4.0 The effect of different zoning schemes on mud crab (*Scylla serrata)* populations in estuaries within the Solitary Islands Marine Park, NSW

4.1 Introduction

Marine Protected Areas provide numerous benefits through increases in abundance, growth rates, and average size and recruitment of fish, as well as ecosystem benefits through reduced disturbance (Chapter 1; Cole *et al.* 1990; Roberts 1994; Childress 1997; Wahl 1997; Butcher 2001 (Appendix 7); Butcher *et al.* 2003 (Appendix 6)). Special natural features such as the Great Barrier Reef, Australia, can be protected, providing ecosystem maintenance and ensuring long-term sustainability (Agardy 1997). Tourism, particularly fishing, is a major cause of concern with its impact on certain areas of the marine system (Russell 1998; Recher 2003). To minimise this pressure, closed areas, harvest refugia and multi-use marine protected areas are being used as tools to protect the marine environment (Agardy 1997). Closed areas or harvest refugia aim to conserve stocks and habitats threatened by over-exploitation and destructive fishing, whereas multi-use marine protected areas safeguard critical habitats while allowing the long-term, sustainable use of marine resources (Chapter 1).

Managers need to be able to demonstrate whether different zoning schemes used in multi-use marine protected areas are effective (Kelleher 1999). Regular evaluations of the zones will enable managers to model the changing conditions and help justify future management decisions (Dahl-Tacconi 2003). A measure of effectiveness can be achieved by collecting baseline information through demographic studies of differences in abundance, size class, sex ratio, and spill-over of indicator species between areas (Chapter 1). These indicators are a qualitative and quantitative measure of the condition of part or a whole system (ANZECC 1998). Ideally, indicator species should be readily caught, taxonomically distinct, relatively abundant, ecologically significant and, preferably, of direct recreational and commercial importance. As well as collecting information on the indicator species being targeted, managers need to compare information on fishing effort and compliance with zoning schemes by users (Causey 2003). This baseline information will help implement management strategies using the latest scientific information (Causey 2003). For example, coral trout (*Plectropomus* *leopardus*) were used as an indicator to show the management implications of closing and opening a coral reef to fishing on Bramble Reef in the Northern Central Section of the Great Barrier Reef Marine Park (Russell 1998). This study demonstrated that populations react to opening and closing of areas to fishing. Closure led to an increase in abundance and size class with a rapid depletion of stock when the reef was re-opened to fishing. In another study within a Caribbean marine reserve, Roberts (1994) found that the abundance and mean size of commercial species of fish were greater in protected areas than in adjacent fished areas.

Without the protection offered by MPAs, overfishing can cause problems to fisher-targeted species. The removal of large spiny lobsters (*Panulirus marginata*) by fishers favours the reproduction of early maturing individuals that are smaller in size. These individuals then dominate future generations (Chubb 1994). The removal of large individuals or selective harvesting from a population can also lead to mating difficulties where larger males are able to mate with a variety of female size classes but smaller males are physically restricted to mate with smaller females. This restriction leads to problems with reproductive success (Wahle 1997).

The formation of marine parks can reduce these types of problems and impacts on species (Chapter 1.2). The Solitary Islands Marine Park (SIMP) was declared in 1998 and is the first and largest Marine Park in NSW. Its primary aim is to protect representative examples of marine diversity, while catering for a broad range of recreational and commercial activities (MPA 2002). The Sandon, Wooli and Corindi estuaries are located in the northern section of the SIMP, with different zones implemented to allow continued commercial and recreational use in some areas while ensuring a sustainable future for fisheries in the SIMP. To determine the effectiveness of these zones in each estuary, the mud crab (*Scylla serrata* Forskal 1775) (Portunidae) was identified as a potential 'condition' indicator species (Chapter 1.3) as it is targeted by commercial and recreational fishers, it is abundant, large, and has a short lifecycle making it responsive to overfishing.

The mud crab inhabits much of the inshore regions of the Indo-Pacific region (Kailoa *et al.*1993). In Australia, it is distributed across the northern coastline and down the eastern seaboard to the Bega River and Exmouth Gulf along the western seaboard (Kailoa *et al.* 1993). Three species of mud crabs occur within the genus *Scylla* (Keenan *et al.* 1998). Differentiation between species was achieved from morphological descriptions and photographs displayed in Keenan *et al.* (1998). Within this region, it inhabits a range of habitats in estuarine, bay and mangrove areas (Hill *et al.* 1982; Hyland *et al.* 1984). Mud crabs are fished by both commercial and recreational sectors with stock depletion from high fishing pressure a concern to managers. At a Mud Crab Workshop held in Terrigal in 1993, managers and scientists from throughout Australia concluded there were many areas that need uniform management approaches for the fishery (Bartleet *et al.* 1993). Resolutions from the meeting included restricting the use of netted dillies, having a uniform measuring method and size limit so the legal size is where 50% of the females are mature, and commencing research into stocks by electrophoretic assessment. While few of these resolutions have been conducted to improve management of this resource, the management of their habitat through marine park zones and understanding of their population demographics from their response to these zones may aid this fishery. This will determine whether marine park zones have any effect on their populations and justify the use of marine park zones in mud crab management.

The primary objective of the present study was to evaluate the effectiveness of the different SIMP zones in each estuary by comparing the demographic structure of mud crab populations between the adjacent fished and unfished zones. I also aimed to assess the levels of depletion and replenishment once areas are reopened or closed to fishing. I hypothesised that if the zoning was currently effective, there should be significantly more crabs in the protected Sanctuary Zone and the average size class of crabs in the fished zone would be smaller owing to the selective harvesting of larger individuals. If the Sanctuary Zone is acting as a 'source' population, there should be a significant number of large crabs recruiting from the Sanctuary Zone to the fished areas. Crabs will also be depleted rapidly within months in areas reopened to fishing due to intense fishing pressure while previously fished sites that become protected will resemble control Sanctuary Zone sites with large numbers or bigger crabs being dominant in the population.

4.2 Methods

4.2.1 Sampling protocol and site selection

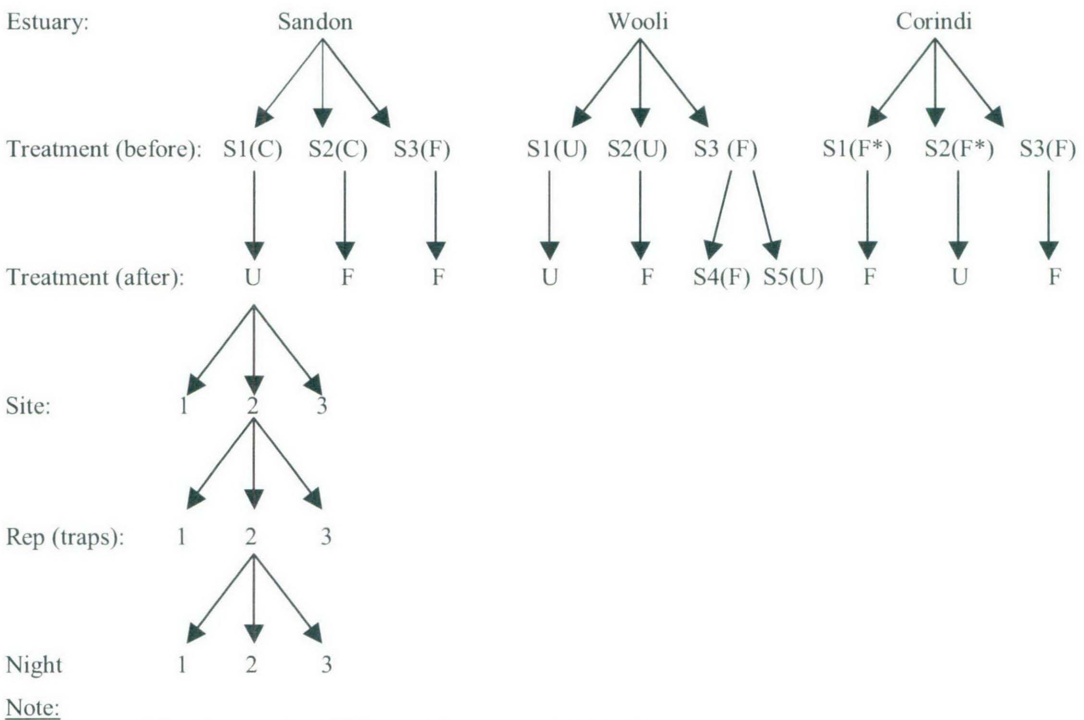
A pilot study in November 1998 at Sandon, Wooli and Corindi estuaries provided the basis for site selection (Appendix 5). Previous work in Moreton Bay, Australia by Hill (1982) and Hyland *et al.* (1984) established that different size classes of crabs moved within and between different habitats for protection and foraging. Therefore, sites in the Wooli, Sandon and Corindi estuaries were selected to sample all habitat and marine park zone types. Three sites were chosen in each estuary with at least one fished and unfished site at Wooli and Corindi and a fished commercial and fished commercial/recreational site at Sandon (Figure 4.0; Table 4.1). Each site was divided into three 200 m areas (Figures 4.1 - 4.3; Appendix 2). One trap was placed at 0 m, 100 m and 200 m and marked with a GPS for future reference. Williams and Hill (1982) found that any distance less than 44 m created competition between adjacent traps. Each area was sampled daily, starting at 07.00 hrs for three consecutive days at approximately the same time each month (Appendix 1). A three-night period was chosen as male crabs entered traps before females (Chapter 3.7) and three, 24 hr trapping would give sufficient time for all crabs that were feeding in the area around the trap time to enter.

4.2.2 Trapping frequency

Trapping was undertaken monthly from December 1998 at Wooli and July 2002 at Sandon and Corindi until August 2003 (Appendix 1). However, sampling did not take place during September and October 1999 at Wooli as this was the period between my honours work and there was uncertainty whether the project would continue as a Ph.D. study. Sampling trips aimed to coincide with a consistent moon phase and tidal range to standardise conditions. Tidal range similarity was necessary to minimise the distribution of bait odour to minimise competition among traps. On large tides, it was likely that the bait odour may move more freely resulting in crabs being attracted further from the traps while moon phase regulated the amount of light penetrating the water.

4.2.3 Design - zoning manipulation

During the study, a five-year zoning update occurred in August 2002, providing an opportunity to detect changes in populations as a direct result of the zoning scheme. The changes in zoning scheme locations and the size of zoning areas in each estuary are described in Table 4.1 and 4.2. A detailed description of sites in each estuary is presented in section 4.2.4. All possible combinations of change were covered to answer the questions outlined in the objectives. The changes included areas which were "fished-fished (FF)", "fished-unfished (FU)", "unfished-fished (UF)" and "unfished-unfished (UU)". Direct changes in zoning histories occurred in all three estuaries (Figure 4.0; Table 4.1). Sandon was the only estuary to have sites that changed from "fished" (commercial only) to "unfished" and "fished" (commercial only) to "fished", while Wooli and Corindi had sites which changed from "unfished" to "fished". As the other sites in each estuary did not change, these were used as controls when comparing spatial and temporal changes (Table 4.1).



Note:
F = commercial and recreational fishers unless otherwise stated
F* = fishing permitted but no trapping or collecting
U = fishing prohibited
C = commercial fishing only and recreational angling by line.
Wooli Site 2 was split into Site 4 and Site 5 in August 2002 due to new zoning plans.

Figure 4.0. Experimental design before and after the zoning change.

Table 4.1. Temporal changes in individual estuary zoning schemes for trapping areas

			Treatment type		
Estuary	**Site**	***<May 1991***	***May 91- Aug 02***	***Post Aug 02***	**Change**
Sandon	Site 1	Yes	C - Commercial	U	C-U
	Site 2	Yes	C - Commercial	F	C-F
	Site 3	Yes	F	F	F-F
Wooli	Site 1	Yes	U	U	U-U
	Site 2	Yes	U	Split- Site 4 and 5	
	Site 3	Yes	F	F (limited)	F-F
	Site 4	Yes	U	F (limited)	U-F
	Site 5	Yes	U	U	U-U
Corindi	Site 1	Yes	U	F	U-F
	Site 2	Yes	U	U	U-U
	Site 3	Yes	F	F	F-F

The Sandon Estuary was the only system that experienced a large increase in area of total protective zoning for mud crabs at the zoning change in 2002. This increased by 38% at Sandon while Corindi and Wooli decreased in protective zoning by 21% and 14% respectively. Among the three estuaries, there was little change in the total percentage area protected from mud crab fishers with 32% before and 34% after August 2002. This accounts for 2.17 km^2 and 2.37 km^2 of total "no take (unfished)" zones before and after the zone change from a total area of 6.96 km^2.

Table 4.2. Changes in zone sizes for trapping in each estuary at the August 2002 zoning change.

Estuary/Site	1991 – August 2002		Post August 2002	
	Not Fished (km^2)	Fished (km^2)	Not Fished (km^2)	Fished (km^2)
Sandon S1		0.46 (comm. only)	0.46	
Sandon S2		1.40 (comm. only)	0.48	0.92
Sandon S3		0.62		0.62
Sub total	0 (0%)	2.48 (100%)	0.94 (38%)	1.54 (62%)
Wooli S1	0.35		0.35	
Wooli S2	1.05		became sites 4 and 5	
Wooli S3		1.82		1.82
Wooli S4				0.48
Wooli S5			0.57	
Sub total	1.4 (43%)	1.82 (57%)	0.92 (29%)	2.3 (71%)
Corindi S1	0.45			0.45
Corindi S2	0.32		0.32	
Corindi S3		0.49	0.19	0.30
Sub total	0.77 (61%)	0.49 (39%)	0.51 (40%)	0.75 (60%)
Total	**2.17 (32%)**	**4.79 (68%)**	**2.37 (34%)**	**4.59 (66%)**

4.2.4 Study site descriptions

Each estuary of the three estuaries investigated was selected based on accessibility, habitat type, location of the estuaries, the different zoning schemes present and the potential for interactions within the estuary because of the different zoning schemes. The later are described for each estuary below.

Wooli Estuary

In 1991, zoning schemes were created as part of the Solitary Islands Marine Reserve. The Wooli Estuary was managed using Recreation and Sanctuary zones (Figure 4.1a; Table 4.1). The Recreational Zone extended from the mouth of the estuary to 8.75 km upstream (Site 3 (Areas 7 - 9)). Upstream of this, all of the tidal waters including all the creeks, bays and tributaries were in a Sanctuary Zone (Site 1 (Areas 1 - 3), Site 2 (Areas 4 - 6)).

In August 2002, the current zoning scheme was implemented in the Wooli Estuary with notable changes in area of each zoning type (Figure 4.1b; Table 4.2 and Appendix 3). The Sanctuary Zone was reduced in size to include all the tidal waters of the northern arm and central basin upstream of the forks (Figure 4.1b). This incorporated Site 1 (Areas 1 - 3) and Site 5 (Areas 6, 11 - 12). The rest of the estuary was designated Habitat Protection Zone. A special area (no crab trapping), which prohibited the taking of crabs by wire crab traps, was located 1 km downstream from the forks and included all of the tidal waters upstream including the left arm of the estuary. This incorporated Site 3 (Areas 7 - 9) and Site 4 (Areas 4 - 5, 10).

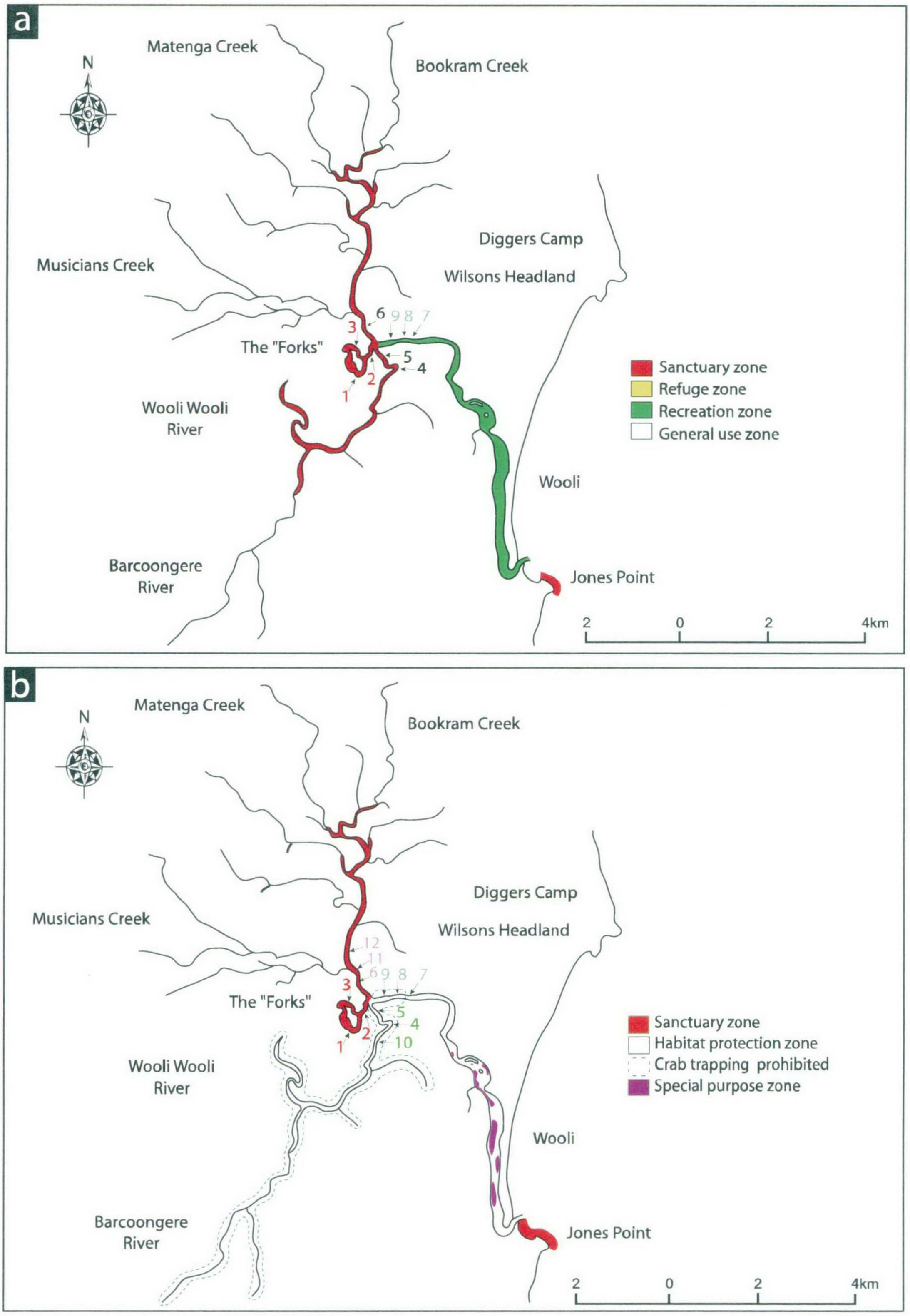


Figure 4.1. The zoning scheme in the Wooli Estuary with sampling locations in each zone. a = 1991 – July 2002, b = August 2002 – present.

Site 1- Swamp (Unfished)

This site is located between the southern and northern arms of the Wooli Estuary at Areas 1 - 3 (Plate 4.1; Figure 4.1). The site is within a Sanctuary Zone, and remained "unfished" before and after the August 2002 zoning change (Table 4.1). It consists of shallow mud flats and extensive intertidal areas, which are dominated by mangroves. There are no major creeks and only a few drainage lines running into this site. It is only accessible by boat. Freshwater backing up from the main arms is the major cause of salinity variation. The inundation time on the intertidal flats is approximately five hours providing time for crabs to use this region. The low current velocity in comparison to the main channel areas provides an environment which may benefit mud crabs as dead prey items will not be washed away quickly, but the dispersal of prey scents may not reach as far in this habitat.

Plate 4.1. Large mud flats and mangroves at Site 1, Wooli Estuary, NSW.

Site 2

This site is located within the northern and southern arms of the Wooli Estuary at Areas 4 - 6 (Plate 4.2; Figure 4.1). One area is located within the northern arm (Area 6) and two areas in the southern arm (Area 4 - 5). When the new zoning scheme was implemented in August 2002, the site was divided into two. Due to changes in zone design by the selection process under NSW MPA criteria, that were beyond my control, further areas were added to eliminate replication problems. A further area was added to the southern arm creating Site 4 (Area 4, 5 and 10 on Figure 4.1b) while 2 areas were added to the northern arm creating Site 5 (Area 6, 11 and 12 on Figure 4.1b) three months prior to the change in August 2002. This gave an "unfished" to "fished" change for Sites 2 to 4 and an "unfished" to "unfished" control for Sites 2 to 5 (Table 4.1). It is approximately 9.25 km upstream from the mouth of the estuary and is a deep-water habitat (depth 2.25 m) with undercut banks and a small percentage of mangroves lining the banks. The intertidal zone is narrow (0 - 2 m wide). The substrate in this region is sand and mud. This site is accessible by 4wd and boat, providing access for illegal fishing.

Plate 4.2. Undercut banks and sparse mangroves in Site 2, Wooli Estuary, NSW.

Site 3 - Fished

This site is located in the Recreation Zone at Areas 7 - 9 (Plate 4.3, Figure 4.1). It is approximately 8 km upstream from the mouth of the Wooli Estuary and only differs from Site 2 in being slightly wider and is exposed to fishing pressure. It is accessible to fishers from the bank in the lower and mid-estuary and by boat near the zone border. This site remained a "fished" site before and after the August 2002 zoning change (Table 4.1).

Plate 4.3. Evidence of fishing pressure by fishers with traps illegally inside the junction of the "fished" and "unfished" zones at Site 3, Wooli Estuary, NSW.

Sandon Estuary

The Sandon Estuary was managed using Recreational and Refuge zones from 1991 to August 2002 (Figure 4.2 and Table 4.1). The Recreational Zone allows crab trapping while the Refuge Zone excludes recreational trapping and only allows specific commercial trapping for crabs and netting for fish to one fisher under NSW Fisheries regulations. The Recreational Zone extends from the mouth of the estuary to 1.5 km upstream where it becomes a Refuge Zone (Site 3 (Area 7 - 9)). The Refuge Zone covers all the tidal waters of Toumbaal Creek (Site 1 (Area 1 - 3), Candole Creek (Site 2 (Areas 4 - 6), and Sandon Estuary (Figure 4.2) including all their creeks, bays and tributaries upstream from the Solitary Islands Marine Park boundary markers.

On the 1st August 2002, a Habitat Protection Zone was placed to incorporate all of the tidal waters from the mouth of the estuary upstream excluding Toumbaal Creek and Sandon Estuary arms. Toumbaal Creek and Sandon Estuary arms were given Sanctuary Zone status (Figure 4.2). Notable changes in area of each zoning type occurred (Figure 4.2b; Table 4.2 and Appendix 3).

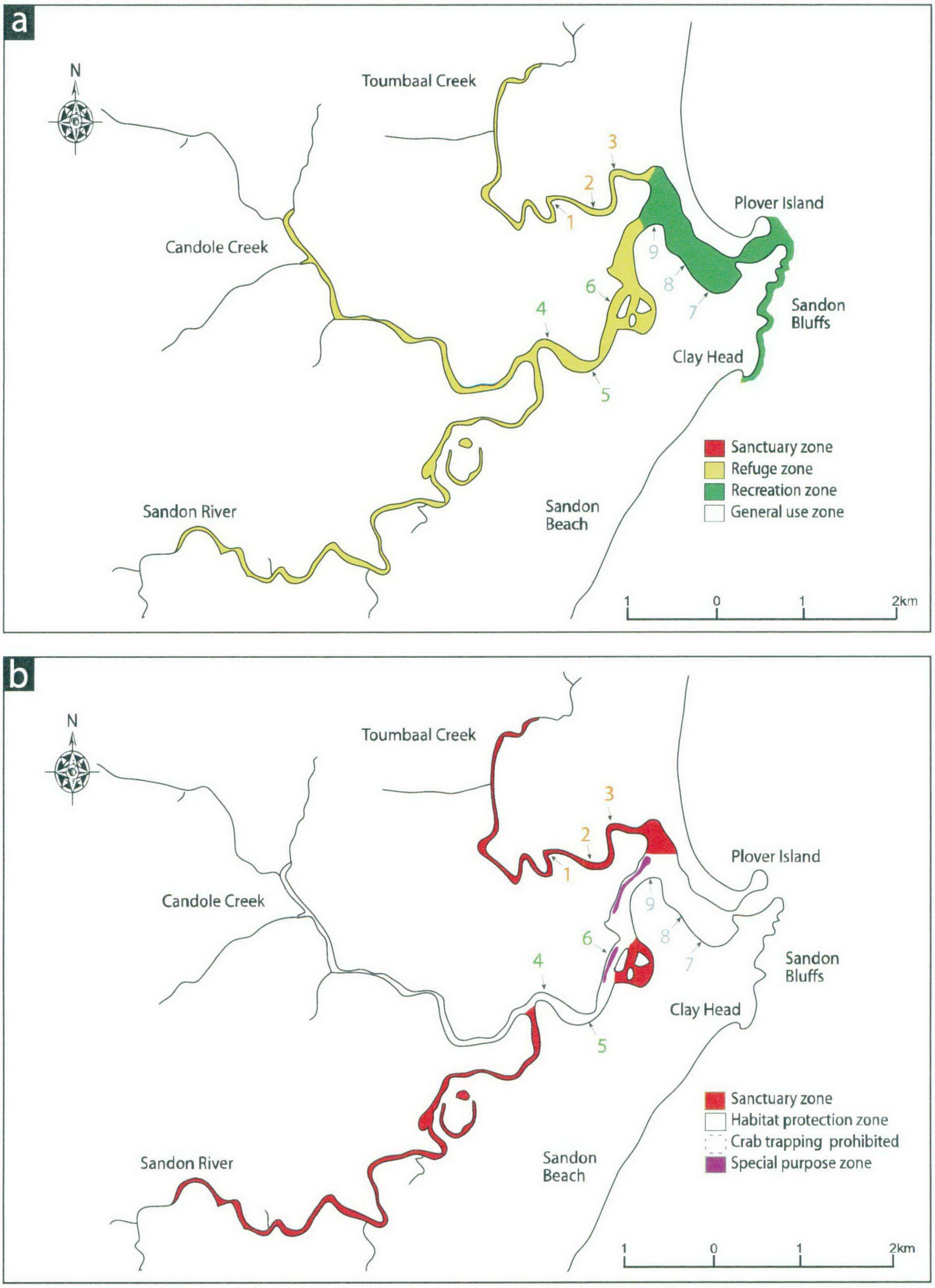


Figure 4.2. The zoning scheme in the Sandon Estuary with sampling locations in each zone.
a = 1991 – July 2002, b = August 2002 - present

Site 1 - Northern Arm (Toumbaal Creek)

This site is located within the northern arm (Toumbaal Creek) at Areas 1 - 3 (Plate 4.4, Figure 4.2). It had a "fished" (commercial only) to "unfished" change when the zoning change occurred in August 2002 (Table 4.1). It is approximately 3 km upstream from the mouth of the estuary and accessible to illegal fishing from boats and walking tracks. It contains habitat of seagrass with mangroves lining the banks. The substrate in this region is sand. The site is subject to flooding as it has many freshwater streams feeding the system.

Plate 4.4. The small intertidal zone at Site 1 in the Sandon Estuary, NSW.

Site 2 - Southern Arm

This site is located within the southern arm of the Sandon Estuary/Candole Creek at Areas 4 - 6 (Plate 4.5, Figure 4.2). It is approximately 4 km upstream from the mouth of the estuary and accessible by fishers from boats and four wheel drive (4wd) in the upper reaches. It had a "fished" (commercial only) to "fished" change when the zoning change occurred in August 2002 (Table 4.1). This region consists of deeper and wider channel areas than Site 1. It has variable banks ranging from rocky, oyster-lined and undercut banks to sand flats opposite and a small percentage of mangroves lining the banks. The substrate in this region is sand.

Plate 4.5. Large expanses of water an small intertidal zones at Site 2 in the Sandon Estuary, NSW.

Site 3 - Fished

This site is located in the Sandon Estuary at Areas 7 - 9 (Plate 4.6, Figure 4.2). It is approximately 1 km upstream from the mouth of the estuary and easily accessible by fishers in boats and on the bank and has good boat launching access. It remained a "fished" site before and after the zoning change in August 2002 (Table 4.1). It contains channel habitats surrounding sand flats and few mangroves lining the banks. The substrate in this region is sand. The site is subject to minor flooding.

Plate 4.6. Access points in the lower reaches of the Sandon Estuary at Site 3.

Corindi

The Corindi Estuary was managed under the same marine park zoning scheme as the Sandon Estuary with a Recreation Zone in the lower estuary and Refuge Zones in the middle and upper reaches. However, the scheme does not allow commercial fishing in the Refuge Zone which extends throughout the Corindi River (Site 1 (Area 1 - 3)) and Saltwater Creek arms (Site 2 (Area 4 - 6). The Recreation Zone extends from the mouth to 1.5 km upstream to where the estuary divides (Site 3 (Area 7 - 9). Above this is a Refuge Zone (Figure 4.3a).

On the 1st August 2002, the Corindi Estuary zoning scheme changed with the Recreational Zone and Refuge Zone (excluding Saltwater Creek) becoming Habitat Protection Zones with major changes in area of each zoning type (Figure 4.3b; Table 4.2 and Appendix 3). The new zoning scheme allows for commercial and recreational trapping and collecting, which had previously been prohibited in the Refuge Zone. The northern arm, Saltwater Creek, will provide further protection from crab trapping with Sanctuary Zone status.

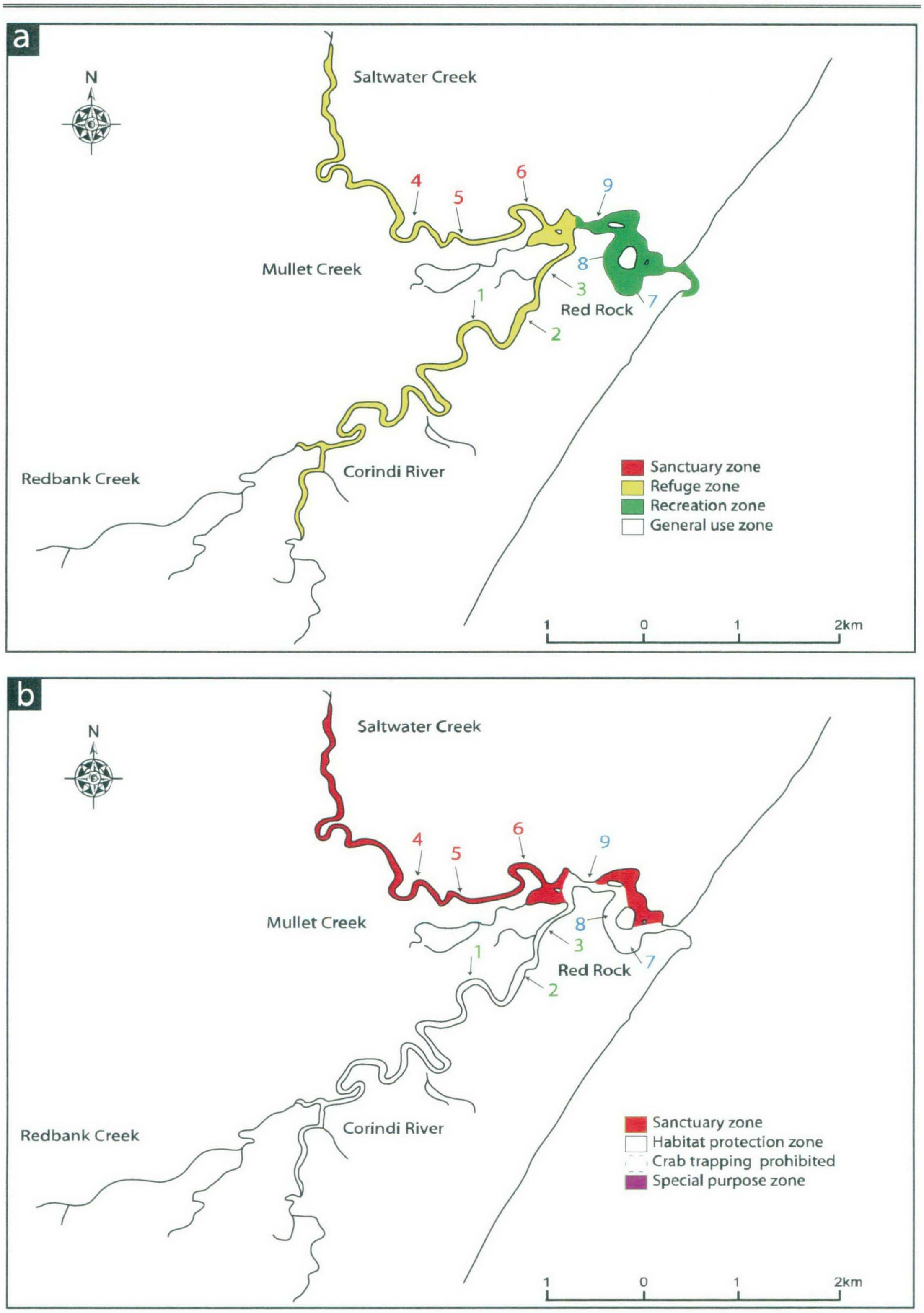


Figure 4.3. The zoning scheme in the Corindi Estuary with sampling locations in each zone.
a = 1991 – July 2002, b = August 2002 - present

Site 1 - Southern Arm

This site is located within the southern arm of the Corindi Estuary at Areas 1 - 3 (Plate 4.7, Figure 4.3). It is approximately 2 km upstream from the mouth of the estuary. It had an "unfished" to "fished" change re-zoning in August 2002 (Table 4.1). It is close to the town of Red Rock and is accessible by 4wd, walking and boats. It has undercut banks, sand flats, and sparse mangroves lining the banks. The substrate in this region is sand. The site is subject to severe flooding

Plate 4.7. Mangroves lining the small intertidal areas at Site 1 in the Corindi Estuary, NSW.

Site 2 - Saltwater Creek

This site is located within the northern arm of the Corindi Estuary at Areas 4 - 6 (Plate 4.8, Figure 4.3). It is approximately 2 km upstream from the mouth of the estuary and is accessible by 4wd and boat. It remained "unfished" before and after the zoning change in August 2002 (Table 4.1). It has mangroves lining the banks and seagrass along the edge of the channels. The size of the intertidal zone is similar to the southern arm and the inundation time at high tide is small. The substrate in this region is sand. The site is subject to severe flooding.

Plate 4.8. Mangroves lining the estuary in the lower reaches of Site 2 in the Corindi Estuary, NSW.

Site 3 - Fished

This site is located in the lower reaches of the Corindi Estuary at Areas 7 - 9 (Plate 4.9, Figure 4.3). It is approximately 1 km upstream from the mouth of the estuary. It remained a "fished" site before and after the zoning change in August 2002 (Table 4.1). It is accessible by foot, car, and boat. It consists of sand flats surrounding the channel areas and sparse mangroves lining the banks. The site is subject to minor flooding.

Plate 4.9. Accessible points for fishing in Site 3 at the mouth of the Corindi Estuary, NSW.

4.2.5 Fishing Pressure

The number of traps, boats and people were counted each month to provide an indication of fishing pressure in each estuary (section 3.10). Prior to the zoning change, these counts were taken in the "fished" Site 3 in each estuary (section 4.2.4) and all areas that are designated as fished areas under zoning requirements in each estuary. After the zoning change, counts continued within the same sites but included Site 2 at Sandon, Site 4 at Wooli and Site 1 at Corindi. These sites were opened to fishing at the zoning change.

Spatial and temporal variation in fishing effort was further assessed by dividing the Wooli Estuary into 1 km intervals (section 3.10). A short-term intensity survey was conducted between 20th December 2002 and 28th January 2003 when high fishing effort associated with school holidays was predicted. Counts of fishers, boats and people were made in each section at 4 pm daily to provide an indication of whether any gradient occurred along the estuary for fisher effort and variation among days within this period. Afternoon counts were made as this seemed to be the best time when fishers where active in the estuary.

4.2.6 Statistical analysis

Generic procedures

Where analysis of variance was used, all data were ln(x+1) transformed to model treatment effects as approximately multiplicative (Zar 1999) and tested for heteroscedasticity using Cochran's test. Where appropriate, to increase the power of the F-test for the term of interest, the Mean Square (MS) denominator was pooled with the residual if it was non-significant at $P>0.25$ (Winer 1971). All significant F-ratios of interest were tested using a *post hoc* Tukey's (HSD) comparison of means test where necessary. The HSD test is the most useful test for comparison of means as it controls the experimentwise-error-rate while retaining strong power (Analytical Software 2001).

Fished vs Unfished

Data from monthly sampling between July 2000 and April 2002 three months prior to the implementation of the management changes provided identical spatial sampling designs to compare "fished" vs "unfished" treatments for Wooli and Corindi (i.e. one "fished" and two "unfished" sites). This was used to test the null hypotheses of no differences in catch per unit effort (CPUE) between Fished (F) v Unfished (U) sites in the Wooli and Corindi estuaries. This allowed an assessment of the possible long-term effects of fishing on mud crab populations via an asymmetrical five-factor ANOVA (Table 4.3a). The design of the asymmetrical ANOVA was based upon the equivalent symmetrical design (i.e. as if there were two unfished and two fished sites in each of the estuaries, rather than the existing two and one respectively). The three main orthogonal factors of interest were 'Fished vs Unfished' (fixed), and 'Estuaries' and 'Months' (both random). The 'Sites' term was spatially nested within the former (Table 4.3a) and was asymmetrically distributed between the "unfished" and "fished" treatments, while the 'Areas' term was nested within 'Sites'. The sums of squares (SS) for terms in the analysis were derived using SS from three less complex, balanced ANOVAs - ANOVAs A, B and C shown in Table 4.3b. The general concept behind the derivation of the SS of terms in the asymmetrical ANOVA can be most simply demonstrated using the Fished v Unfished term as an example (Table 4.3a). The Fished v Unfished distinction among sites is ignored in the designs of ANOVAs A, B and C (Table 4.3b). The Sites term (and its associated interaction terms) in ANOVA A uses data from all three sites in each of the two estuaries. This provides an overall estimate of variability among all three sites, regardless of whether they are fished or unfished. However, the equivalent term in ANOVA B uses data from only the two unfished sites in each estuary, providing an estimate of variability among only the unfished sites. By subtracting the SS of the Sites term from ANOVA B from that of ANOVA A we derive an estimate of the additional variability contributed by the fished site, therefore deriving a SS (and df) for the Fished v Unfished term in the asymmetrical ANOVA in Table 4.3a. The interaction and nested terms in the asymmetrical ANOVA are derived in a similar fashion using the same principle, (Table 4.3). It is worth noting that the total df and SS for the asymmetrical ANOVA equals those for ANOVA A, providing a useful check for the validity of the design. Glasby (1997) provides a comprehensive description of the general statistical methodology behind the above procedure.

Analysis of crab captures in individual months were also tested to determine where temporal differences occurred between “fished” v “unfished” treatments. However, this method did not work as the degrees of freedom (DF) of the numerator and denominator for the F- ratio for the (F v U) term was (1,1) respectively, rendering the analysis relatively powerless when the (Estuary x (Fished v Unfished)) interaction term could not be pooled (Table 4.4).

To detect differences in CPUE between "fished" and "unfished" sites within and among estuaries each month, I refined my analysis to a series of simpler ANOVAs conducted on data from each month with CPUE as the dependent variable and 'Sites' nested within 'Estuaries' and 'Areas' nested within 'Sites' as the independent random variables. Where estuaries in the same analysis gave a significant 'Site' difference, the analysis was refined further to analyse the two estuaries (Wooli and Corindi) separately using a nested ANOVA ('Areas' nested within 'Sites'). In each analysis the 'Areas' term was pooled with the residual where appropriate (i.e. $P > 0.25$) to increase the power of the test for detecting the main effects of 'Sites' (Winer 1971). Significant main effects were then further investigated using *post hoc* Tukey's (HSD) tests to compare means among the sites and determine whether there was a significant difference between "fished" and "unfished" sites in each estuary.

Table 4.3. (a) Summary of ANOVA designed to detect differences in abundance between Fished (F) v Unfished (U) sites in the Wooli and Corindi estuaries and (b) individual ANOVAs used from 'F' and 'U' treatments to formulate sums of squares in (a) to detect a difference between treatments.

(a)

Source of Variation	**DF**	**Derived Sums of Squares from ANOVA (A, B & C) below**	**F-ratio - denominator**
Fished v Unfished – FvU	1	SITES (A) - SITES (B)	-
Estuary - E	1	ESTUARY (A)	-
E x FvU	1	E x S (A) - E x S (B)	-
Sites (ExU) - S(U)	2	SITES (B) + E x S (B)	-
Areas (S(ExU)) - A(S(U))	8	AREA (B) + E x A (B)	A(S(U)) x M
Area (ExF) - A(F)	4	AREA(C) + E x A (C)	A(S(U)) x M
Month - M	21	MONTH (A)	E x M
FvU x M	21	S x M (A) - S x M (B)	FvU x E x M
E x M	21	E x M (A)	S(U) x M
FvU x E x M	21	E x S x M (A) - E x S x M (B)	S(U) x M
S(U) x M	42	S x M (B) + E x S x M (B)	A(S(U)) x M
A(S(U)) x M	168	A x M (B) + E x A x M (B)	Residual
A(F) x M	84	A x M (C) + E x A x M (C)	Residual
Residual	**792**	**Residual (A)**	
Total	**1187**		

(b)

ANOVA A (all data) & ANOVA B (Unfished Areas)			ANOVA C (Fished Areas)	
Source of Variation	**DF (A)**	**DF (B)**	**Source of Variation**	**DF (C)**
Estuary	1	1	Estuary	1
Site	2	1	Area	2
E x S	2	1	E x A	2
Area (Site)	6	4	Month	21
E x Area	6	4	E x M	21
Month	21	21	A x M	42
E x M	21	21	E x A x M	42
S x M	42	21		
E x S x M	42	21	**Residual**	**264**
A x M	126	84	**Total**	**395**
E x S x M	126	84		
Residual	**792**	**528**		
Total	**1187**	**791**		

Table 4.4. Initial ANOVA produced to detect any monthly differences in abundance between Fished v Unfished sites in the Wooli and Corindi estuaries

Source of Variation	DF	SS Derivation	F - denominator
Fished v Unfished - FvU	1	SITES (A) - SITES (B)	E x FvU
Estuary - E	1	ESTUARY (A)	Area(U)
E x FvU	1	E x S (A) - E x S (B)	Area(U)
Sites (ExU) - S(U)	2	SITES (B) + E x S (B)	Site(A(U))
Areas (S(ExU)) - A(S(U))	8	AREA (B) + E x A (B)	Residual
Area (ExF) - A(F)	4	AREA(C) + E x A (C)	Residual
Residual	**36**	**Residual (A)**	
Total	**53**		

ANOVA A (all data) & ANOVA B (Unfished Areas - U)			ANOVA C (Fished Areas - F)	
Source of Variation	**DF (A)**	**DF (B)**	**Source of Variation**	**DF (C)**
Estuary	1	1	Estuary	1
Site	2	1	Area	2
E x S	2	1	E x A	2
Area(Site)	6	4		
E x Area	6	4		
Residual	**36**	**24**	**Residual**	**12**
Total	**53**	**35**	**Total**	**17**

Detecting impacts from changes in management status

Specialised sampling designs and data-analysis techniques can be used to assess whether a particular perturbation has resulted in an impact (permanent or temporary) to a dependant variable (Underwood 1991). In the current study, the perturbations relate to changes in management status for some sites in each of the three estuaries (i.e. re-opening to or restricting fishing pressure), and the dependent variable is the abundance of mud crabs. These specific perturbations form the bases of the 'Treatments' terms (and their interactions with temporal terms) used in the analyses outlined below (Tables 4.5 - 4.7). In the Wooli and Corindi estuaries, a site was re-opened to commercial and recreational crab trapping (i.e. unfished to fully fished – UF), while there were no changes to the status of the remaining unfished (i.e. unfished to unfished – UU) and fully fished (i.e. fully fished to fully fished – FF) sites. I aimed to test the null hypotheses that there was no change in CPUE once fishing was introduced to a previously protected site between December 1998 (Wooli) and July 2000 (Corindi) till August 2003. In contrast, the Sandon Estuary consisted of two commercially fished sites, one of which was opened to recreational fishing (i.e. commercially fished to fully fished – CF), while the other was closed to all fishing (i.e. commercially fished to unfished – CU). The remaining site was fully fished throughout the sampling (i.e. FF). I aimed to test the null hypothesis that there was no change in CPUE after the removal of fishing pressure.

The catch data for each of the three estuaries were transformed ($\ln(x+1)$) so that treatment effects would be modelled as (approximately) multiplicative (Zar 1999), tested for heterocedasticity using Cochran's tests and then analysed using appropriately designed BACI-type (Before-After-Control-Impact) ANOVAs (Tables 4.5 - 4.7; Underwood, 1991). The original design plan for the ANOVAs was identical for each estuary and involved modelling Before vs After (BvA) and Treatment terms as fixed factors, with 'Months' nested within Before v After and 'Areas' nested within Treatments, as per the Corindi and Sandon ANOVAs shown in Tables 4.5 and 4.6. However, one of two UU sites in Wooli had to be spatially divided into two separate sites of differing treatments (UU and UF) three months from the date of the planned management change (Section 4.2.4). This change reduced the number of 'before' months from 42 to three, and introduced the need for an asymmetrical BACI design, involving two UU sites and one each of UF and FF in the three treatments considered in that analysis (Table 4.7a,b).

Sandon and Corindi

As explained earlier in section 4.2, sampling was done at three sites in each of these two estuaries with each site having a unique treatment designation with respect to management status (Table 4.1). The remaining aspects of the sampling design (i.e. sampling times, number of areas within sites, time of management change, etc.) are the same for each estuary. Consequently, the designs of the separate BACI-type ANOVAs used to address hypotheses relating to each estuary are identical.

The ANOVA design is a mixed model with 'Before vs After' (BvA) and 'Treatment' (T) as the main fixed, orthogonal factors (Table 4.5 - 4.6). There are three treatments (corresponding to the three different sites) for each estuary. Other factors included in the ANOVA design are 'Months' nested within BvA, and 'Areas' nested within Treatments. Three traps were fished within each Area (n = 3). Further details regarding specifics of the sampling design are in Section 4.2.1 - 4.2.3.

To detect a potential impact from a change in management status for a given treatment (i.e., at a given site) in an estuary, the temporal patterns in the differences in relative abundance of mud crabs between the impacted and a designated 'control' treatment must change significantly from the time of the impact (Underwood, 1991). This change may be quite fast (i.e., the site may reach its new 'equilibrium' within a month or two) or gradual (takes many months). If the change is gradual and with sufficient temporal replication (i.e. sampling months before and after the impact) to account for potentially substantial among-month variability, the difference may be detectable by examining the 'Months(BvA) x Treatments' interaction term. The SS and DF for this source of variation can be repartitioned both temporally (Months) and spatially (Treatments) so that the mean square estimates (MS) for the interactions 'Months(Before) x Impacted vs Control' and 'Months(After) x Impacted vs Control' can be calculated. An F-ratio derived from these two mean square estimates can then be used to test (two-tailed) for a significant impact (Underwood, 1991).

For example, the Corindi Estuary has a potentially impacted treatment (unfished to fully fished – UF), and two separate control treatments where there was no change to the management status (i.e. UU and FF). Therefore, by constructing the F-ratio 'Months(After) x UFvUU'/'Months(Before) x UFvUU', we have a valid test for detecting a change if it occurs (Underwood, 1991). The 'Months(After) x UFvFF'/'Months(Before) x UFvFF' F-ratio can also be used. However, in general, a significant impact can only be detected via these F-ratios if there are enough replicate sampling months (i.e., degrees of freedom) before and after the 'impact' to provide a suitably powerful test (Underwood, 1991). Initially, this specific approach was used to address the specific hypotheses proposed for each of the two estuaries - Corindi and Sandon.

Table 4.5. BACI: Replicated before/after sampling at three locations (one control (FF) and two potentially impacted (CU and CF) sites) taken at 25 monthly times before and 13 monthly times after the change in zoning scheme in each Treatment in the Sandon Estuary.

Source of variation	**DF**	**F-ratio denominator**
Before v After - BvA	1	
Treatments - T	2	
BvA x T	2	
Months(BvA) - M(BvA)	36	A(T) x M(BvA)
M(BvA) x T	72	A(T) x M(BvA)
* Months(Before) x Treatments	48	
* Months(Before) x CUvFF	24	
* Months(Before) x CFvFF	24	
*Months(After) x Treatments	24	
* Months(After) x CUvFF	12	
* Months(After) x CFvFF	12	
Areas (T)	6	A(T) x M(BvA)
A(T) x BvA	6	A(T) x M(BvA)
A(T) x M(BvA)	216	Residual
Residual	**684**	
Total	**1025**	

* Repartitioned sources of variation

Table 4.6. BACI: Replicated before/after sampling at three locations (two control (UU and FF) and one potentially impacted (UF) sites) taken at 25 monthly times before and 13 monthly times after the change in zoning scheme in each Treatment in the Corindi Estuary.

Source of variation	**DF**	**F-ratio denominator**
Before v After - BvA	1	
Treatments - T	2	
BvA x T	2	
Months(BvA) - M(BvA)	36	A(T) x M(BvA)
M(BvA) x T	72	A(T) x M(BvA)
* Months(Before) x Treatments	48	
* Months(Before) x UFvUU	24	
* Months(Before) x UFvFF	24	
*Months(After) x Treatments	24	
* Months(After) x UFvUU	12	
* Months(After) x UFvFF	12	
Areas(T)	6	A(T) x M(BvA)
A(T) x BvA	6	A(T) x M(BvA)
A(T) x M(BvA)	216	Residual
Residual	**684**	
Total	**1025**	

* Repartitioned sources of variation

Wooli

A more complicated approach to that outlined above was needed with data collected in the Wooli Estuary (Table 4.7a). As a major change to the sampling design was made three sampling months before the implementation of the changes to management status for the 'impacted' site (Section 4.2.4), this allowed only the three sampling months immediately prior to the 'impact' for use as 'before' data in the BACI-type ANOVA design. This severely lessened the chance of detecting an impact using this approach for the reasons stated above (Underwood, 1991). However, the change to sampling design did provide a second UU site so that there were two UU sites, a UF site and a FF site (but still only three 'Treatments' with respect to the ANOVA design). This meant that an asymmetrical ANOVA design was required to analyse the data. A 'Sites' term was nested within the UU treatment, with the 'Areas' term nested within this 'Sites' term. For the remaining two treatments (UF and FF), the 'Sites' term was nested directly in the Treatments term. The SS for the terms in this analysis were calculated using SS from ANOVAs shown in Table 4.7b, following the general procedure used by Otway and Macbeth (1999). Despite the differences from the design used for Corindi and Sandon, the 'Months(BvA) x Treatments' term can still be repartitioned and the two-tailed F-ratio test used to test for an impact, as described above.

To determine seasonal trends in differences among Treatments in each estuary after the BACI-style ANOVA approach, the data was separated by month (i.e. 25 months before and 13 months after the 'impact'), and analysed as separate two-factor, nested ANOVAs (Areas nested within Sites). Tukey's (HSD) pairwise comparison of means tests was then used to further investigate any significant differences among Sites. The 'Treatments' term used in the Wooli ANOVA was not adopted for these monthly ANOVAs, with the four sites analysed as such.

Table 4.7a. BACI: Replicated before/after sampling at four locations (three treatments), three control (UU - Site 1, FF - Site 3 and UU - Site 5) and one potentially impacted (UF - Site 4) site taken at 3 monthly times before and 13 monthly times after the change in zoning scheme in each Treatment in the Wooli Estuary.

Source of variation	DF	SS derivation	F-ratio denominator
Before v After - BvA	1	BvA [A]	-
Treatments - T	2	S [A] - S [B]	-
BvA x T	2	BvA x S [A] - BvA x S [B]	-
Months(BvA) - M(BvA)	14	M(BvA) [A]	S(UU) x M(BvA)
M(BvA) x T	28	M(BvA) [A] - M(BvA) [B]	S(UU) x M(BvA)
* Months(Before) x Treatments	4		
* Months(Before) x UFvUU	2		
* Months(Before) x UFvFF	2		
* Months(After) x Treatments	24		
* Months(After) x UFvUU	12		
* Months(After) x UFvFF	12		
Sites(UU) - S(UU)	1	S [B]	-
S(UU) x BvA	1	BvA x S [B]	-
S(UU) x M(BvA)	14	M(BvA) x S [B]	A(UU) x M(BvA)
Areas(UU) - A(UU)	4	A [B] + A x S [B]	A(UU) x M(BvA)
A(UU) x BvA	4	A x BvA [B] + A x BvA x S [B]	A(UU) x M(BvA)
A(UU) x M(BvA)	56	A x M(BvA) [B] + A x M(BvA) x S [B]	Residual
Areas(FF) - A(FF)	2	A [D]	A(FF) x M(BvA)
A(FF) x BvA	2	A x BvA [D]	A(FF) x M(BvA)
A(FF) x M(BvA)	28	A x M(BvA) [D]	Residual
Areas(UF) - A(UF)	2	A [C]	A(UF) x M(BvA)
A(UF) x BvA	2	A x BvA [C]	A(UF) x M(BvA)
A(UF) x M(BvA)	28	A x M(BvA) [C]	Residual
Residual	**384**		
Total	**575**		

* Repartitioned sources of variation

Table 4.7b. Individual ANOVA from ALL Sites, UU and FF/UF used to construct BACI: Replicated before/after sampling design in Table 4.7a. (Underwood 1991)

ANOVA A (all sites) & ANOVA B (UU site)		
Source of Variation	**DF (A)**	**DF (B)**
Before v After - BvA	1	1
Sites - S	3	1
BvA x S	3	1
Months(BvA) - M(BvA)	14	14
M(BvA) x S	42	14
Areas - A	2	2
A x S	6	2
A x BvA	2	2
A x BvA x S	6	2
A x M(BvA)	28	28
A x M(BvA) x S	84	28
Residual	**384**	**192**
Total	**575**	**287**

ANOVA C (FF site) & ANOVA D (UF site)	
Source of Variation	**DF (C)&(D)**
Before v After - BvA	1
Months(BvA) - M(BvA)	14
Areas - A	2
A x BvA	2
A x M(BvA)	28
Residual	**96**
Total	**143**

Size class of crabs

To determine whether smaller size classes of crabs occur in fished areas as a result of the selective harvesting of larger individuals by fishers or if larger crabs occur in the unfished areas as a result of protection, a Kolmogorov–Smirnov tests was used to test the hypotheses of no differences in size class distributions among treatments. This test is sensitive to any differences between the size-class distributions, including differences in means and variances within classes (Analytical Software 2001). "Areas" within "Sites" were pooled to provide "before" and "after" totals for each zoning period. Each pooled "Site" was tested against the same "Site" before and after the zoning change and among "sites" for the corresponding zoning period.

Even if there are no differences in size class distributions between populations using the Kolmogorov–Smirnov test, differences may lie in the number of crabs caught within particular size classes before and after the zoning change. A two-sample t-test (months pooled) was used to test the null hypothesis of no difference in the total number of crabs among sites within each size class category before and after the zoning change (i.e. is there a difference among Site 1 (UU), 2 (UF) and 3 (FF) ("Areas" as replicates) in the 125 mm size class before the zoning change?). This may give an indication of the selective harvesting of individual size classes once fishing commenced.

Gender

To test the null hypotheses that there is no association between area and gender between the same sites and among sites before and after the zoning change in each estuary, a χ^2 square analysis was conducted. It was expected that male crabs are dominating catches in protected sites because they are more aggressive around traps. If so, the ratio of males to females at fished sites may be similar, as males are being taken by fishers. The test was carried out individually in each estuary on the total number of males and females caught in each "site". Firstly, I wanted to know if there was a difference in the number of male or female crabs caught between fished or unfished sites in the same estuary and whether this trend continued among estuaries before and after the zoning change. Secondly, I wanted to determine if there was a change in the sex ratio once the zoning scheme changed and sites were influenced by different zoning schemes (i.e. is there an association between sites and gender at sites which change zoning type while no association between sites which have the same zoning type before and after the zoning change?).

Movement patterns

To test the null hypotheses that there was no change in the origin of recaptured crabs caught during the study in each site between and among sites before and after the zoning change, a χ^2 square analysis was conducted. It was expected that the majority of recaptured crabs would be crabs originally released at that site in the unfished sites while fished sites will have a mixture of recaptures from the same site and those around it (especially the sanctuary zone if spill-over is occurring). Firstly, analyses were conducted by comparing the same sites before and after the zoning change to determine if recaptured crabs moved from different locations before being captured in that site (i.e. once fishing is introduced or removed from sites in an estuary, the source location of crabs that are recaptured in that site or sites around it may change). Secondly, sites were compared in both periods before and after the zoning to determine if different source locations occurred between sites (i.e. Site 1 may have more crabs recaptured that were originally released at Site 1 while Site 3 may have an even mix or crabs from all sites).