unfished. Three more sites were added to form an unfished (U^2) and fished (F^2) location

MATERIALS AND METHODS

Study site and sampling design

The study was done in the 3 largest estuaries within the SIMP — Wooli (lat. 29° 53′ S), Corindi (29° 58′ S) and Sandon (29° 40′ S) — between December 1998 and April 2007 (Fig. 1). These estuaries were selected based on general accessibility, suitability of habitat, and incumbent and planned changes to zoning schemes within them (see next paragraph and Fig. 2). Field sampling was initially monthly from December 1998 in Wooli estuary, and July 2000 in Corindi and Sandon estuaries, until August 2003. From then until April 2007, sampling was done only in December and April each year to specifically represent the general beginning ('early-season') and end ('late-season'), respectively, of the east-coast summer mud-crab trapping season; a distinction of importance to the suite of hypotheses addressed by this study. Only data from December and April across the 1999–2007 sampling period are presented and analysed here, with 4 sampling instances (i.e. 'years') before and 5 after the August 2002 zoning update at Wooli, and 2 sampling years before and 5 after the update in Corindi and Sandon estuaries, for each month category.

Some sections within each of the 3 estuaries were subjected to a change in zoning scheme as part of the 2002 zoning update, while for other sections the zoning scheme was unaltered (Fig. 2). Three 'locations' were originally chosen in each estuary, with a pilot study (in November 1998) to identify potentially productive areas in relation to the incumbent zoning scheme and proposed changes to that scheme. In all locations sampled in this study, the before/after treatment profile relating to a change (or not) in zoning scheme contained 1 or 2 of the following zoning-scheme 'treatments' for the use of crab traps in those specific areas: unfished (U), commercially fished (C), and fully fished (F, i.e. recreational plus commercial). The treatment profiles for locations sampled in each of the 3 estuaries are based on the presence or absence of crab trapping being permitted in these areas (Fig. 2). Hence, subsequent notation in the text is, for example, 'UU' for unfished before and after the zoning update, 'UF' for unfished before and fully fished after the zoning update, etc. (Fig. 2).

Prior to the 2002 zoning change, trapping was prohibited in sections of each estuary by sanctuary (Wooli) and refuge (Sandon and Corindi) zones (Fig. 2). Refuge zones were considered as 'unfished' locations in Corindi. However in the Sandon estuary, trapping for giant mud crabs was permitted for one commercial fisher under government fisheries regulations during this period so the Sandon refuge-zone location was classified as 'commercially fished' for our analyses. All fishing, trapping and collecting was permitted in the remainder of each estuary under recreational zone status (i.e. fully fished). After the zoning change, all locations within the 3 estuaries were classified as either unfished (sanctuary) or fished (habitat protection zone).

Each sampling location comprised three 200 m transects (termed 'sites') spaced at least 500 m apart. Wire traps (50 mm mesh, 1.0 × 0.8 × 0.5 m) with one opening at either end (0.3 × 0.25 m) were placed at 0, 100 and 200 m along the transect (n = 3 traps site^{-1}), all at depths of between 1 and 3 m at low tide. Williams & Hill (1982) found that any distance <44 m between adjacent traps created competition for catches. At the same time during each sampling month, each trap was baited with mullet *Mugil cephalus*, set and then retrieved following a 24 h deployment, 3 times within approximately 72 h. Upon retrieval, any giant mud crabs present in the trap were measured for carapace width (CW, cm) between the tips of the ninth antero-lateral spines, sexed, tagged with 55 mm anchor T-tags (Hallprint) and immediately released at the capture site. For each trap, the total number of giant mud crabs caught in that trap (excluding recaptures of tagged crabs caught at the same site during that month) across the 72 h sampling period formed the raw data for analysis.

Data analysis

ANOVAs were used to test hypotheses concerning temporal changes in abundances of giant mud crabs (catch per unit effort [CPUE] as the mean catch trap^{-1}) in response to changes in the zoning scheme. Although specific changes to zoning schemes in each of the 3 estuaries required specific ANOVA designs (see below), some general data-analysis protocols were common for all cases. All CPUE data were $\ln(x+1)$ transformed to model treatment effects as approximately multiplicative, and then tested for heteroscedasticity using Cochran's *C* test prior to ANOVA.

ANOVA terms 'Location' (all estuaries) and 'Period' (Corindi and Sandon only) were treated as fixed factors, while 'Year' and 'Site' were random factors and, where appropriate, nested within Period and Location, respectively. The main ANOVA term of interest for addressing hypotheses relating to each estuary (see 'Treatment profiles and analyses') was the 'Location × Year' interaction term or, in cases where the Year term was nested within Period and that interaction was not significant at $\alpha = 0.05$, the 'Location × Period' term. Where the p-value for the lowest-level interaction term was >0.25, its sums of squares (SS) and degrees of freedom (df) were pooled with those of the residual term to increase the power of the *F*-test for the interaction term of interest (Underwood 1991, 1992). Significant *F*-ratios for terms of interest were further investigated using post hoc multiple comparisons tests: either a Student-Newman-Keuls (SNK) test or, where the number of means being compared exceeded 3, Ryan's *Q* test to prevent unacceptable increases in the probability of experiment-wise Type 1 error (i.e. erroneously concluding a significant difference between means). These were preferred to other tests because (1) they are relatively more powerful with respect to detecting a difference between means if a significant difference does indeed exist, and (2) the number of means being compared to each other in each case here did not exceed 4, so excessive Type 1 error was a minor issue (Day & Quinn 1989, Underwood 1997).

Treatment profiles and analyses

Wooli. For all sampling done in the Wooli estuary before the 2002 zoning update, 3 locations were sampled — 2 unfished ('U' and 'U^1') and one fully fished ('F') — with the U^1 location earmarked for re-zoning to a fully fished location at the time of the update. However, a change to the final, implemented zoning plan necessitated spatial partitioning of the U^1 location after re-zoning such that only 2 of its 3 sites changed to fully fished, while the third site remained as unfished. To maintain a balanced sampling design after re-zoning (i.e. 3 sites within each location sampled), extra sites were added to the sampling design to create 2 new 3-site locations (replacing the U^1 location) to be sampled after the zoning update — 1 fully fished ('F^2') and 1 unfished ('U^2'). This meant that after re-zoning, 2 unfished and 2 fully fished locations were sampled (Fig. 2).

As a consequence of this sampling-site discontinuity, pairs of ANOVAs ('early-season' and 'late-season') were done for (1) locations (U, U^1 and F) sampled across the 4 'before' sampling years, and (2) locations (U, U^2, F^2 and F) sampled across the 5 'after' years. To test the hypothesis that mean catches of crabs would be significantly greater in unfished than in fished locations before and after the zoning change, for each of the four 3-factor (Location, Year and Site(Location)) ANOVAs, the appropriate significant term of interest (i.e. either Site(Location) × Year interaction, Location × Year interaction or Location,

Table 1. Overview of the total catch (n), mean (±SE) catch per unit effort (CPUE) and carapace width (CW) for giant mud crabs caught in fished, unfished and commercial only zones in the Wooli, Corindi and Sandon estuaries

Estuary	Total catch (n)		CPUE (crabs trap^{-1})						CW (cm)
	Dec	Apr	Unfished		Commercial		Fished		Mean ± SD
			Dec	Apr	Dec	Apr	Dec	Apr	(range)
Wooli	793	611	3.7 ± 0.2	3.1 ± 0.1	–	–	1.5 ± 0.1	0.9 ± 0.1	13.8 ± 2.3 (7.5–19.7)
Corindi	309	251	2.5 ± 0.2	2.2 ± 0.1	–	–	1.0 ± 0.1	0.7 ± 0.1	13.6 ± 2.3 (9.0–19.0)
Sandon	284	191	3.1 ± 0.2	2.0 ± 0.2	1.5 ± 0.2	0.9 ± 0.2	0.8 ± 0.1	0.6 ± 0.1	14.0 ± 2.4 (9.1–19.9)

in that order of priority) was examined further via post hoc multiple comparisons tests. It is important to note that collectively, these ANOVAs only partially address hypotheses concerning the relationship between zoning changes and any differences in catch rates, rather than directly test them, so the results can only be considered as indicative of the possibility of such a relationship.

Corindi. In the Corindi estuary, 3 locations were sampled: 1 unfished ('UU'), 1 fully fished ('FF'), and 1 re-zoned from unfished to fully fished at the time of the 2002 zoning update ('UF') (Fig. 2). As for Wooli, early-season and late-season datasets were considered separately, with each full dataset comprising data collected during the 2 yr immediately prior to and the 5 yr immediately following the re-zoning. To maintain balanced ANOVAs with respect to temporal factors, these 7 sampling years were categorised into 'Periods' comprising 2 sampling years (1) before the zoning change ('B') (2) shortly following the zoning change ('A1'), and (3) at least 3 yr following the zoning change ('A2'); with the middle sampling year of the 5 'after' years excluded from the analyses. To test the hypotheses that for each of the Periods B, A1 and A2 (or years within those periods) catches of crabs would be significantly greater in unfished than in fished locations, for each of the two 4-factor (Location, Period, Year(Period) and Site(Location)) ANOVAs, the appropriate significant interaction term of interest (i.e. Location × Year, unless any of the lower-level interaction terms were significant) was examined further via SNK tests.

Sandon. In the Sandon estuary, 3 locations were sampled: 1 fully fished ('FF'), 1 re-zoned from commercially fished to fully fished at the time of the 2002 zoning update ('CF'), and 1 re-zoned from commercially fished to unfished at the time of the update ('CU') (Fig. 2). All other aspects of the sampling design and data analyses were the same as those described above for the Corindi estuary, although the specific hypotheses tested were that catches of crabs would be (1) significantly greater in commercially fished locations than in the fully fished location during Period B, and (2) significantly greater in the unfished than in fully fished locations during Periods A1 and A2.

RESULTS

Overview

Total catch (n), catch rates (mean CPUE) and carapace width (CW) for all fished and unfished treatments are given in Table 1 and Figs. 3, 4 and 5. Total catches were higher during early- than late-season sampling (Table 1). Sizes of giant mud crabs were also similar within and among estuaries (Table 1).

The overall mean catch rate (±SE) across all location/year sampling instances (all 'before' and 'after' years combined) for unfished locations in the early- and late- season was 2.5 ± 0.2 to 3.7 ± 0.2 and 2.0 ± 0.1 to 3.1 ± 0.1 crabs trap^{-1}, respectively (Table 1, Figs. 3 to 5). In contrast, for all fully fished locations (including those that were only commercially fished only at Sandon) the corresponding overall mean catch rates for early- and late-season sampling were lower, at 0.8 ± 0.1 to 1.5 ± 0.1 and 0.6 ± 0.1 to 0.9 (± 0.2) crabs trap^{-1} respectively (Table 1, Figs. 3 to 5).

Wooli estuary

Analysis of early-season sampling of giant mud crabs done before the 2002 zoning update detected significant variability in catches among sites within locations and a significant interaction between locations and years (Fig. 3A, Table 2A). Subsequent SNK tests revealed that mean catches were significantly greater in unfished locations than in the fished location for 3 of the 4 'before' years (1998, 2000 and 2001), whereas the 2 unfished locations were not significantly different for 3 of the 4 years (1998–2000) (Fig. 3A, Table 2C). Analysis of late-season sampling done before the zoning update detected a significant difference among locations and among years, with the lack of significant interaction between the 2 factors indicating consistency in the pattern of difference among locations across the 4 years (Fig. 3B, Table 2A). SNK tests found a significant difference in mean catches between the 2 unfished locations, but mean catches in both unfished locations were significantly greater than in the fished location (Fig. 3B, Table 2C).

Analysis of early-season sampling done after the 2002 zoning update detected a significant interaction between locations and years (Fig. 3A, Table 2B). Subsequent Ryan's Q tests found that mean catches were significantly greater in both unfished locations than in both fished locations for only 1 of the 5 'after' years (2004), while the pattern in significant differences among locations for the other 4 'after' years (2003–2006) varied (Fig. 3A, Table 2C). There was a significant interaction between locations and years also for late-season sampling done after the 2002 zoning update (Fig. 3B, Table 2B). However, in contrast with the early-season sampling, Ryan's Q tests found that mean catches were significantly greater in both unfished locations than in both fished locations for 4 of the 5 'after' years (2004–2007) (Fig. 3B, Table 2C).

Given the above, our hypothesis specifically predicting that catches would be significantly greater in unfished than in fished locations before and after the zoning change must be rejected. However, it is important to note that (1) mean catches in unfished locations exceeded those in fully fished locations in all 9 years for both early- and late-season sampling (Fig. 3), and (2) in the case of late-season sampling, the only cause to reject the hypothesis was the lack of a statistically significant difference between U^2 and F^2 locations in 2003 (Table 2B).

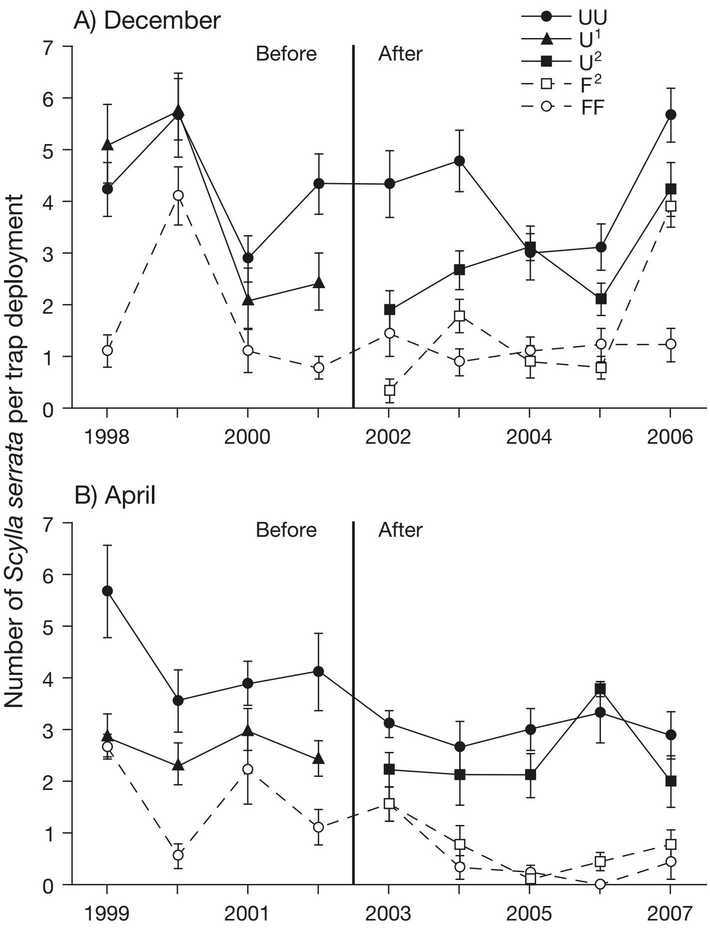

Fig. 3. Catch per unit effort (± SE) of *Scylla serrata* during annual (A) December and (B) April sampling, at 3 locations across 4 sampling years 'Before' the 2002 zoning update (UU and U^1: unfished; FF: fully fished) and 4 locations across 5 years 'After' the update (UU and U^2: unfished; FF and F^2: fully fished) within the Wooli estuary (n = 9 trap deployments). Note: specific sampling positions within UU and FF locations consistent across all 9 sampling years

Corindi estuary

Analysis of early-season sampling of giant mud crabs in the Corindi estuary detected no interaction between location and year or period. However, there was significant variability in catches between years within periods and a significant difference among the 3 locations that was consistent across the temporal factors (Fig. 4A, Table 3A). Subsequent SNK tests revealed that mean catches were significantly greater in the consistently unfished location (U) than the other unfished site (U), which had significantly greater mean catches than the consistently fully fished (FF) location (Fig. 4A, Table 3C).

The corresponding analysis of late-season sampling detected significant variability in catches between years within periods but, in contrast with the early-season ANOVA, also detected a significant interaction between location and period (Fig. 4B, Table 3A). SNK tests revealed that before the zoning change (Period B) mean catches in the 2 unfished locations were similar to each other, with both significantly greater than catches in the fully

Table 2. Summary of results of 3-factor ANOVA comparing trap catches of *Scylla serrata* among 'Locations' ('L': fixed factor) within the Wooli estuary sampled over (A) 4 years before (3 locations: UU, U^1 and FF; 2 unfished and 1 fished) and (B) 5 years after (4 locations: UU, U^2, F^2 and F; 2 unfished and 2 fished) the 2002 zoning update. See 'Methods' and Fig. 2 for explanations of Location categories. Each Year ('Y': random factor), sampling was done early (December) and late (April) in the trapping season, with data associated with each of these 2 categories analysed separately for the 'before' (4 y) and 'after' (5 yr) periods. Three 'Sites' were sampled within each location ('S(L)': nested), with 3 fixed-position replicate 'traps' used to sample within each site (n = 3). Each n represented the cumulative catch from 3 consecutive overnight trap-sets (excluding recaptures). 'Pooled': sums of squares and degrees of freedom for that term pooled with those of the residual ('Res') term (see 'Materials and methods: Data analysis' for explanation of pooling protocol). All data were $\ln(x+1)$ transformed; variances were homogenous for each analysis ($p > 0.05$; Cochran's *C* test). (–) term not considered. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. (C) Summary of results of post hoc multiple-comparisons tests of means of interest where appropriate (Student-Newman-Keuls test [>: $p < 0.05$; ≫: $p < 0.01$] unless marked with 'ǂ': Ryan's *Q* test [>: $p_{adjusted} \approx 0.0253$]; groups ranked in order of decreasing value of mean)

Source of variation	(A) Before (UU, U^1 and FF locations; 4 years)							(B) After (UU, U^2, F^2 and FF locations; 5 years)						
		Early-season			Late-season				Early-season			Late-season		
	df	MS	*F*-den	p	MS	*F*-den	p	df	MS	*F*-den	p	MS	*F*-den	p
L	2	5.850	–		5.384	L × Y	**	3	8.253	–		11.937	–	
Y	3	3.340	–		1.227	Res	***	4	1.809	–		0.903	–	
L × Y	6	0.531	Res	**	0.312	Res	ns	12	0.597	Res	***	0.466	Res	**
S(L)	6	0.557	Res	**	Pooled			8	0.113	Res	ns	0.150	Res	ns
S(L) × Y	18	Pooled			Pooled			32	Pooled			Pooled		
Residual (pooled)	72	(0.160; df = 90)			(0.154; df = 96)			120	(0.156; df = 152)			(0.162; df = 152)		
(C) Multiple comparisons														
		1998: U^1 = UU ≫ FF			UU > U^1 > FF				ǂ 2002: UU ≫ U^2 = FF ≫ F^2			ǂ 2003: UU = U^2 = FF = F^2		
		1999: U^1 = UU = FF							ǂ 2003: UU > U^2 = F^2 = FF			ǂ 2004: UU = U^2 ≫ F^2 = FF		
		2000: UU = U^1 > F							ǂ 2004: UU = U^2 ≫ FF = F^2			ǂ 2005: UU = U^2 ≫ FF = F^2		
		2001: UU > U^1 ≫ F							ǂ 2005: UU = U^2 = FF = F^2			ǂ 2006: U^2 = UU ≫ F^2 = FF		
									ǂ 2006: UU = U^2 = F^2 ≫ FF			ǂ 2007: UU = U^2 ≫ F^2 = FF		

fished location (Fig. 4B, Table 3C). In contrast, there were no significant differences in catches among locations for the 2 yr period shortly following the zoning change (Period A1). The 2 yr period beginning 3 yr after the zoning change (Period A2) was characterised by significantly greater mean catches in the unfished location than in the fully fished location changed from unfished, which had significantly greater mean catches than in the consistently fully fished location. No mud crabs were caught in the latter location via late-season sampling in the 2 Period A2 years (2006 and 2007), while in the 2 unfished locations mean catches trended upwards from the 2006 to the 2007 late-season sampling instance (Fig. 4B).

As was the case for Wooli, our hypothesis that catches would be significantly greater in unfished than in fished locations for all 3 periods before and after the zoning change is rejected.

Sandon estuary

Analysis of early-season sampling in the Sandon estuary detected no interaction between location and year or period, and only a significant difference among the 3 locations (Fig. 5A, Table 3B). SNK tests showed that mean catches were significantly greater in the commercially fished location changed to unfished (CU) than in the commercially fished location changed to fully fished (CF), with both of those means significantly greater than mean catches in the consistently fully fished (FF) location (Fig. 5A, Table 3C). Despite these results, the temporal trends in catches among locations apparent in Fig. 5A superficially appear to offer some support to the stated hypotheses for the Corindi estuary. That is, the fully fished location appears to have yielded far fewer crabs than the commercially fished locations before the zoning change, while for years after the zoning change catches in the unfished location appear to have consistently exceeded those in the fully fished locations, which look quite consistently similar with respect to mean catches (Fig. 5A).

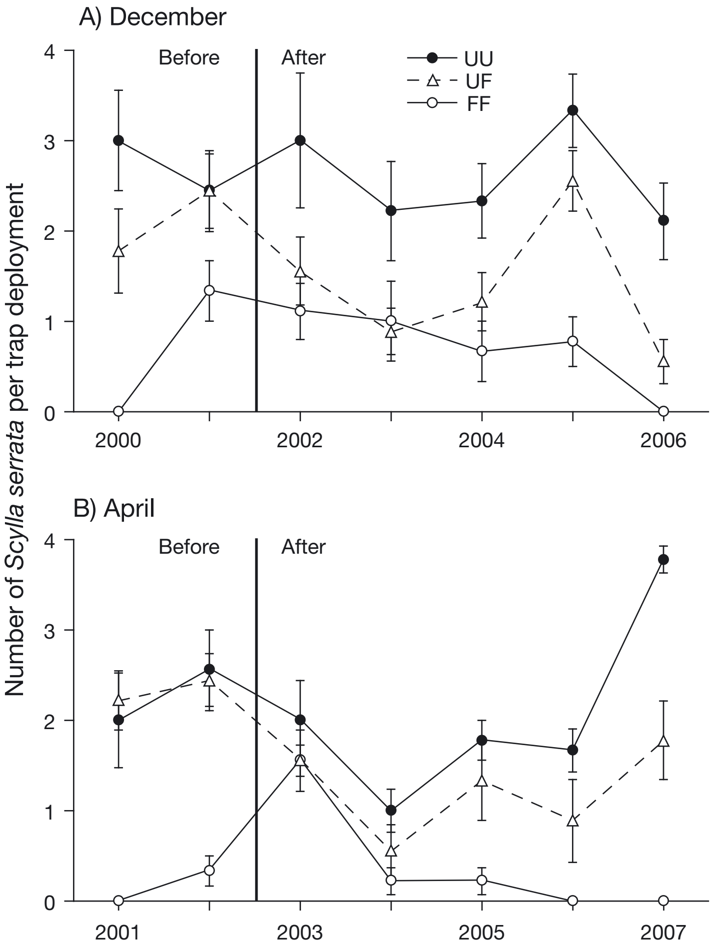

Fig. 4. Catch per unit effort (±SE) of *Scylla serrata* during annual (A) December and (B) April sampling, at 3 locations within the Corindi estuary (UU: unfished–unfished; UF: unfished–fully fished; FF: fully fished–fully fished) across 7 sampling years, 2 'Before' and 5 'After' the 2002 zoning update (n = 9 trap deployments)

The late-season ANOVA detected a significant interaction between location and year (within period) (Fig. 5B, Table 3B). The relevant SNK tests found that although the ranked order of mean catches (decreasing) with respect to the 3 locations was the same for 5 of the 6 years involved in the analysis (i.e. CU, CF, then FF for 2001, 2002, 2003, 2006 and 2007), the pattern of significant differences among the locations was inconsistent among years (Table 3C). For example, before the zoning change there was no significant difference in catches among locations in 2001, while in 2002 mean catches in the 2 commercially fished locations were significantly greater than in the fully fished location (Fig. 5B, Table 3C). In the cases of the 4 years following the zoning change involved in the ANOVA, the pattern of differences among locations in 2003 was similar to 2002 while in 2004 and 2007, the mean catch in the unfished location significantly exceeded those for the 2 fully fished locations, which did not significantly differ from each other. Finally, there was no significant difference among locations in 2006 (Fig. 5B, Table 3C).

DISCUSSION

Benefits of sanctuary zones for giant mud crabs

With the SIMP established in 1991, completely unfished 'sanctuary zones' had been in place for nearly a decade when our sampling commenced. Sampling prior to the 2002 zoning change (i.e. between 1998 and 2002) demonstrated that, when considered collectively across the estuaries sampled, catch rates of giant mud crabs were consistently greater in sanctuary zones (i.e. 'U' locations) compared with fully fished zones ('F' locations) — a result indicating benefits of spatial protection for this species. Further, where the zoning did not change (i.e. UU and FF locations), these differences were generally maintained during the 5 yr period following the zoning change. Similar results were found in a comparable study of the effects of fishing closures on giant mud crab populations in the Moreton Bay Marine Park, Queensland, with catch rates at least double, and male crabs 10 % larger, in unfished compared to non-fished areas (Pillans et al. 2005). However, in the absence of data collected before 1991 in the SIMP, it is not possible to make definitive conclusions based on those pre-zoning-change sampling years, nor on any sampling years at locations for which there was no zoning change made in 2002, as the observed differences could have been due to natural estuarine variation in crab populations (cf. Garcia-Charton et al. 2000, Meynecke et al. 2011).

The 2002 change in zoning at some locations within each of the 3 estuaries provided the opportunity for direct comparisons in catch rates of giant mud crabs between (1) locations that changed from unfished to fully fished (Wooli and Corindi) or commercially (i.e. partially) fished to unfished or fully fished (Sandon), and (2) unfished and/or fully fished locations that were not changed. Our sampling indicated that following rezoning in 2002, catch rates from

Table 3. Summary of results of 4-factor ANOVA comparing trap catches of *Scylla serrata* among 3 'Locations' ('L': fixed factor) within (A) Corindi (treatments UU, UF and FF) and (B) Sandon (treatments CU, CF and FF) estuaries sampled during three 2-yr sampling 'Periods' ('P': fixed; Periods B, A1 and A2). See 'Materials and methods' and Fig. 2 for explanations of Location and Period categories. Each year, sampling was done early (December) and late (April) in the trapping season, with data associated with each of these 2 categories analysed separately for each estuary. Hence, there were 2 sampling months, or 'Years', within each Period ('Y(P)': nested factor). Three 'Sites' were sampled within each location ('S(L)': nested), with 3, fixed-position, replicate 'traps' used to sample within each Site (n = 3). Each n represented the cumulative catch from 3 consecutive overnight trap-sets (excluding recaptures). 'Pooled': sums of squares and degrees of freedom for that term pooled with those of the residual ('Res') term (see 'Materials and methods: Data analysis' for explanation of pooling protocol). All data were ln(x+1) transformed; variances were homogenous for each analysis ($p > 0.05$, Cochran's C test). (–) term not considered. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; ns: not significant. (C) Summary of results of post hoc multiple comparisons tests of means of interest where appropriate (Student-Newman-Keuls test [>: $p < 0.05$; ≫: $p < 0.01$]; groups ranked in order of decreasing value of mean)

Source of variation		**(A) Corindi (UU, UF and FF locations)**						**(B) Sandon (CU, CF and FF locations)**					
		Early-season			Late-season			Early-season			Late-season		
	df	MS	*F*-den	p	MS	*F*-den	p	MS	*F*-den	p	MS	*F*-den	p
L	2	8.315	L × Y(P)	**	9.846	–		10.727	L × Y(P)	**	5.243	–	
P	2	0.166	Y(P)	ns	0.326	–		1.919	Y(P)	ns	2.838	–	
L × P	4	0.503	L × Y(P)	ns	1.845	L × Y(P)	*	0.577	L × Y(P)	ns	0.218	–	
Y(P)	3	2.038	Res	***	2.123	Res	***	0.326	Res	ns	1.370	Res	***
L × Y(P)	6	0.414	Res	ns	0.221	Res	ns	0.274	Res	ns	0.411	Res	*
S(L)	6	Pooled			0.108	Res	ns	Pooled			0.174	Res	ns
S(L) × P	12	Pooled			Pooled			Pooled			Pooled		
S(L) × Y(P)	18	Pooled			Pooled			Pooled			Pooled		
Residual (pooled)	108	(0.224)	(144)		(0.146)	(138)		(0.160)	(144)		(0.164)	(138)	
(C) SNK test results:													
		UU > UF > FF			Period			CU ≫ CF > FF			Year(Period)		
					B: UU = UF ≫ FF						2001(B): CU = CF = FF		
					A1: UU = UF = FF						2002(B): CU = CF ≫ FF		
					A2: UU > UF ≫ FF						2003(A1): CU = CF > FF		
											2004(A1): CU > FF = CF		
											2006(A2): CU = CF = FF		
											2007(A2): CU ≫ CF = FF		

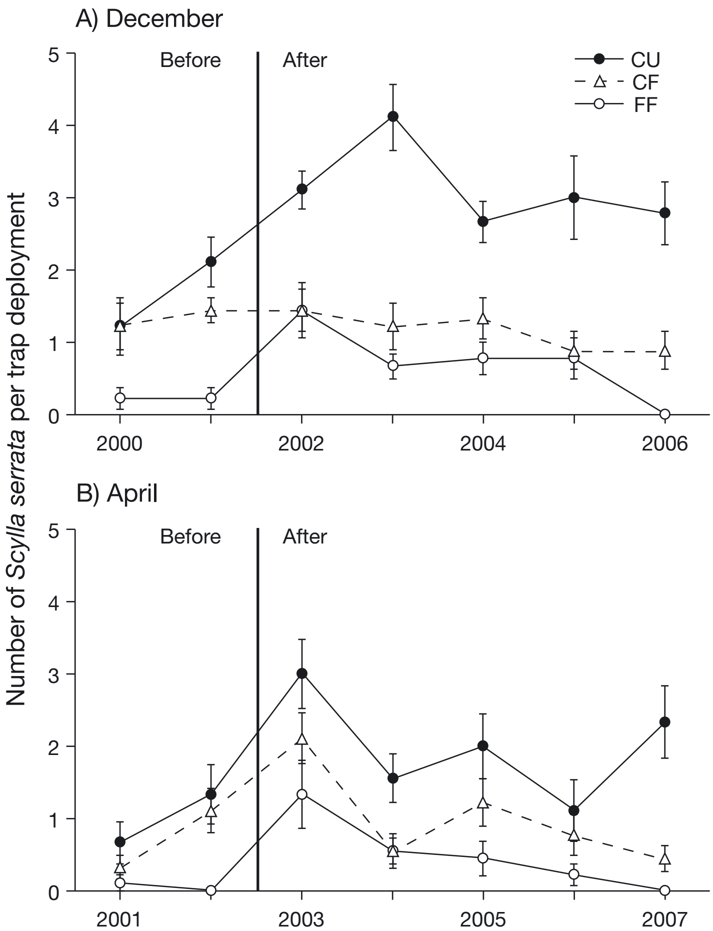

Fig. 5. Catch per unit effort (± SE) of *Scylla serrata* during annual (A) December, and (B) April sampling, at 3 locations within the Sandon estuary (CU: commercially fished–unfished; CF: commercially fished–fully fished; FF: fully fished–fully fished) across 7 sampling years, 2 'Before' and 5 'After' the 2002 zoning update (n = 9 trap deployments)

locations that changed from unfished to fully fished became more similar to those that were fully fished over all years and less similar to those that remained unfished. Similarly, catch rates at a commercially fished location that changed to fully fished became more similar to a fully fished location that was not changed than did a commercially fished location that changed to unfished, with the latter demonstrating an increase in catch rates.

Temporal and spatial variability

There was marked annual variability among years within both fished and unfished areas, as has been noted in other studies on giant mud crabs (Heasman 1980, Butcher 2004, Pillans et al. 2005, Meynecke et al. 2011). We expected this given the likely variation in recruitment associated with environmental variability, larval supply, settlement and survivorship in these subtropical estuaries (Fowler & Jennings 2003). Although there was some synchronicity, peaks and troughs in catch rates were generally inconsistent between estuaries. For example, there were peaks in the Sandon estuary in 2003, Corindi in 2002, 2005 and 2007, and Wooli in 2002, 2003 and 2006. Likewise, troughs did not correspond well between estuaries. This lack of consistency in temporal patterns in catch rates between estuaries suggests that inter-estuarine spatial variability in recruitment may be just as important as annual variability in recruitment across the entire region in influencing abundances of giant mud crabs in the estuaries from year to year (Meynecke et al. 2011). This variability indicates the management value in repeating protection across a network of estuaries (Gaines et al. 2010).

Although there was general synchronicity in patterns of annual variability in catch rates apparent among locations within estuaries, and particularly for locations experiencing the same treatment during the 'before' or 'after' periods, there were some anomalies. For example, there were random peaks in fished locations in the Wooli (December 2006) and Corindi (April 2003) estuaries, while there was considerable annual variability in the differences in catch rate between unfished locations in the Wooli estuary. These observations could be a result of recruitment variability among locations and years within an estuary, local variability in fishing pressure at those spatial and temporal scales, or both. In any case, any real effects resulting from spatial protection might be masked by such smaller-scale variability in our study — a feature common to other marine systems, with patterns sometimes more dissimilar at finer scales than at regional scales (Curley et al. 2002).

With some exceptions, catch rates generally decreased from early season (December) to towards the end of the primary 'fishing season' (April) for most years in each estuary. Given the short life history (~3–4 yr) and rapid growth rate of giant mud crab, we expected stronger differences in catch rates between 'fished' and 'unfished' areas during April sampling due to cumulative depletion in the fished areas. This was not borne out, as the observed differences were not always strongest in April (e.g. Corindi: UU and

UF from December 2006 to April 2007). In any case, the general pattern was probably driven by not only removal of giant mud crabs from fished locations during the trapping season, but also natural variability in abundance and inter-location movements during the trapping season, as the pattern was also evident in the unfished areas. Another contributing factor may have been decreased catchability caused by reduced activity of giant mud crabs as the water temperature is lower in those estuaries during April. Deviations from the pattern at some locations in some years in some estuaries might have been a result of localised variability in environmental factors such as salinity, rainfall (flooding), and/or temperature, as these are known to influence catch rates of giant mud crab (Williams & Hill 1982).

At locations where there was a zoning change, the apparent changes to catch rates of giant mud crab from before to after the 2002 zoning changes are consistent with findings elsewhere for other species targeted by fishers (Russ & Alcala 1996, Mapstone et al. 2004). For example, coral trout were used to indicate management implications of closing and opening a coral reef to fishing in the Great Barrier Reef Marine Park (GBRMP). Closure (3.5 yr) led to an increase in abundance (300 %) and size class, with a rapid depletion of stocks by 60 % in 8 wk and 100 %, 2 yr after the reef was re-opened to fishing (Ayling & Ayling 1998, Russell 1998). The large-scale and long-term effects of line fishing seen in another study in the GBRMP also demonstrated a response to change in zoning, although the response was stronger closer to urban populations and areas with higher fishing pressure (Mapstone et al. 2004).

Implications for management of the giant mud crab fishery in the SIMP

Although Wooli and Corindi are geographically isolated, during the summer (December–April) there is a large influx of holiday visitors and trapping for giant mud crabs is a popular activity (Butcher 2004). The extent of trapping relative to the size of the estuaries is considerable and traps are often densely aggregated around zone boundaries during these periods (Butcher 2004). Given that primary objectives of MPAs include conservation of habitat, provision of unfished populations and maintenance of biodiversity, and as giant mud crabs are likely to be crucial to the ecology of those estuaries, permanent sanctuary zones within estuaries is a suitable strategy to protect incumbent crab populations. Protection of crab populations can be achieved while the local fishery remains productive, with spill-over of giant mud crabs as they move across boundaries between effectively placed sanctuary zones into fished zones (Butcher 2004, Pillans et al. 2005). Species with home ranges that exceed zone boundaries can still benefit from marine reserves (Moffitt et al. 2009).

Pending demonstration of a strong stock-recruitment relationship for this species, using fishing closures might also be a successful tool for developing recovery plans for overfished giant mud crab stocks if this problem arises in the NSW fishery. Areas commercially fished in the Sandon estuary prior to the zoning change showed a significant increase in abundance at the next sampling period (4 mo) following being declared a protected area. This type of response by targeted species to the removal of fishing has been evident in many case studies (see syntheses and reviews by Edgar & Stuart-Smith 2009, Lester et al. 2009, Babcock et al. 2010) including within estuaries (Ley et al. 2002). Although decade-scale response times may be required to demonstrate marine park effects for many marine taxa, communities, and trophic cascades (McClanahan & Graham 2005, Molloy et al. 2009, Babcock et al. 2010), responses may be much faster for shorter-lived, fast-growing species such as giant mud crabs as demonstrated here.

Given the above, several management implications arise from our study in relation to the hypotheses tested. As we found significantly more giant mud crabs in sanctuary than in fished zones and crab abundance increased in areas that were closed to fishing but decreased in unfished areas opened to fishing, it appears that sanctuary zones within estuaries, and more specifically, the current placement of these zones, are helping protect populations of giant mud crab within the SIMP. However, holistic and systematic planning and modelling of the environment, ecology and anthropogenic exploitation within the SIMP is important with respect to ongoing monitoring of the effectiveness of the current and future zoning arrangements (Stewart et al. 2003). For example, mud crab populations have been sustained in the highly exploited waters of the SIMP through their high fecundity, protracted spawning, rapid growth and early sexual maturation. Nonetheless, if habitats are destroyed (e.g. destruction of mangrove habitats would affect juvenile development) and/or fishing pressure increases (Williams 2002), these attributes may not suffice to maintain viable populations (Heasman 1980). Furthermore, the current zoning scheme in each of the 3 estuaries examined here provides little protection from fishing pressure on females emigrating from sanctuary zones (sometimes in the upper reaches of the river) to the ocean to spawn.

Study limitations

We make these interpretations above despite (1) a lack of replication of the unchanged locations within estuaries, (2) forced alterations to the sampling design in one estuary, and (3) some variability at most spatial and temporal scales; due to the consistency in pattern across all 3 estuaries. Suitable replication of 'control' locations (in this case, either unfished or fished locations) within estuaries would have enabled more definitive conclusions regarding the effect of changes to permissible fishing levels on giant mud crab populations in each estuary. With replicate unfished and fished locations, levels of natural spatial and temporal variability among unfished and fully fished locations could be quantified, thereby providing a more rigorous logical and statistical test to detect any changes in catch rates that could be confidently attributed to a change in zoning status (Underwood 1991, 1992). Further, the forced alteration to the sampling design in the Wooli estuary negated the potential analytical benefit of having identical sampling designs in 2 estuaries. Consequently, we have interpreted our results cautiously and the following conclusions remain tentative.

CONCLUSIONS

Our study has highlighted the benefits of unfished areas in protecting giant mud crab populations. However, as we specifically set out to use giant mud crabs as a single species 'condition indicator' to compare 'fished' and 'unfished' zones within the SIMP, our conclusions regarding the benefits of protecting areas from fishing pressure may not apply to other taxa and communities in this area. This is especially pertinent where such zoning measures relate to specific types of fishing method (e.g. trapping) yet not others (e.g. line fishing). Protection of any key scavenger or large predator species, which mediate fundamental ecosystem processes, usually has flow-on effects (Babcock et al. 1999). Giant mud crabs are likely to be an important component of many ecosystem processes and trophic pathways in subtropical estuaries, and so their presence would contribute to overall system health.

This study has shown that estuarine protected areas could be an effective and important management tool for protecting the recreationally and commercially fished giant mud crab in the SIMP. This approach could be used to manage other globally exploited crab stocks. We have shown that closing an area to fishing resulted in a sustained increase in catch rate over a time scale of years. Conversely, opening areas to fishing following an extended period of protection led to rapid decreases in crab abundance (as catch-per-unit of sampling effort), most likely due to fishing-down effects. In conclusion, management strategies that avoid opening closed areas and that concentrate on effective placement and size of closed areas are likely to be highly effective, even in estuaries and for species other than fish.

Acknowledgements. We acknowledge the support provided by University of New England, Armidale and NSW Department of Primary Industries (NSW Fisheries and NSW Marine Parks Authority). We appreciate the contributions made by the many volunteer fishers and Steve Smith and staff at these respective institutions. Special thanks to Geoff Butcher and the late Wally McDonald for the countless volunteer hours they spent on this project.

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Editorial responsibility: Romuald Lipcius, Gloucester Point, Virginia, USA

Submitted: July 2, 2013; Accepted: May 15, 2014
Proofs received from author(s): July 24, 2014