

The influence of zoning (closure to fishing) on fish communities of the shoals and reef bases of the Great Barrier Reef Marine Park

Results of repeated surveys of the southern banks and
Cardwell shoals, and an overview with regional comparisons

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Acronyms Used In This Report

AIMS	Australian Institute of Marine Science
BRUVS	Baited Remote Underwater Video Stations
CERF	Commonwealth Environment Research Facilities
DEWHA	Department of the Environment, Water, Heritage and the Arts
GBRMP	Great Barrier Reef Marine Park
GBRWHA	Great Barrier Reef World Heritage Area
GPS	Global Positioning System
MPA	Marine Protected Area
MTSRF	Marine and Tropical Sciences Research Facility
RAP	Representative Area Program (2004)
RRRC	Reef and Rainforest Research Centre Limited
SBRUVS	Stereo Baited Remote Underwater Video Stations
SCUBA	Self-Contained Underwater Breathing Apparatus
UVC	Underwater Visual Census

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Executive Summary

This report presents the results of repeated surveys of pairs of discrete “shoals” off Cardwell in the north and on either end of the Capricorn shelf in the south of the Great Barrier Reef Marine Park. We also provide coarse regional comparisons of these results with “snapshots” of mean and median abundances from shoal pairs in five other regions obtained during the four years of this project.

Within each pair, one shoal was zoned “green” (closed to fishing) and the other “blue” or “yellow” (open to line fishing). The demersal habitats and vertebrate communities were sampled using non-extractive Baited Remote Underwater Video Stations (BRUVS), which revealed a diverse fauna of fish, sharks, rays and sea snakes, including species prized by fishers, taken as bycatch, or not vulnerable to hook and line fishing.

Non-linear mixed-effects models were used to estimate the influence of zoning on the maximum number of fish observed by each BRUVS (*MaxN*) for specific components of the fish community. Sampling *year* and shoal *pair*, or *region* of the GBRMP, were used as random factors in testing the (fixed) effect of *zone*. Interquantile distances around median counts of fish were also used to assess the significance of these factors in explaining the *MaxN* of species groups.

The most parsimonious model generally showed that *year* was not significant, but *zone* and *pair* were. This was because the change with increasing time of closure to fishing was inconsistent, with the gap widening between “green” and “blue” for one pair of southern banks but not the other. This apparent interaction between *year* and *pair* was not statistically significant, with ratios between banks open or closed to fishing averaging about 1.8 to 2.6 for “prized” and “target” species.

Comparisons of global means, with no accounting for differences in type of substratum or habitat type, showed the effects of zoning were not consistent amongst regions and species groups. The Cairns and Pompeys reef bases showed more target fish in “green” zones, but the Swains and Capricorn-Bunkers reef bases had less in green zones. The diffuse Townsville shoals had less target and bycatch species in “green” zones, whilst the nearby, discrete, Cardwell shoals showed very high ratios of ~5 to ~17 for target groups between “closed” and “open” fishing zones.

The use of a novel stereo-video technique enabled us to show precisely and accurately that more, larger “target” species were accumulating on southern banks closed to fishing. There was a larger proportion of larger coral trout, red emperor, red-throat emperor and Venus tuskfish on the shoals closed to fishing, far above the legal minimum size at first capture. In contrast, the “unfished” starry triggerfish and collared sea bream showed no major displacement amongst modes between zones.

A number of explanations were invoked for the different patterns and regions described in this report. The lack of a consistent trend amongst regions, pairs of shoals, species groups, and individual species, should the recognize the limits to pairwise comparisons of “shoals” and use them to direct future research questions about movements across zone boundaries and the role of “shoal type”.

Introduction

During the extensive community consultation that accompanied the rezoning of the Great Barrier Reef Marine Park, anecdotal information emerged about the importance of submerged “shoals” and low-relief seabed features as intensified targets for commercial and recreational fishing.

In the offshore domain, there was evidence of effort shift in the commercial fishery for live coral trout from shallow reef flanks to deeper inter-reefal shoals because of the more valuable red colour of coral trout living at depth. In the coastal zone, there was evidence of effort shift in the recreational fishery from shallow reefs to deeper waters away from the immediate vicinity of emergent and island fringing reefs.

While part of this shift in effort may have been in response to the high fishing pressure placed upon accessible and popular reefs, technology creep (such as affordable colour echo sounders and GPS units) has allowed recreational fishers to find and return to small habitat features supporting alternative species. This appears to be a major driver for increased interest in the prized lutjanid red snappers (red emperor, small- and large-mouth nannygais). Fisheries managers are not well equipped to deal with this shift in fishing effort in either domain because there is almost no information about the distribution and nature of these submerged seabed habitats and their biology (see Mapleston *et al.* 2006).

In the first year of this task (ARP 1), AIMS searched the seafloor in the vicinity of Cairns, Cardwell, Townsville, the Whitsundays, Rockhampton, and Gladstone using a multibeam acoustic swathe mapper, ground-truthed by towed video, to develop baselines in comparable “pairs” of fished (“blue”) and unfished (“green”) submerged shoals. The fish populations on these shoals were then sampled with baited remote underwater video stations [BRUVS] because the habitats of interest were below diving depth (i.e. >20 m) (Speare and Cappo 2006; Speare and Stowar 2007).

In ARP2, the core sites (Cardwell, Townsville) were resampled with only partial success due to the exceptional wet season of 2007/08 and a very strong La Nina (Speare and Stowar 2008). On the advice of GBRMPA, Cairns shoals were abandoned because of uncertainty about the level of fishing effort there. Southern shoals (Barcoo and Karamea Banks; East and West Warregoes) were sampled intensely in order to recommend an optimal strategy for sampling large, discrete, submerged shoals. Although there were some mixed results, these large shoals showed differences in the abundance of a dozen key “target” species consistent with an effect of fishing detectable since the rezoning (blue to green) of one shoal from each pair in July 2004 (Speare and Stowar 2008; Stowar *et al.* 2008). There was also evidence from pilot stereo-video measurements that target species might be bigger around the southern banks closed to fishing (Johansson *et al.* 2008).

In contrast, the low relief shoals in the vicinity of Townsville known as the Magnetic Shoals did not show any impact from the rezoning -- despite the likelihood of good enforcement resulting in substantial differences in fishing effort on blue and green shoals (Speare *et al.* 2008). We believed that this was because the low-relief habitat was only a transient habitat for the large “target” species and that the mobility of these species soon exposed them to fishing.

In ARP3 we used our ability to assess fish abundance in deep water to investigate the abundance of fish species vulnerable to line fishing around the bases of reefs where there was evidence of strong fishing effects. We focussed on the three southern regions (Pompeys, Swains and Capricorn-Bunker Groups) where there was evidence of a sustained

and growing impact of fishing upon the coral trout populations in shallow water (Russ *et al.* 2008).

Our focus in ARP3 remained on deep water coral trout, emperors, snappers, cods and tuskfish. BRUVS were used to sample fish abundance in deep (~45-60 m) water around 16 “blue/green” reef pairs where diver surveys had shown either weak or strong contrasts in coral trout abundance in shallow water (Cappo *et al.* 2009a).

Our second major objective in ARP3 was “desktop” work to refine the use of baited video techniques to establish definitive methods to detect differences in fish abundance and length compositions amongst “green” and “blue” reefs (Cappo *et al.* 2009b). Those desktop studies showed almost 100% of the variation amongst tapes was due to the location of collection of the tape for the major study species – not the expertise of the reader or the time of reading. Secondly, smaller individuals of economically important species were shown to be visiting the BRUVS earlier than bigger ones, and we developed a measurement protocol to obtain the optimal length compositions to represent zoning effects. Such effects were detected, with more bigger and smaller red emperor around the deep bases of “green” shoals, and more coral trout and venus tuskfish above the legal minimum size around the same banks. In contrast, the unfished “controls” showed no such difference in the shape of the length compositions (Cappo *et al.* 2009b).

During ARP4 in 2009/2010, we aimed to finalise the “shoals” study by re-sampling and tying the various components together. We tested if the “effect of fishing” signals detected in ARP2 for deepwater sweetlips (*Lethrinus miniatus*), snappers (*Lutjanus* spp), cods (e.g. *Plectropomus leopardus*, *Epinephelus undulatostratus*) and tuskfish (*Choerodon venustus*) were more, or less, perceptible since the 2004 RAP zoning. The abundant starry triggerfish (*Abalistes stellatus*) and collared sea bream (*Gymnocranius audleyi*) were analysed as unfished “controls” to ensure comparability in habitats.

The activities in ARP4 can be summarised under two main objectives, to:

1. Repeat the sampling of the southern shoals and Cardwell shoals to establish if the prevailing effects of zoning have been maintained or increased; and
2. Synthesise the studies on effects of zoning on “shoal” habitats made during the four-year life of the MTSRF project.

Materials and Methods

Repeated sampling of the southern banks

We conducted three studies in 2009 to compare the effects of zoning amongst the two pairs of southern banks studied in 2006/2007 (see Stowar *et al.* 2008). Firstly, we sampled as much of the banks as possible (Figure 1). Secondly, we re-visited (within 5-15 metres) the earlier sites from ARP2 where repeated samples already existed. Finally, we deployed stereo BRUVS (SBRUVS) on sites where large numbers of economically important species were seen in earlier BRUVS samples to examine temporal changes in length frequency compositions amongst RAP zones.

Our database was insufficient to stratify sampling by both depth and habitat type as there was no “habitat map” produced for each shoal at the whole-of-shoal level. To develop a sampling plan we laid out regular and random points in a spatial design that encompassed all the relevant gradients on the banks (position, direction, exposure, depth, habitat) known to influence the “target” species of interest. We knew that most of these species live where the shoal/reef bases join the surrounding sand plain (e.g. red emperor *Lutjanus sebae*/ Venus tuskfish *Choerodon venustus*) or on the shoal tops (e.g. coral trout *Plectropomus leopardus*/red-throat sweetlip *Lethrinus miniatus*).

We manually traced the bases of the banks from the multibeam swath maps where the shoal joined the sand, to make a polygon. Each shoal had a different area, shape and topography (see Figure 3 for examples). Three passes were made around and within the polygon for each shoal to choose points (and priorities) for the October field trip aboard RV “Tom Marshall” (see Table 1). Each pass involved:

1. Selecting 32 regularly spaced sampling sites along the shoal base;
2. Selecting 32 regularly spaced centroids on top of the banks, then selecting 32 random points within 100-450 metres around each centroid; and
3. Selecting sites from ARP2 where there existed at least two repeated measures of fish communities at the same site.

In May 2010, we made 12 BRUVS sets on each of Brook Shoal and Forty-Foot Rock near Cardwell (Figure 2). This enabled a temporal comparison with the 16 sets on each of the shoals during 2006/2007 in ARP2 (Speare *et al.* 2008).

Tape interrogations were made under the standards imposed by the BRUVS2.1.mdb software (Ericson and Cappo, AIMS 2006, BRUVS2.1.mdb[®]) interface to record the identity of each species and the maximum count of each species in the field of view (*MaxN*) using the existing reference image library built up in ARP1-3. The timing of arrival and accumulation of *MaxN* was also recorded in the database. The general approach using BRUVS has been reviewed by Willis *et al.* (2000) and Cappo *et al.* (2003, 2004).

Table 1. The number of BRUVS drops at each shoal according to the three selection protocols.

Bank	Regular-base	Random-top	Repeated	Nsites	Bank Area (km ²)
Barcoo Bank	30	24	18	72	4.8988
Karamea Bank	30	25	17	72	3.5112
Eastern Warregoes	24	25	23	72	1.19030
Western Warregoes	24	27	21	72	1.3090
Total				288	

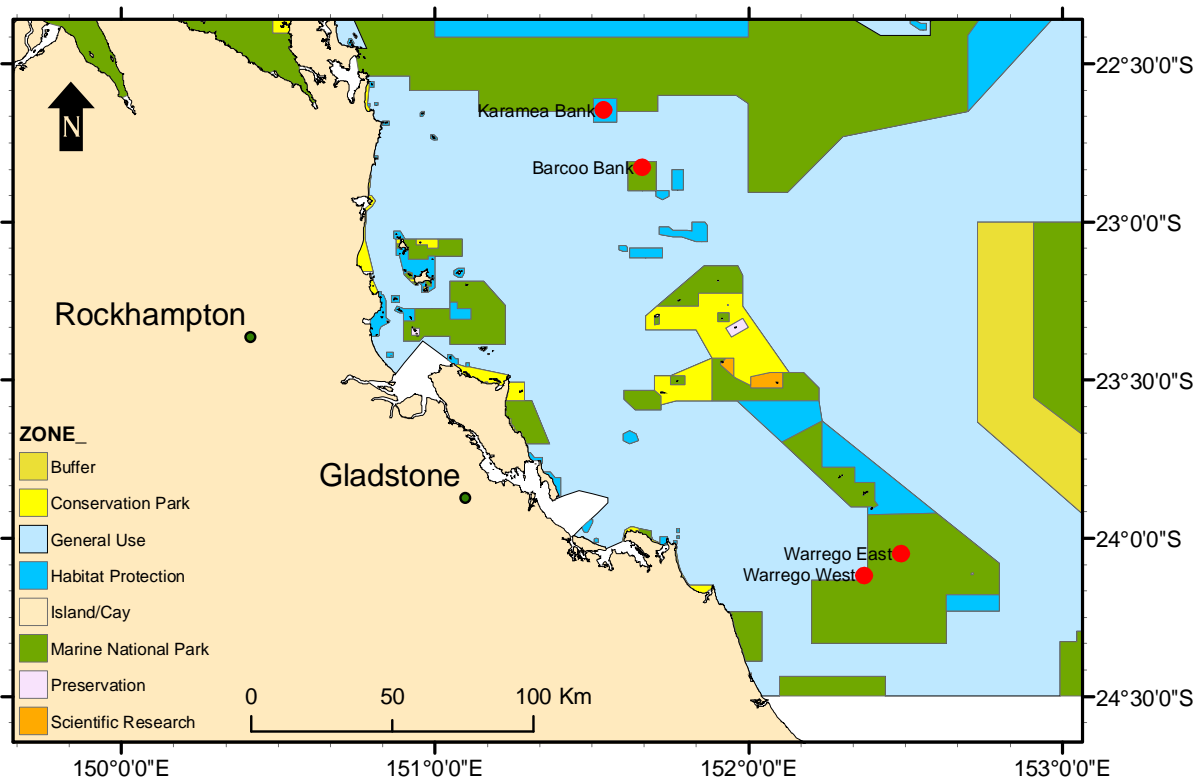


Figure 1. Location of the four submerged shoals in the southern Great Barrier Reef, showing the 2004 GBRMPA zones (re-drawn from Stowar *et al.* 2008).

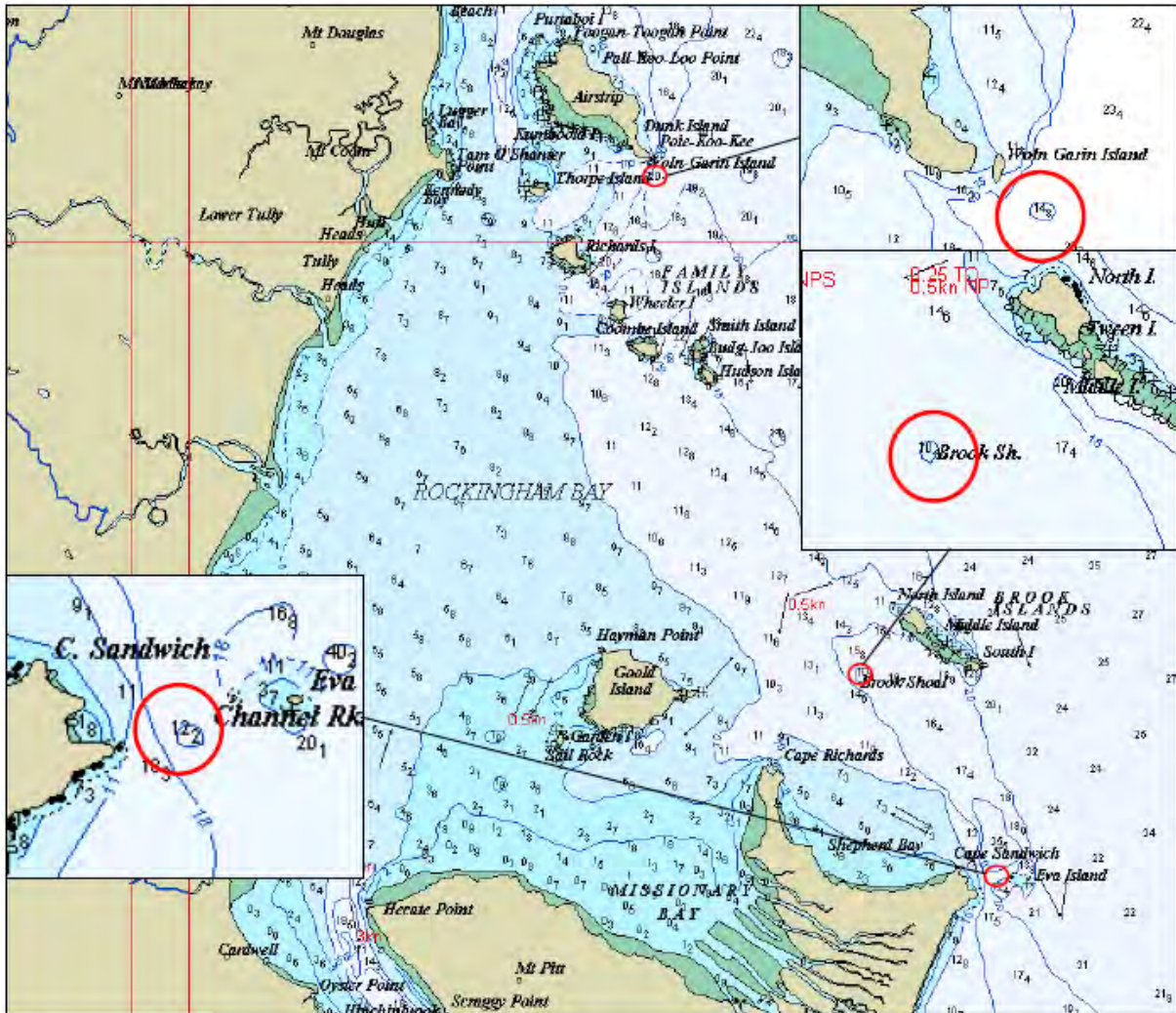


Figure 2. Location of Brook shoal (Closed) and Forty-Foot Rock offshore (Open) from Cardwell in Rockingham Bay, showing the 2004 GBRMPA zones (redrawn from Speare and Stowar 2007).

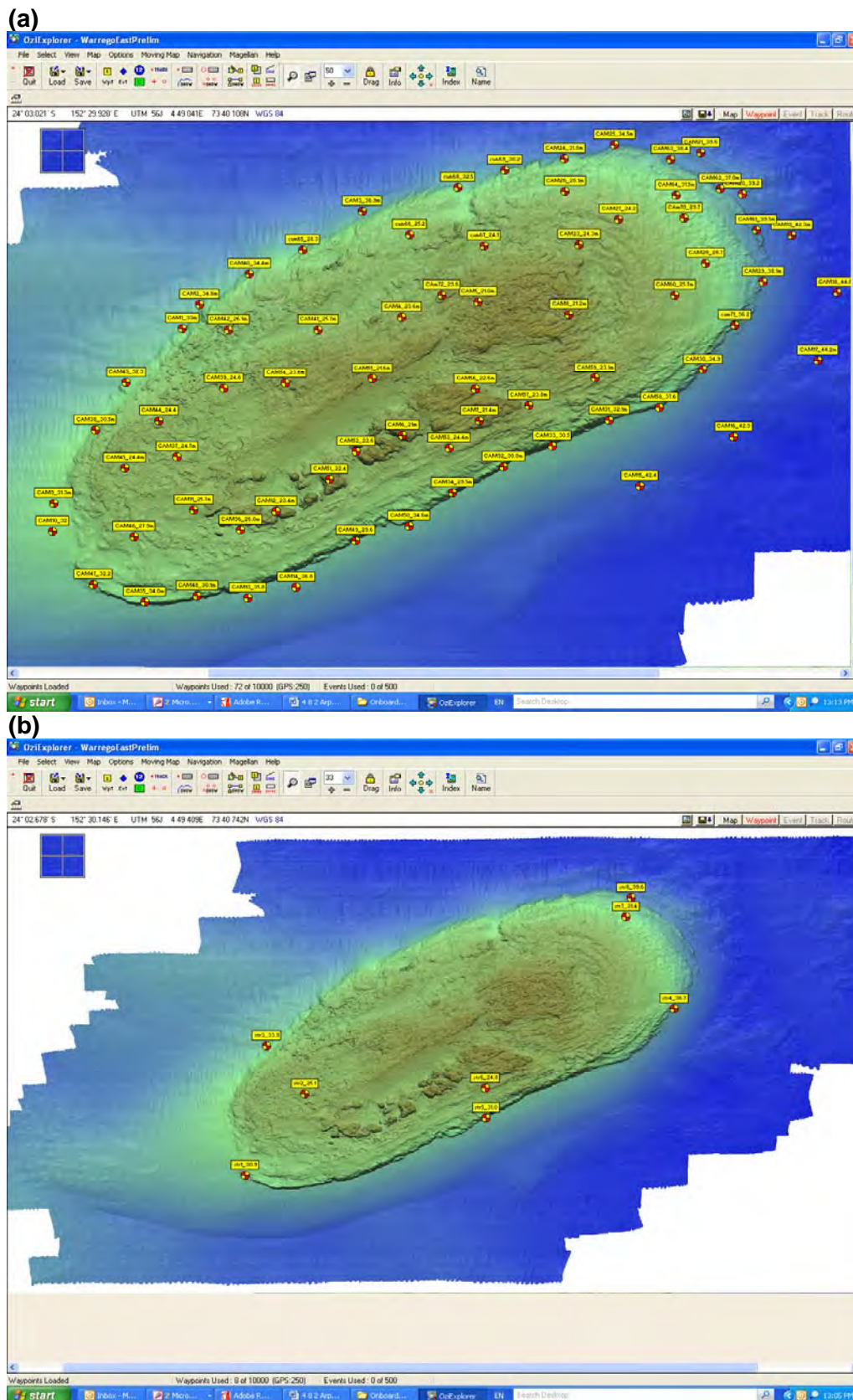


Figure 3. Single (a) and stereo (b) BRUVS sampling sites at the Eastern Warrego in October/ November 2009. Swathe maps of the other three banks sampled in the Capricornia region can be found in Stowar *et al.* (2008).

Univariate analyses

Fish abundances and species richness were analysed using univariate statistical approaches with the R statistical package (R Development Core Team, 2005). The *MaxN* data were overdispersed or highly skewed by counts made when shoals of pelagic fish passed the field of view, so raw data was analysed with a “quasipoisson” (or “log-link”) function.

The univariate analyses assessed differences in species richness and abundances between the zoning status (*zones*), *regions* and *years* using non-linear, mixed-effects models with a quasipoisson link function. The factor *zone* was fixed and all other factors were treated as random.

Separate analyses were done on species abundances pooled according to four subsets based on species vulnerability to line fishing. These were the “prized”, “target”, “bycatch” and “unfished” categories (see below Appendix 1 and Appendix 2).

Target status of species

For the purposes of assessing the possible direct and indirect effects of fishing on “shoal” communities, fish species have been categorized by Stowar *et al.* (2008) into four sets depending on the likelihood they would be caught and retained by line fishers. The comparisons presented here focused on:

- i. *PRIZED TARGETS*- “*Prized species*”. These included the most desirable demersal species, based on their landed catch and size, as well as their reef-dwelling habits, such as red emperor and coral trout.
- ii. *ALL TARGETS*- “*Sought-after species*”. These included the prized species and other desirable demersal and pelagic species, based on their landed catch and size, as well as their reef-dwelling habits. This was a pooling of categories (i) and (ii) of Stowar *et al.* (2008).
- iii. *BYCATCH*- “*All species considered likely to be caught by line fishers including by-catch*”. Comprised the undesirable fishes, sharks and rays known to take a baited hook.
- iv. *NOT CAUGHT* –“*Species considered unlikely to be caught by line fishers*”. This list included all species unlikely to be caught because of their dietary preferences (e.g. herbivores such as scarid parrotfishes) or small size (e.g. pomacentrid damselfishes and chaetodontid butterflyfishes).

Comparison of length compositions from SBRUVS measurements

A total of 70 (34 “green” and 36 “blue”) stereo-video tapes were pooled in analyses from 2007 and 2009. Red emperor (*Lutjanus sebae*), coral trout (*Plectropomus leopardus*), red-throat emperor (*Lethrinus miniatus*) and Venus tuskfish (*Choerodon venustus*) were measured as prized “target” species on the tapes. The collared sea bream (*Gymnocranius audleyi*) and starry triggerfish (*Abalistes stellatus*) were chosen as unfishes “controls”.

The four underwater stereo-video rigs (SBRUVS) were described in Johansson *et al.* (2008), and were calibrated by analysing footage of a labelled cube using the software “Cal”™ (www.SeaGis.com.au). The footage from each replicate was interrogated using BRUVS2.1.mdb to record times where species appeared (T_{arr}) and where *MaxN* occurred (T_{MaxN}). These events were used to drive the stereo-video measurement software to points of interest on .avi files. Length measurements from caudal fork to snout tip (LCF) were performed using “PhotoMeasure”™ (www.SeaGis.com.au).

It was shown clearly by Cappel *et al.* (2009b) that the smallest red emperor, coral trout and Venus tuskfish were measured earlier in the tape, within the first 15 minutes of the stereo-BRUVS settling on the seabed. This implied an imperative to measure immediately after the time of first arrival (T_{arr}) as well as T_{MaxN} . The protocol used here included the times when the species was first seen (T_{arr}), and before and after the sighting of *MaxN*.

The accuracy and precision of stereo-video measurements for fish has been reviewed by Harvey *et al.* (2002, 2003).

Results

Repeated sampling at very small spatial scales on southern banks and Cardwell shoals

Southern Banks

Repeated BRUVS sets in August 2007 and October/November 2009 were made within 5-15 metres of the original sets made in February 2007. Both 2007 samples were pooled as replicates within the year 2007, with the working assumption that major changes in the fish populations would not occur at the time scale of 6 months.

There was some evidence of different levels of overall richness and abundance of fish between the southern and northern pairs of sunken banks (Figure 4). This indicated a random effect of *pair* should be accounted for in comparison of fish abundances amongst zones. The southern (Warregoes) banks apparently had higher richness and abundance than the northern banks.

Throughout this report we use boxplots showing the median and 95% Confidence Intervals for the median. The notches represent 1.5 x (interquartile range of $MaxN/SQRT(n)$). If the notches do not overlap this is 'strong evidence' that the two medians differ, at the 5 percent level, independent of any assumptions about normality of data distributions or equivalence of variances (Chambers *et al.* 1983, p. 62). This is a robust method of visualising the effects of zoning on the counts ($MaxN$) of four species groups recorded in the field of view of the BRUVS.

The median counts for the "prized" and "target" species were significantly higher (by a factor of about 2) on both pairs of the southern banks closed to fishing in 2004 (Figure 5). The difference between "open" and "closed" appeared to widen between 2007 and 2009 for the Warregoes, but not the northern pair. There were inconsistent differences between zones and years for the "bycatch" species and no detectable differences for the "unfished" species (Figure 6).

The following linear, mixed-effects models with both fixed (*zone*) and random (*year, shoal pair*) factors were compared for measures of mean abundance for the four species groups, with a quasipoisson link function:

$$\begin{aligned} abundance &\sim zone + (1|pair) \\ abundance &\sim zone + year + (1|pair) \\ abundance &\sim zone * year + (1|pair) \\ abundance &\sim zone * pair + (1|year) \\ abundance &\sim zone * pair + (1|pair) \end{aligned}$$

The most parsimonious model was always the first one for the species groups, where *year* was not significant, but *zone* and *pair* were.

However, we were interested in identifying coefficients for each combination of *pair* and *year*, so a dummy random factor with four levels (*pair_year*) was included in the model:

$abundance \sim zone * pair_year + (1|pair_year)$. The group means for *zone* given *pair_year* are shown in Figure 7. The model coefficients are shown in Table 2.

Plots of means showed about a two-fold increase in “prized” and “target” species in banks closed to fishing. The change with increasing time of closure to fishing was inconsistent, with the gap widening between “green” and “blue” for the Warregoes but not the northern pair (Figure 7). This apparent interaction between year and pair became insignificant in the mixed effects model (Table 2), with ratios between banks open or closed to fishing averaging about 1.8 to 2.6 for “prized” and “target” species.

Table 2. Coefficients of the model $abundance \sim zone * pair_year + (1 | pair_year)$ for the four species groups sampled repeatedly in two years on the two pairs of southern banks. Repeated BRUVS sets in August 2007 and October/November 2009 were made within 5-15metres of the original sets in February 2007. The 2007 samples were pooled as replicates within the year 2007.

	Year	Ratio Closed:Open	MaxN.Closed	MaxN.Open
Prized targets				
Barcoo-Karamea	2007	2.12	7.07	3.34
	2009	2.61	8.51	3.26
East-West Warregoes	2007	2.19	8.14	3.72
	2009	1.89	7.94	4.2
All targets				
Barcoo-Karamea	2007	1.99	8.36	4.21
	2009	2.57	10	3.89
East-West Warregoes	2007	2.04	9.07	4.45
	2009	1.81	9.05	5
Bycatch				
Barcoo-Karamea	2007	0.79	16.32	20.71
	2009	1.46	17.43	11.94
East-West Warregoes	2007	0.61	15.48	25.38
	2009	1.35	20.45	15.15
Unfished				
Barcoo-Karamea	2007	0.71	75.01	105.05
	2009	0.88	27.95	31.76
East-West Warregoes	2007	1.33	80.29	60.37
	2009	0.58	18.35	31.64

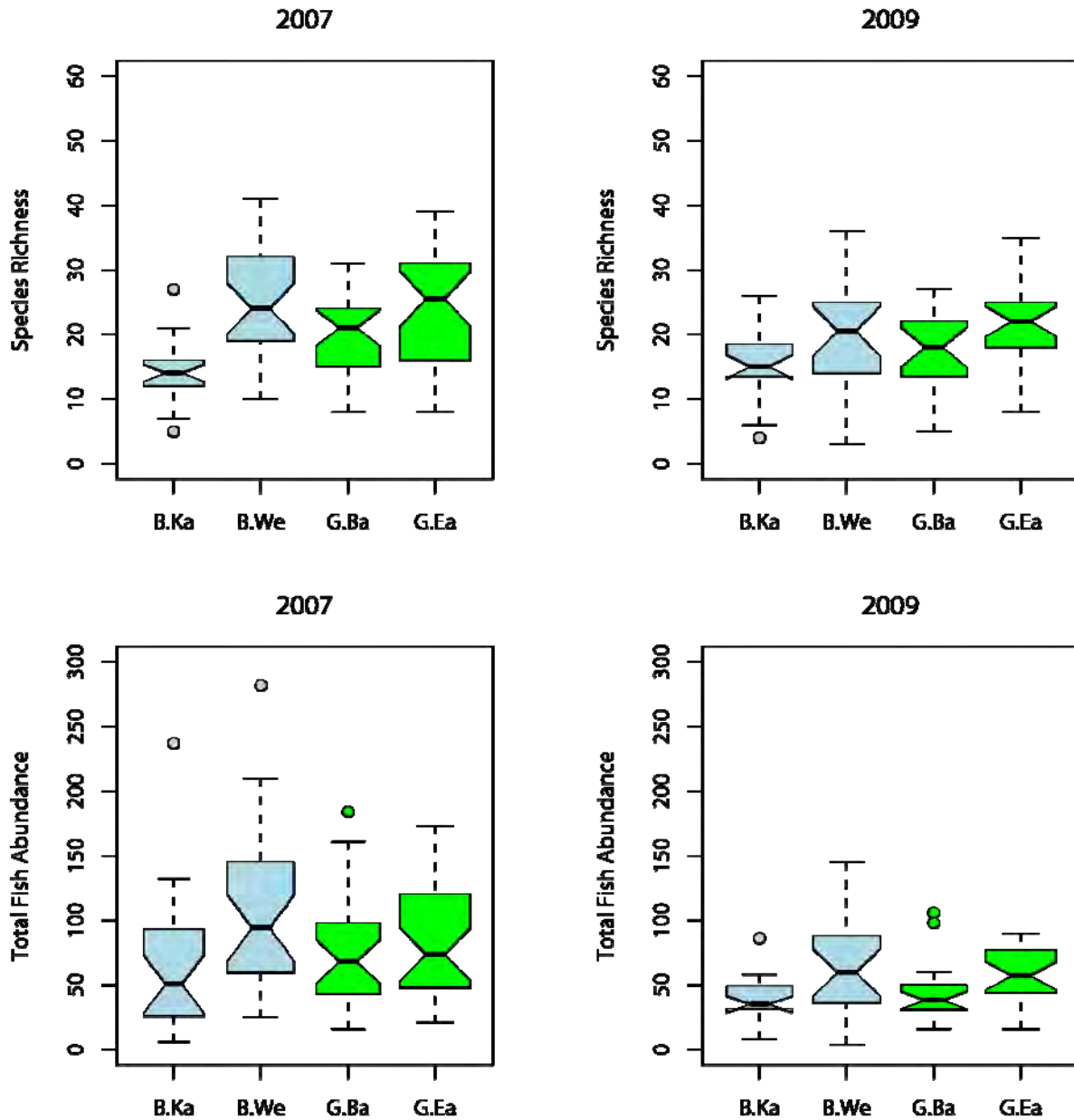


Figure 4 Comparisons of the median, total fish abundance and median species richness amongst zones and years in the two pairs of southern shoals. Abbreviations are “B” (Blue zones, open to fishing), “G” (Green zones, closed to fishing), “Ka” and “Ba” (Karamea and Barcoo banks), “We” (Western Warregoes) and “Ea” (Eastern Warregoes). The boxplots show the median and 95% Confidence Intervals. The notches represent $1.5 \times$ (interquartile range of $MaxN/SQRT(n)$). If the notches do not overlap this is ‘strong evidence’ that the two medians differ, independent of any assumptions about normality of data distributions or equivalence of variances (Chambers *et al.* 1983, p. 62).

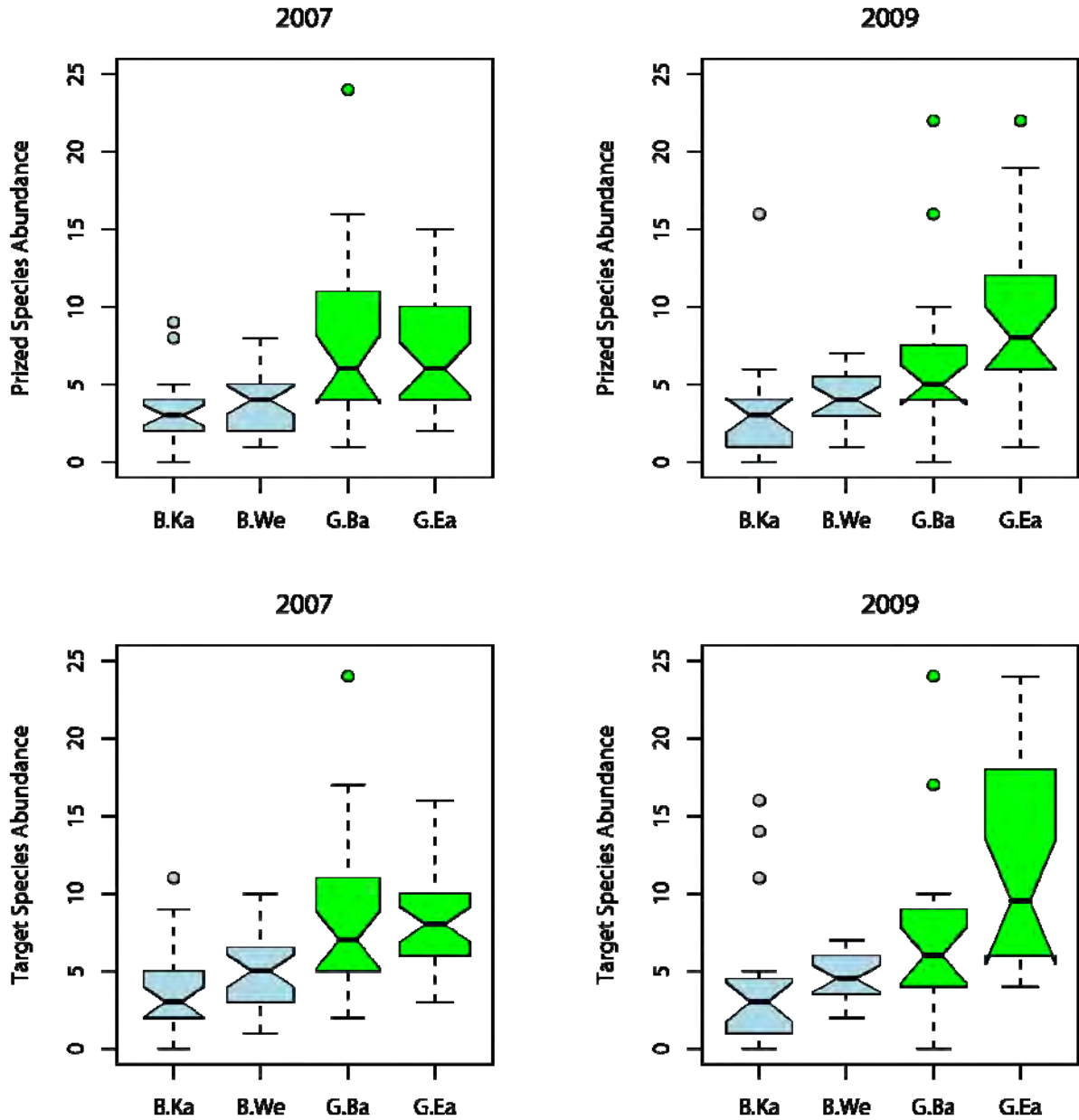


Figure 5. Comparisons of the median abundance of “prized” and “all target” species groups amongst zones and years in the two pairs of southern shoals. All conventions as in Figure 4.

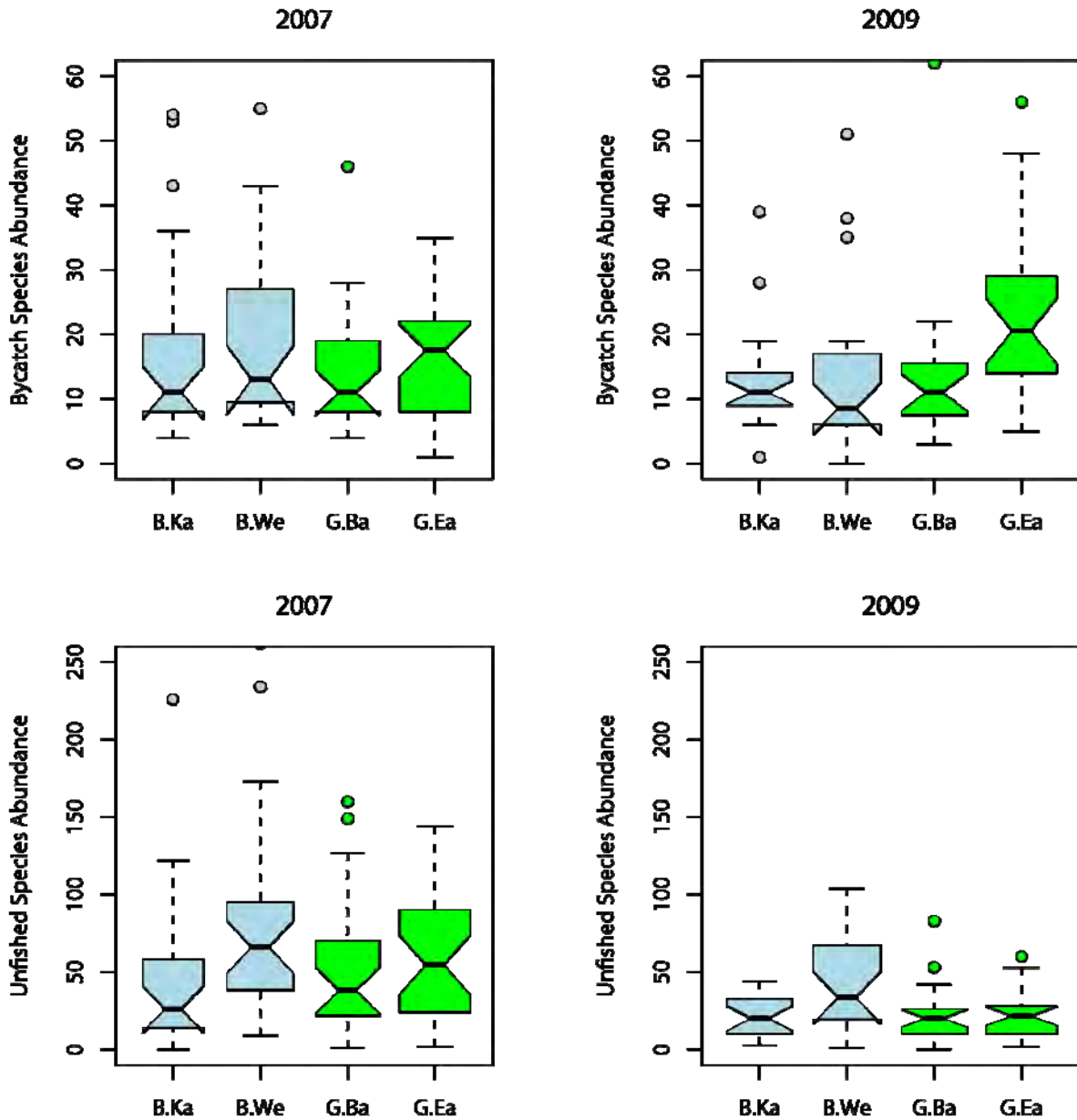


Figure 6. Comparisons of the median abundance of “bycatch” and “unfished” species groups amongst zones and years in the two pairs of southern shoals. All conventions as in Figure 4.

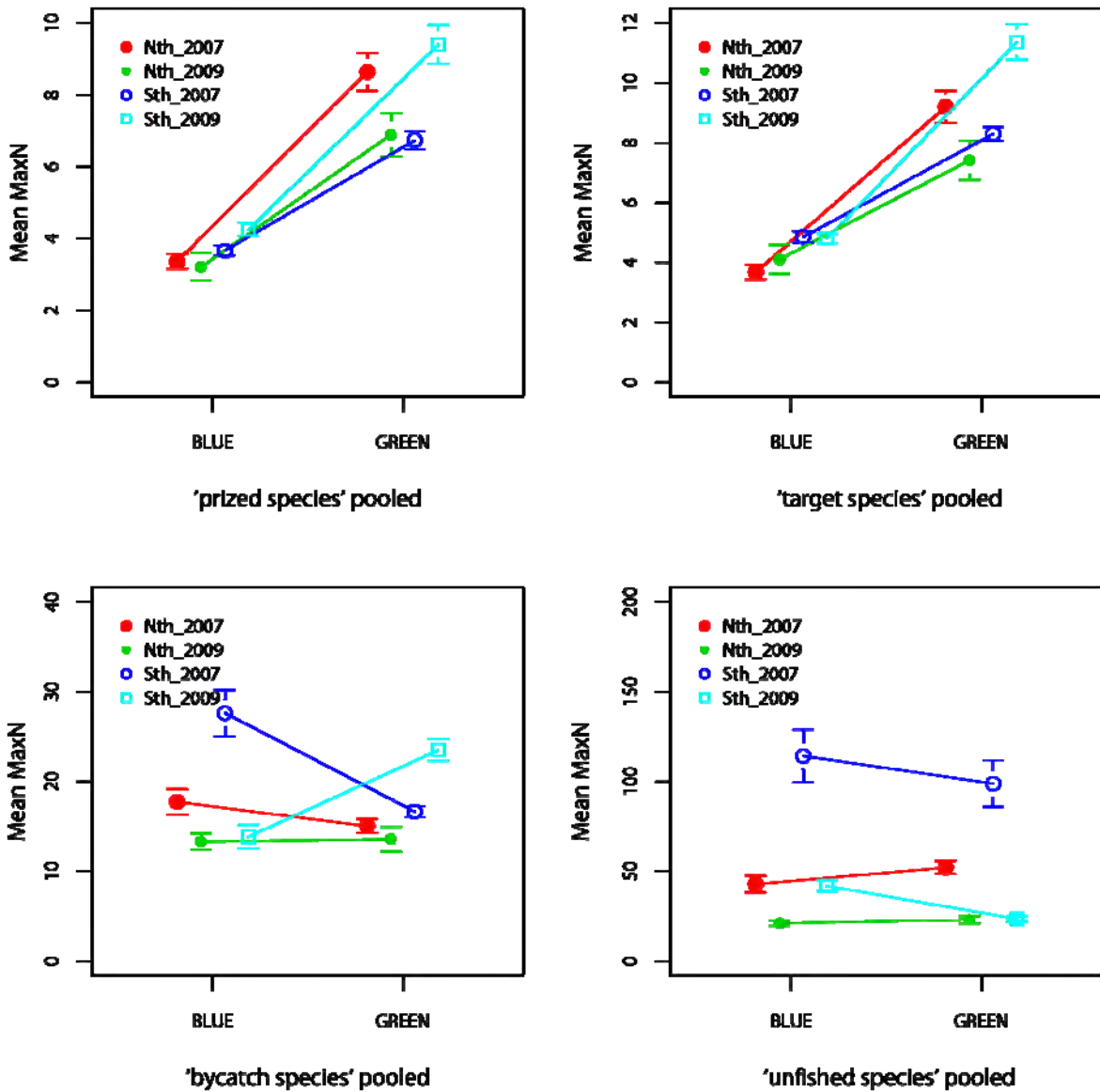


Figure 7. Plots of the means, with 95% Confidence Intervals, for the four species categories sighted on the two pairs of southern banks between sampling years and management zones. These temporal replicates were repeated within 5-15 metres of the original sets. The mean number of prized and target species appeared to be increasing through time on the southern bank (Eastern Warregoes), closed to fishing in 2004, but not on the northern Barcoo bank (see Table 1).

Cardwell shoals

Repeated sampling on the very small, discrete features of the Brook shoals and Forty-Foot Rock showed no detectable differences in richness or abundance (Figure 8), but there were many more “target” species on Brook shoals and this difference increased between 2007 and 2010 (Figure 9).

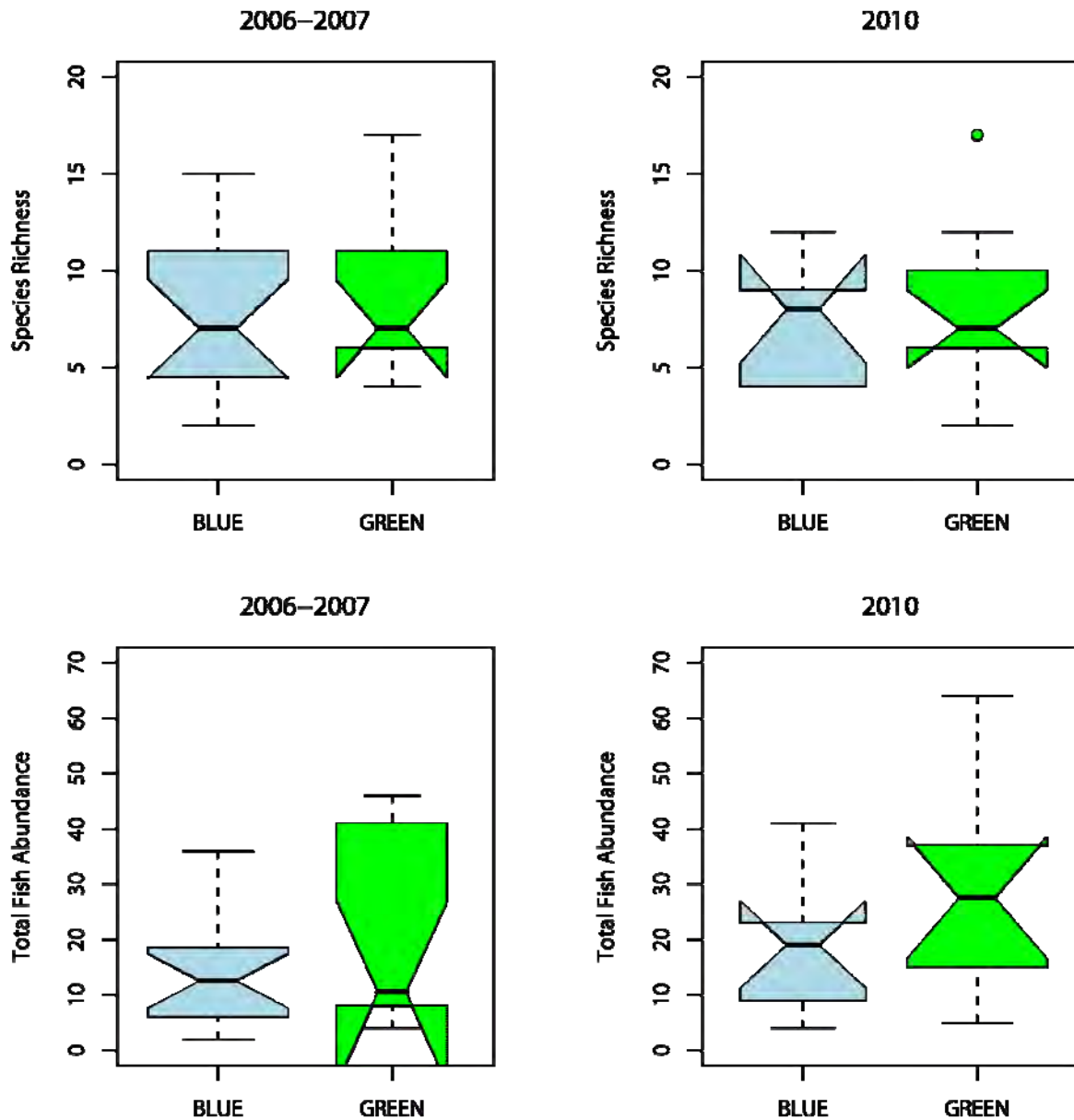


Figure 8. Comparisons of the median species richness and median species abundance between management zones of the Cardwell shoals. All conventions as in Figure 4.

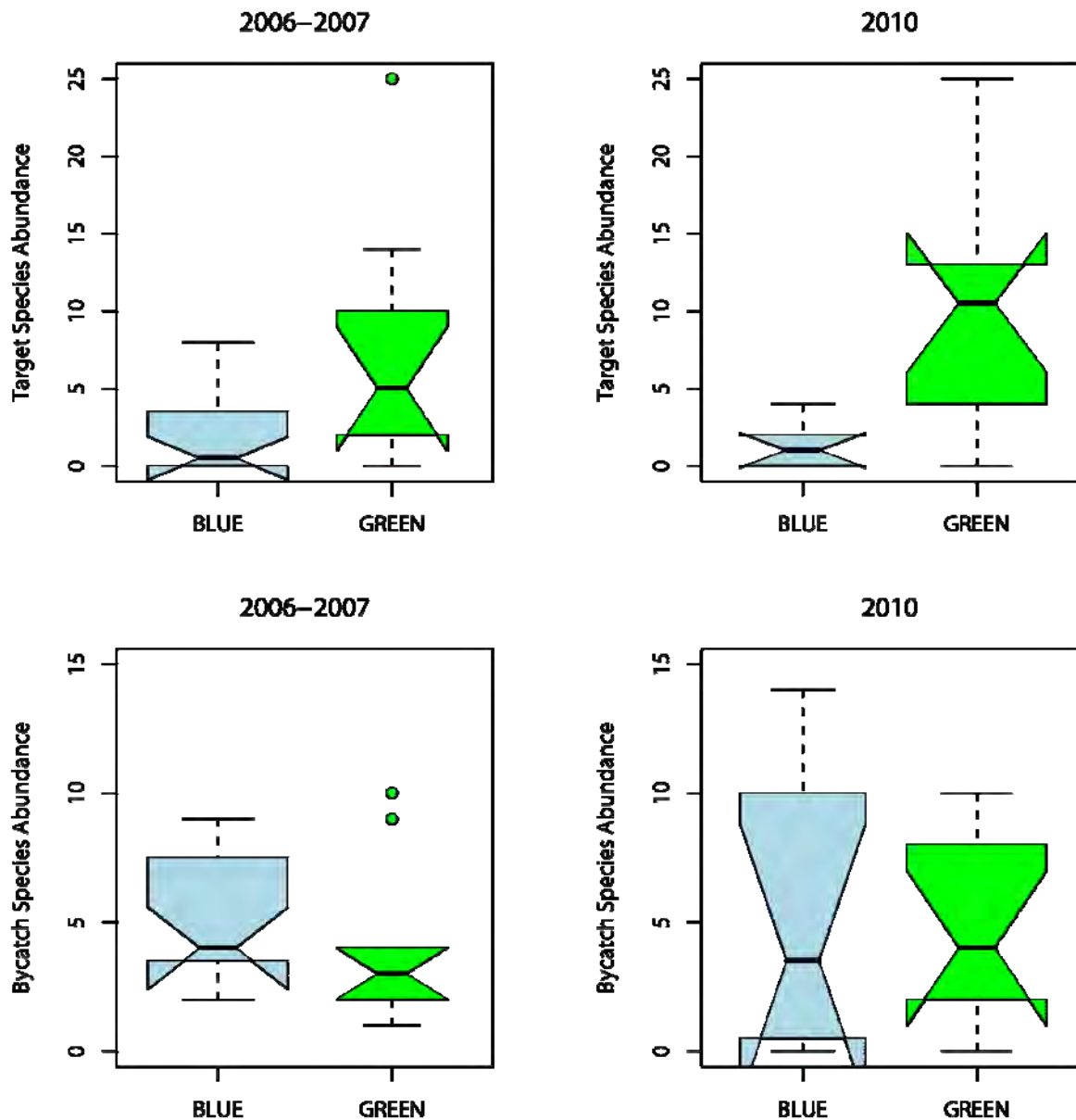


Figure 9. Comparisons of the abundance of “prized” and “all target” species groups amongst zones and years in the Cardwell shoals. All conventions as in Figure 4.

A mixed effect model was constructed for the Cardwell shoals “target” species group, with *year* as the random factor ($abundance \sim zone + (1|year)$). The few samples in 2006 and 2007 were lumped together as one level of *year* in this analysis. The coefficients from this model showed 5.17 times as many “target” fish in the Brook shoals closed to fishing. This represented 8.4 target fish on Brook shoals and only 1.62 on Forty-Foot Rock samples. A simple plot of means by all sampling years showed a trend that the numbers of target fish were increasing from 2006 through 2007 to 2010 on Brook shoals and decreasing in the “blue” zone nearby (Figure 10), but these differences were not statistically significant.

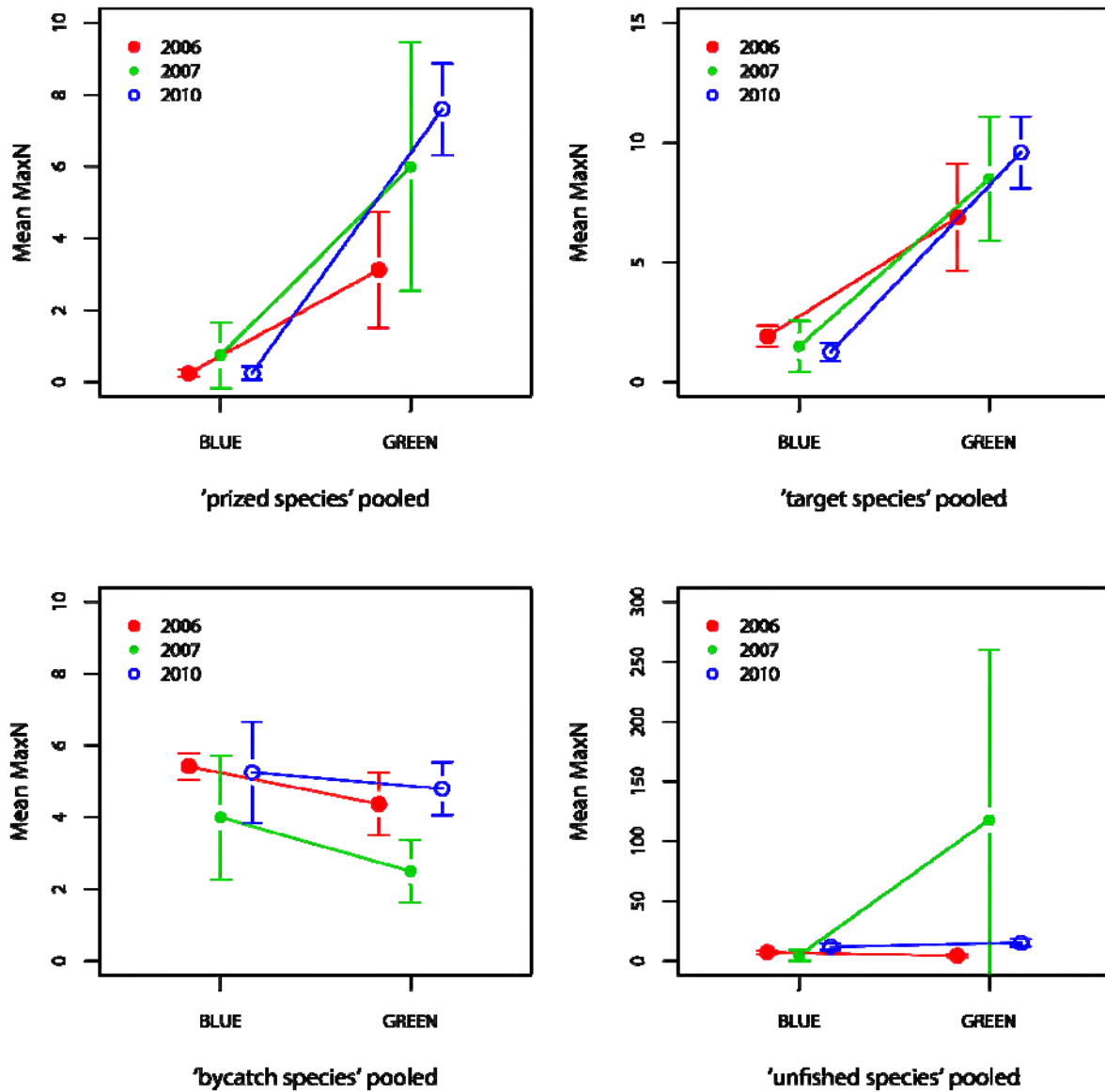


Figure 10. Plots of the means, with 95% Confidence Intervals, for the four species categories sighted at Cardwell shoals amongst sampling years and management zones. The mean number of target species appeared to be increasing through time on Brook shoal, closed to fishing in 2004, but these temporal differences were not statistically significant.

Comparison of broader-scale sampling on southern banks between years

The non-random, repeated sampling summarized above was restricted to a subset of the overall dataset collected randomly on the southern banks in 2007 and 2009. Counts of the species groups in this more comprehensive dataset showed a consistent decline in the numbers of prized, target and bycatch species on the Western Waragoes open to fishing from 2007 to 2009, and a significant increase in the same groups nearby on the Eastern Waragoes closed to fishing since 2004 (Figure 11, 12). The decline in the species groups on the Karamea bank was similar in magnitude, but the higher numbers on nearby Barcoo bank in the “green zone” did not increase between 2007 and 2009 (Figure 11, 12). “Bycatch” species showed a decline on the Western Waragoes and a corresponding increase, with time, on the Eastern Waragoes – but this pattern was not repeated on the northern pair of shoals (Figure 13). Unfished species declined on all four shoals between 2007 and 2009 (Figure 14).

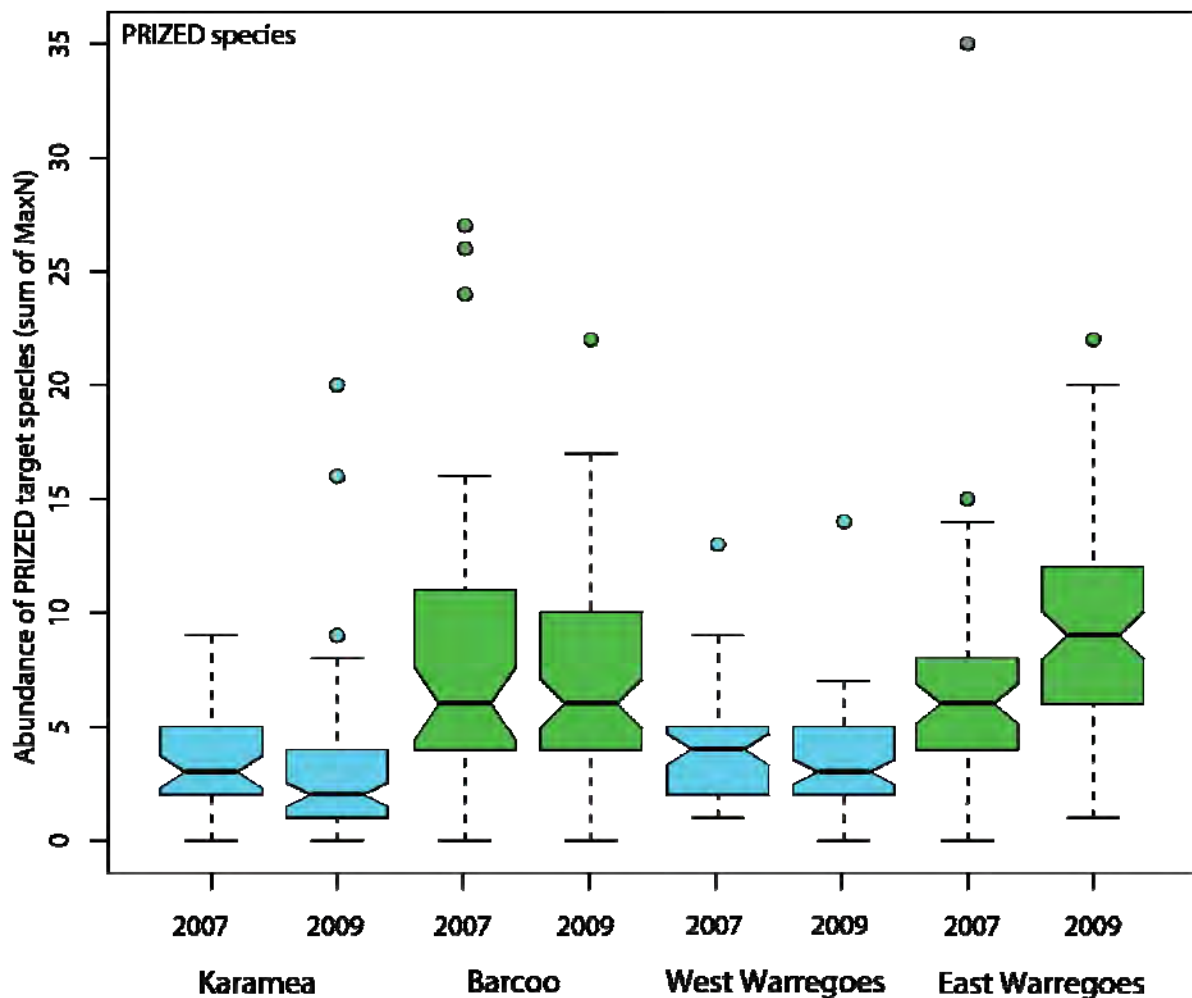


Figure 11. Comparisons of the median abundance of “prized” species (red emperor, coral trout, venus tuskfish, red-throat emperor, southern snapper) amongst zones and years in the two pairs of southern shoals. All conventions as in Figure 4.

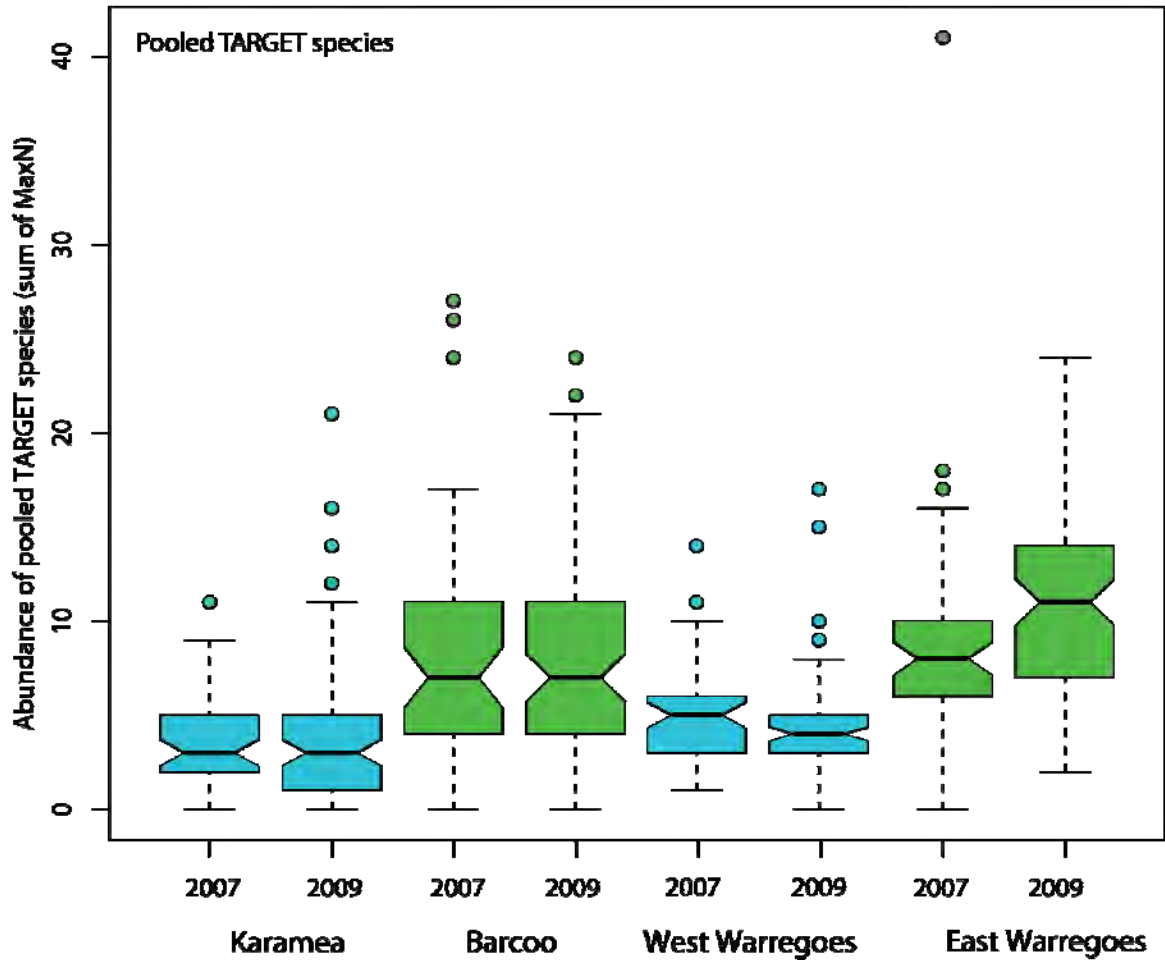


Figure 12. Comparisons of the median abundance of “all target” species groups (cods, sea perches, emperors, pelagics) amongst zones and years in the two pairs of southern shoals. All conventions as in Figure 4. The difference between fished and unfished shoals increased over the two sampling years at the Warregoes.

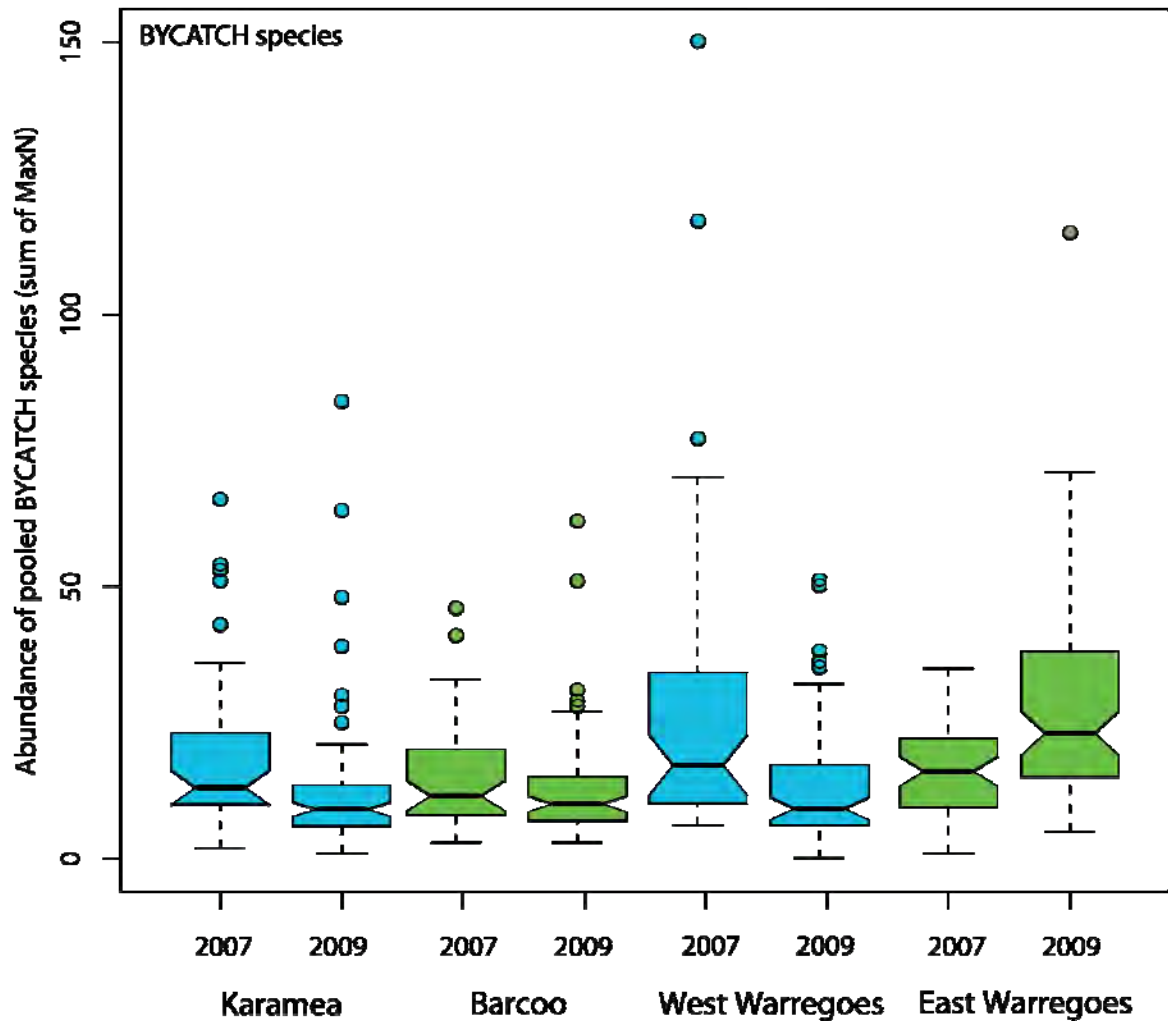


Figure 13. Comparisons of the median abundance of “bycatch” species groups (including sharks) amongst zones and years in the two pairs of southern shoals. All conventions as in Figure 4. The difference between fished and unfished shoals increased with time for bycatch species on the Warregoes.

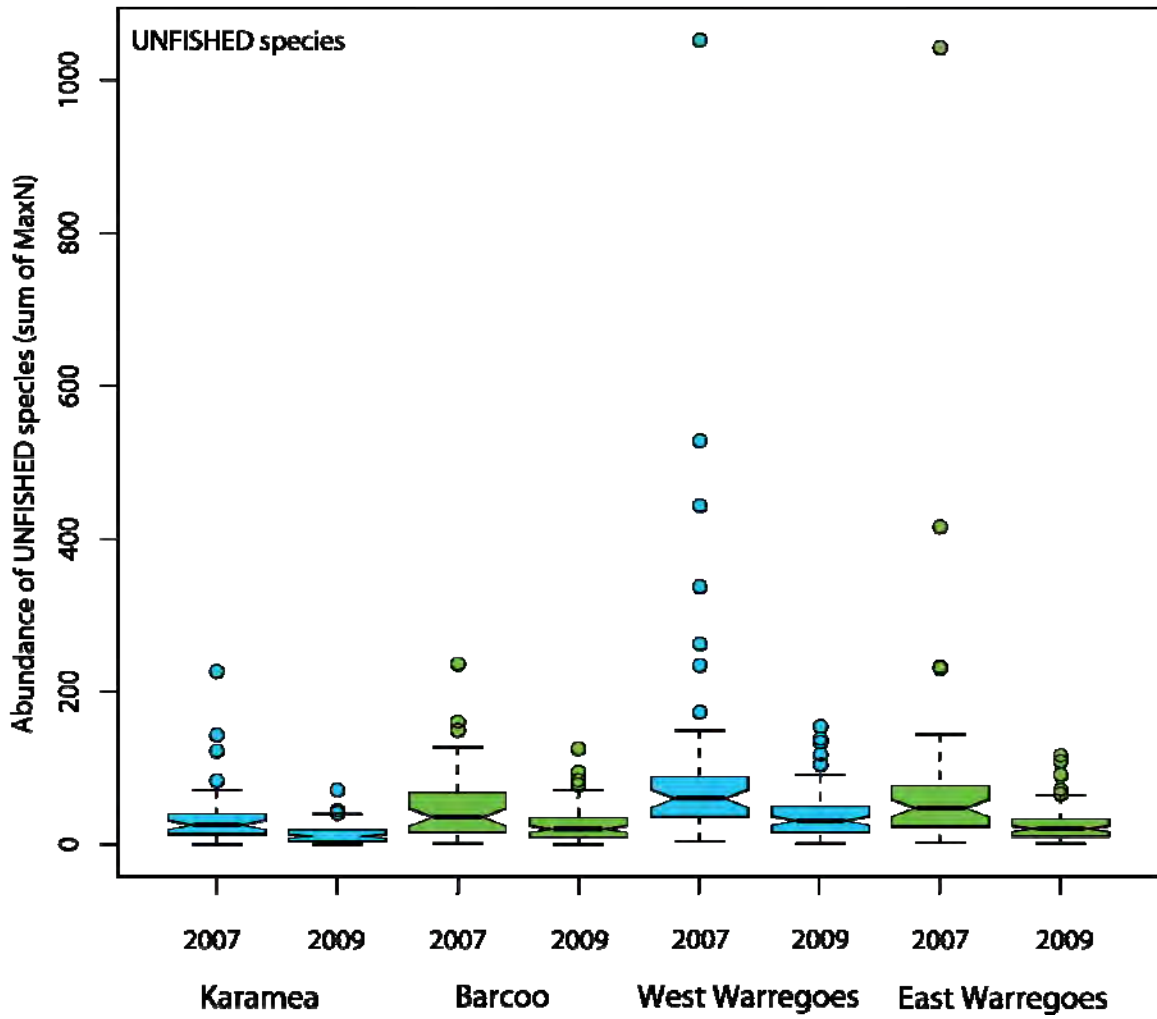


Figure 14. Comparisons of the median abundance of “unfished” species groups (such as damselfishes, fusiliers and parrotfish) amongst zones and years in the two pairs of southern shoals. All conventions as in Figure 4. Unfished species declined on all shoals between 2007 and 2009.

An overview of median counts amongst zones and regions of the GBRMP for species groups

During the course of this four year project, we have sampled reef bases in the Cairns, Pompeys, Swains and Capricorn-Bunker regions, very small discrete shoals off Cardwell, large, discrete banks on the Capricorn shelf, and sparse, diffuse “shoals” off Townsville. In this section we give an overview of the regional differences in the effects of zoning detected by this sampling.

The effects of zoning were not consistent amongst regions and species groups (Table 3). The Cairns and Pompeys reef bases showed more target fish in “green” zones, but the Swains and Capricorn-Bunkers reef bases had less. The diffuse Townsville shoals had less target and bycatch species in “green” zones, whilst the nearby, discrete, Cardwell shoals showed very high ratios of 5.17 to 16.95 for target groups between “closed” and “open” fishing zones.

The Cardwell shoals were lowest in median richness and abundance, and the southern banks had consistently high medians for these parameters – with significant differences between zones (Figure 15, Figure 16). Only the Cardwell shoals and southern banks showed significantly higher median counts of both target groups (Figure 17, Figure 18), and only the southern banks had significantly higher counts for bycatch species (Figure 19). “Unfished” species were more abundance in the green zones of the Townsville shoals and Pompey reef bases, but not elsewhere (Figure 20).

Table 3. Coefficients of the model $abundance \sim zone * region + (1|region)$ for the four species groups sampled in four major regions of the GBRMP.

PRIZED	Open:Closed ratio	MaxN.Closed	MaxN.Open
Cairns	1.66	1.16	0.7
Cardwell	16.95	5.65	0.33
Townsville	0.5	2.09	4.18
Pompeys	1.26	5.74	4.56
Swains	0.81	3.42	4.22
Capricorn-Bunkers	0.7	2.6	3.71
Southern banks	2.23	8.02	3.6

TARGET	Open:Closed ratio	MaxN.Closed	MaxN.Open
Cairns	1.49	1.39	0.93
Cardwell	5.17	8.4	1.62
Townsville	0.51	2.91	5.71
Pompeys	1.21	6.16	5.09
Swains	0.85	3.76	4.42
Capricorn-Bunkers	0.68	3.02	4.44
Southern banks	2.22	9.32	4.2

BYCATCH	Open:Closed ratio	MaxN.Closed	MaxN.Open
Cairns	0.9	6.58	7.33
Cardwell	0.86	4.4	5.12
Townsville	0.88	21.08	23.95
Pompeys	1.06	14.92	14.08
Swains	1.03	11.06	10.74
Capricorn-Bunkers	0.92	12.48	13.57
Southern banks	1.1	18.52	16.84

UNFISHED	Open:Closed ratio	MaxN.Closed	MaxN.Open
Cairns	0.72	18.48	25.76
Cardwell	2.51	21.19	8.44
Townsville	1.78	41.33	23.22
Pompeys	1.56	45.83	29.38
Swains	0.79	34.76	44
Capricorn-Bunkers	1.17	74.38	63.57
Southern banks	0.93	40.55	43.6

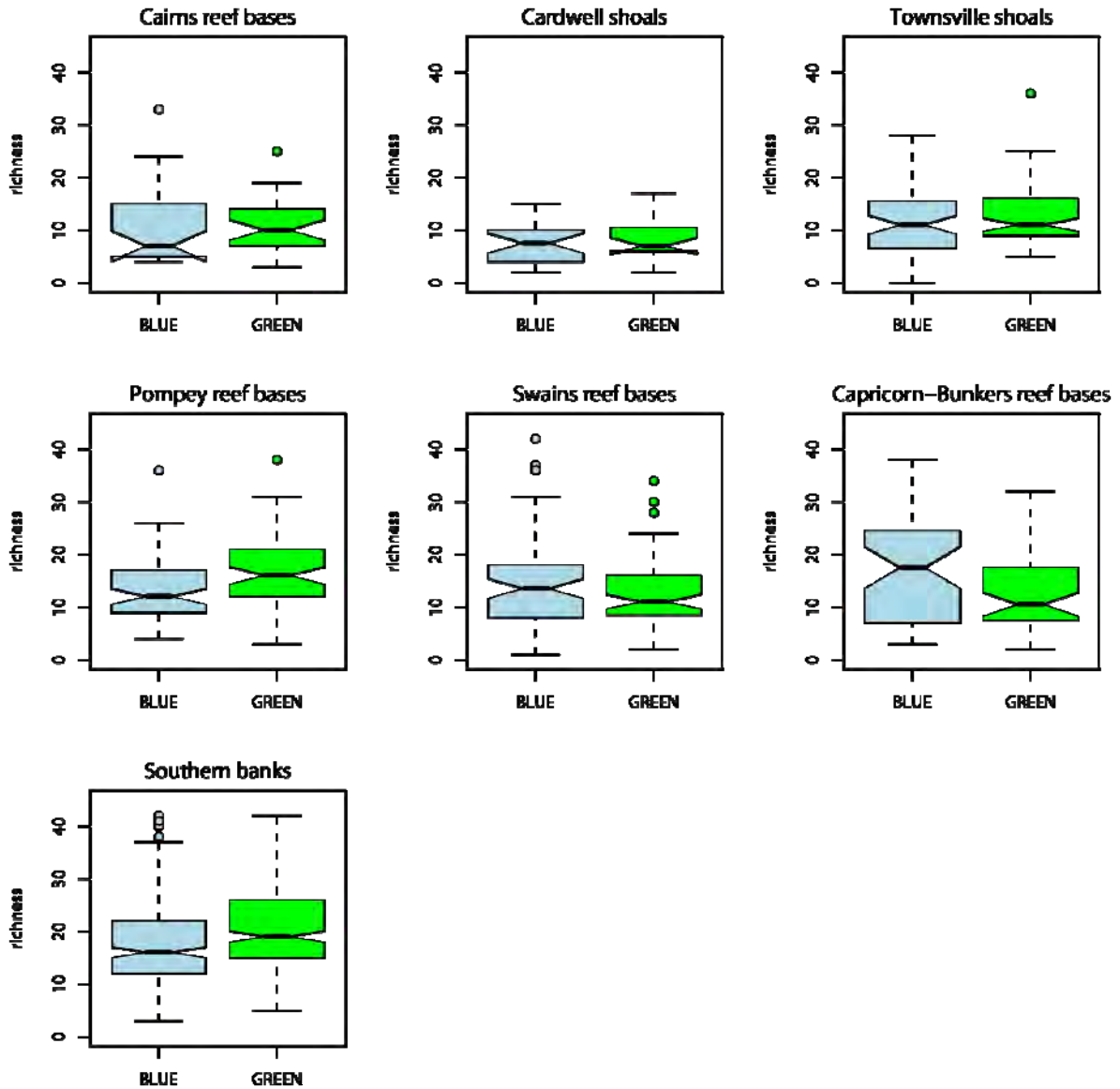


Figure 15. Comparisons of the median species richness between zones on shoals within 7 regions of the GBRMP from north to south. The boxplots show the median and 95% Confidence Intervals. The notches represent $1.5 \times$ (interquartile range of $MaxN/SQRT(n)$). If the notches do not overlap this is 'strong evidence' that the two medians differ, independent of any assumptions about normality of data distributions or equivalence of variances. Differences in richness were inconsistent between zones.

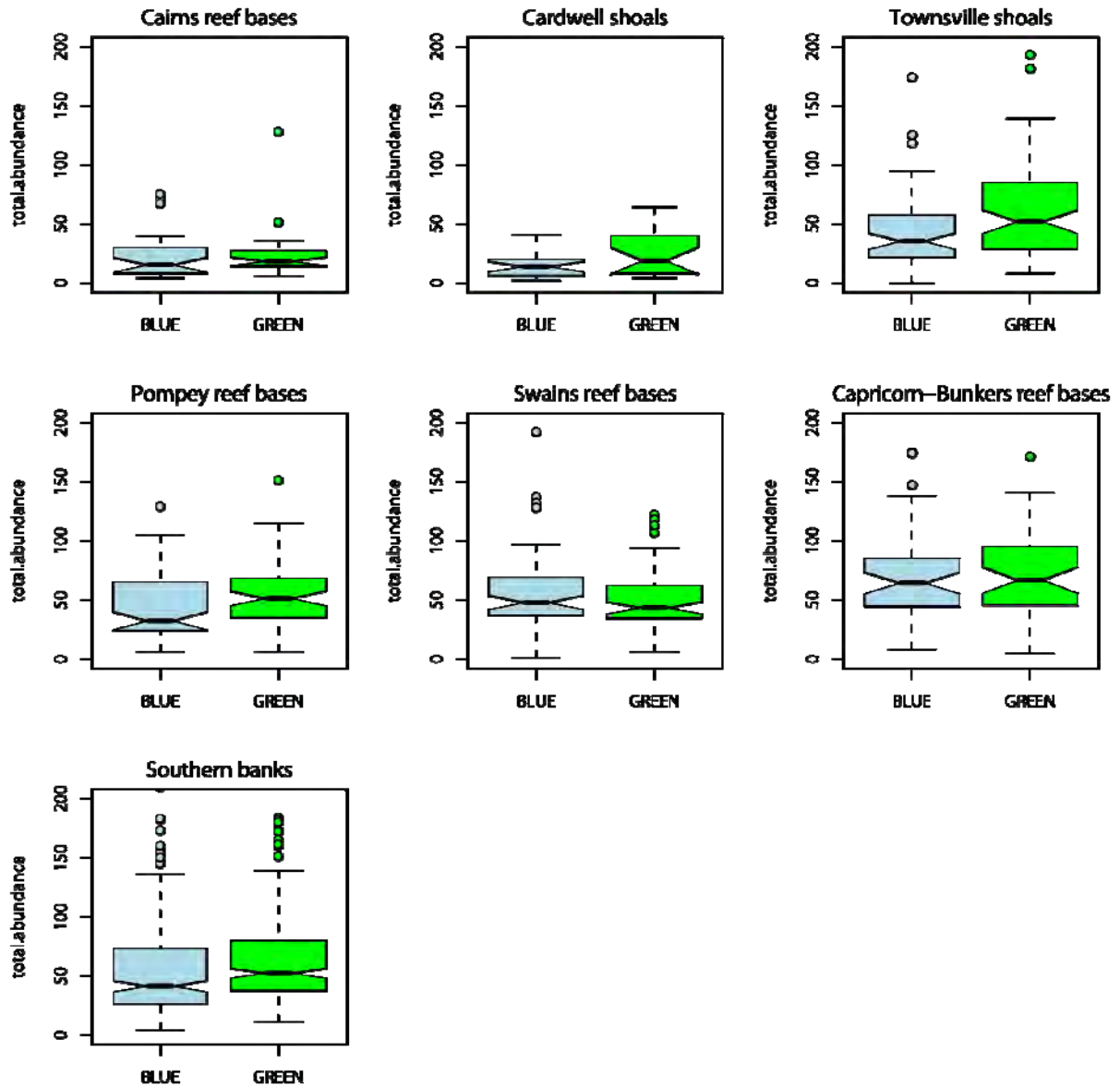


Figure 16. Comparisons of the median abundance (all species pooled) between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. Differences between zones were inconsistent.

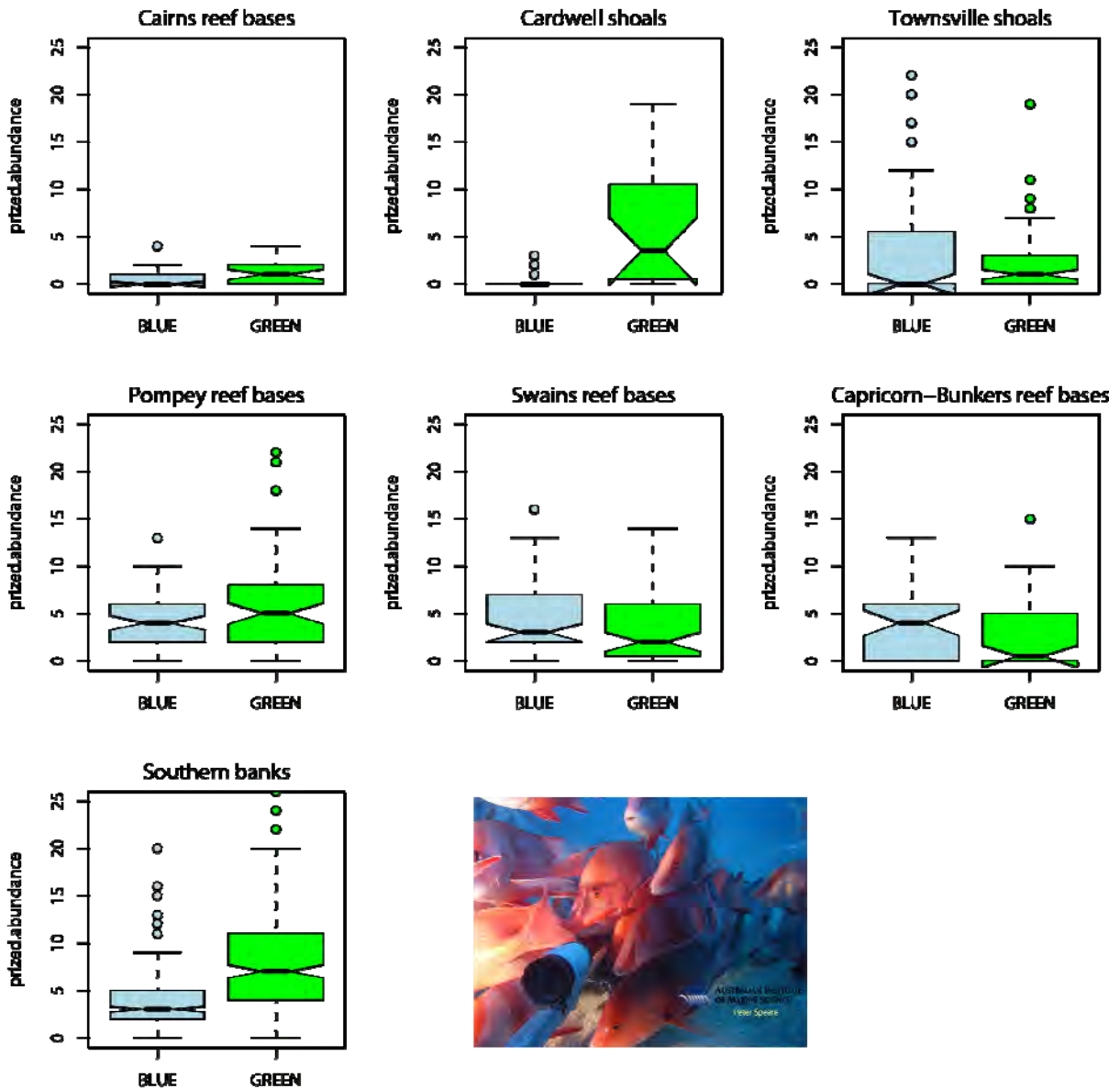


Figure 17. Comparisons of the median abundance of “prized species” between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. The most striking differences between zones occurred on the southern banks and Cardwell shoals. There appeared to be a higher median abundance of "prized" species around the reef bases of the Swains and Capricorn-Bunker Island group.

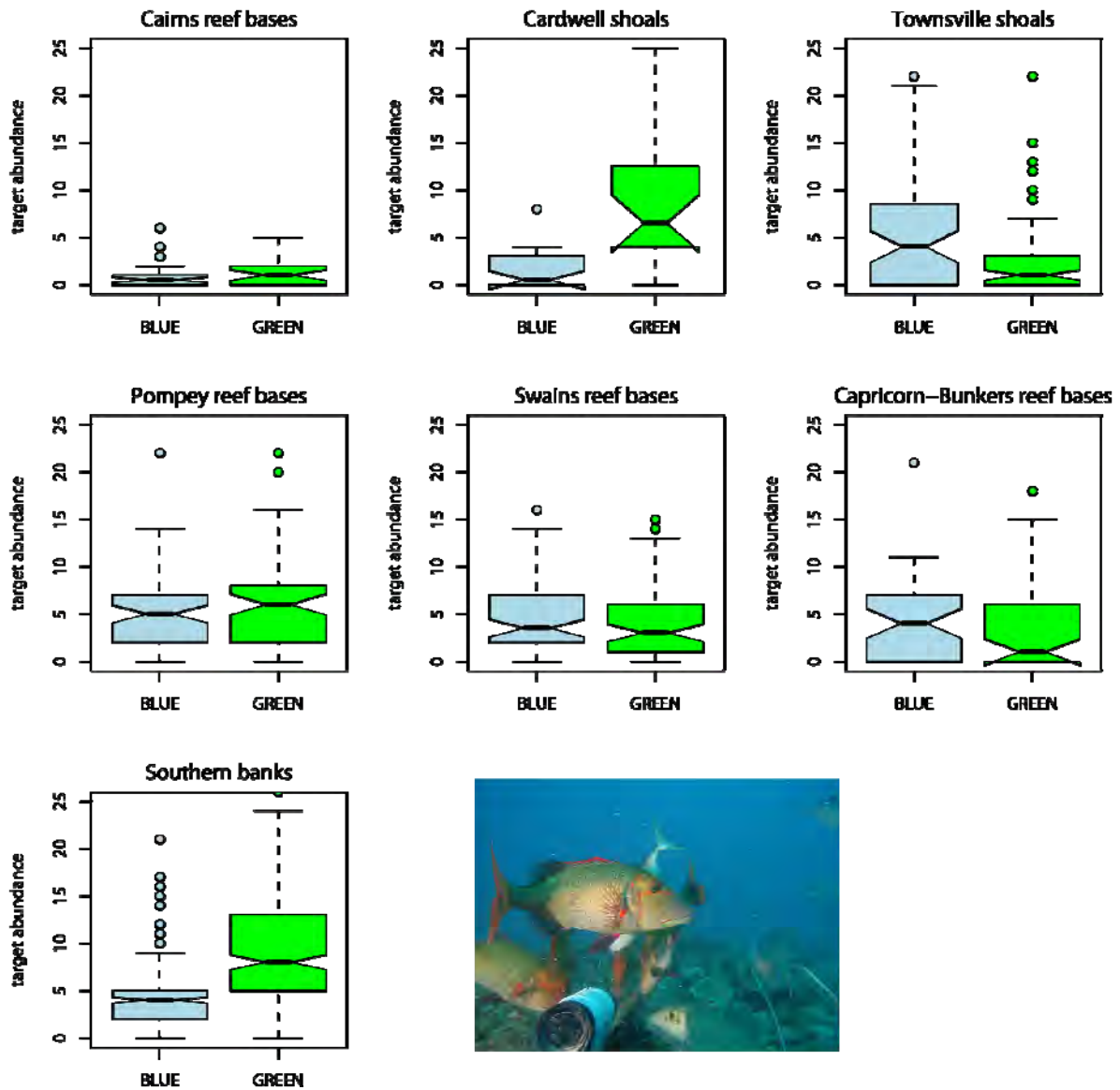


Figure 18. Comparisons of the median abundance of "all target species" between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. The most striking differences between zones occurred on the southern banks and Cardwell shoals, with a clear indication of higher median counts in the "blue" zones of the Capricorn-Bunker Island group.

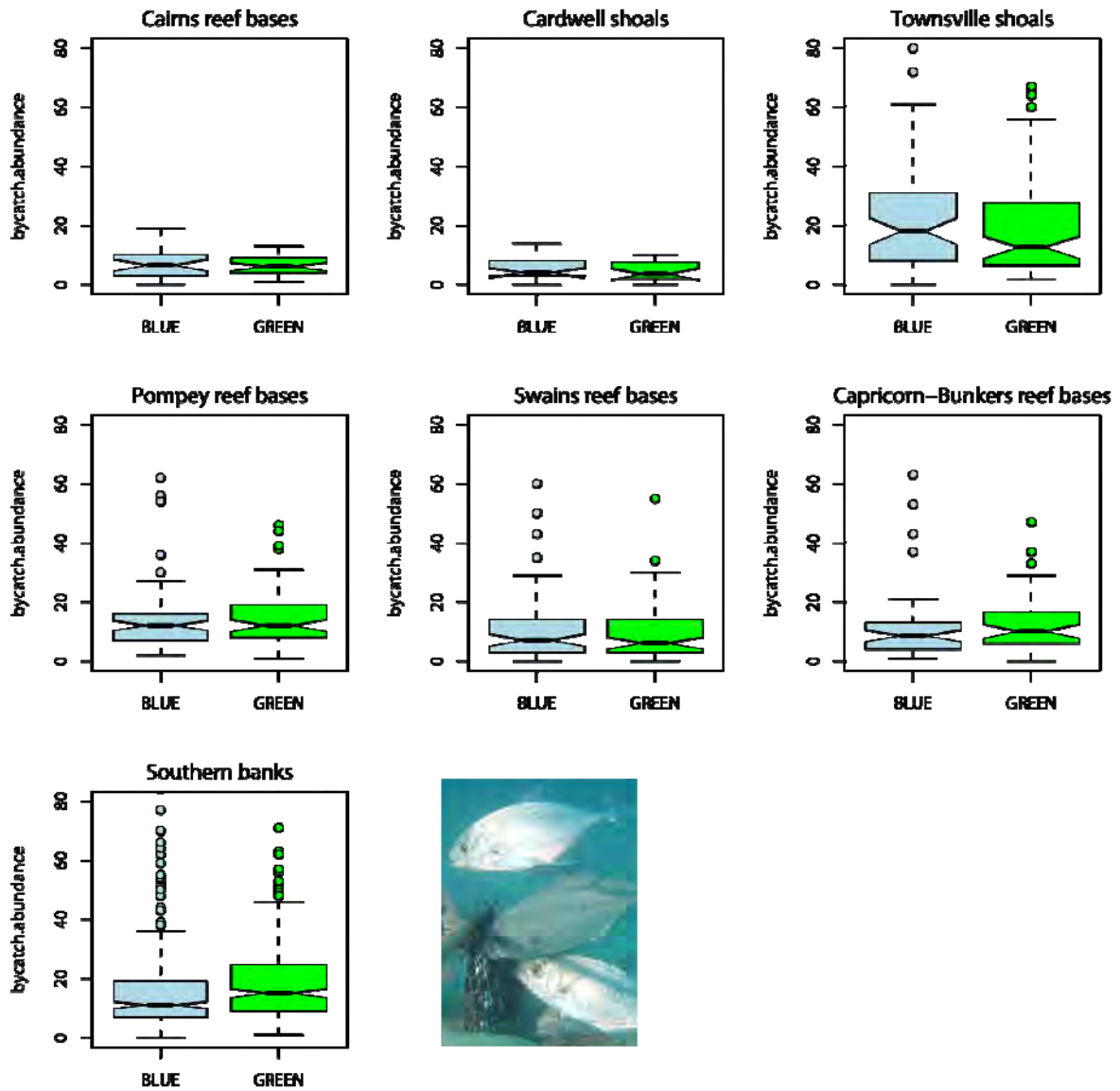


Figure 19. Comparisons of the median abundance of “bycatch species” between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. Differences between zones were not detected for all the regions except the southern banks.

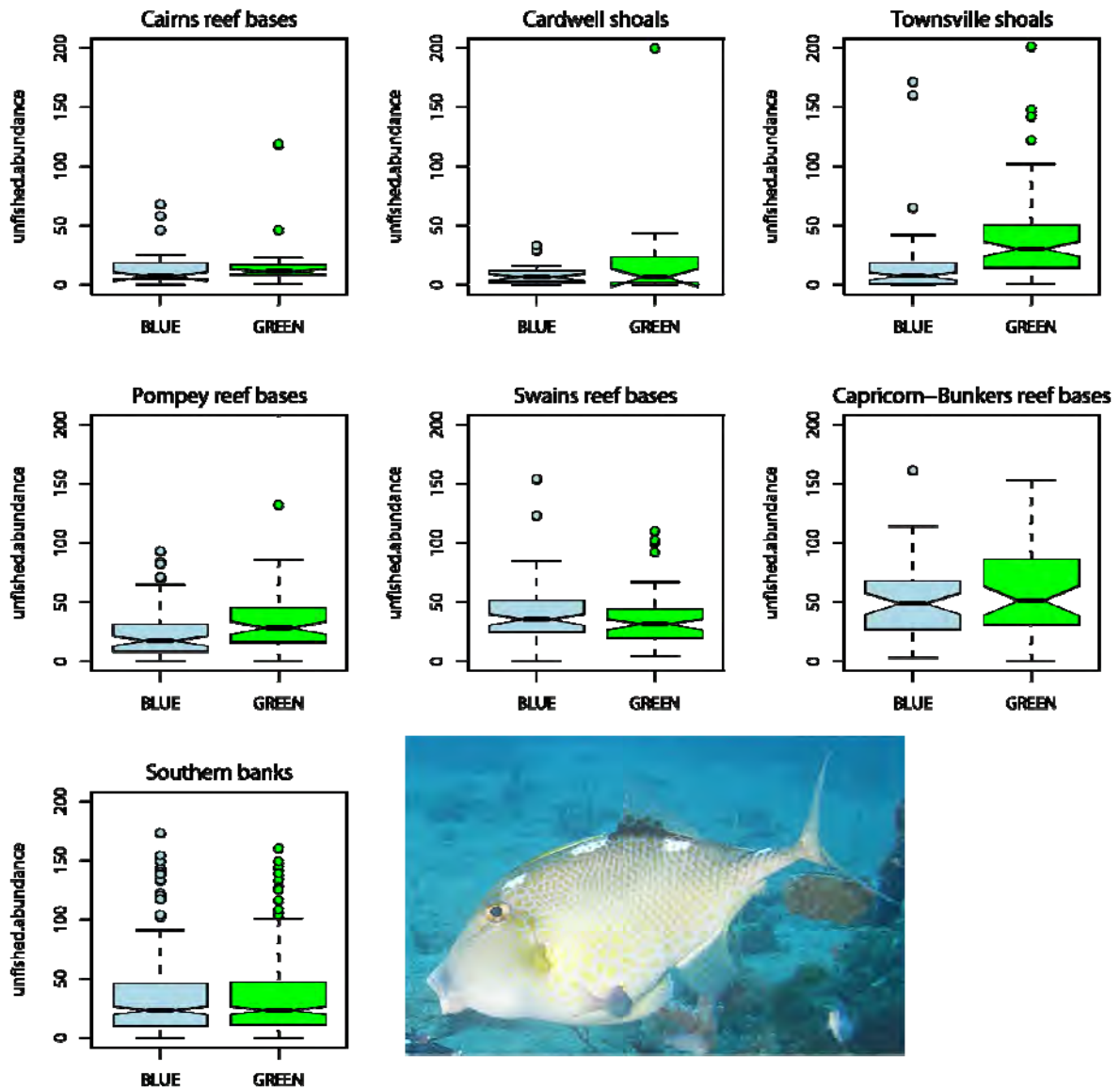


Figure 20. Comparisons of the median abundance of “unfished species” between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. The most striking differences between zones occurred on the Townsville shoals and Pompey Reef bases. “Unfished” species were more abundant in the “green” zones there.

An overview of median counts amongst zones and regions of the GBRMP for individual species

Differences between zones were not detected when counts of coral trout *Plectropomus leopardus* were pooled for the different regions (Figure 21). Higher median counts of red emperor *Lutjanus sebae* in green zones were detected for the southern banks, and for the Pompeys reef bases, but small numbers elsewhere gave inconsistent comparisons (Figure 22). Higher median counts of red-throat emperor *Lethrinus miniatus* in green zones were detected only for the southern banks, but this species was rare in the shoals in the northern part of the GBRMP, and small numbers elsewhere gave inconsistent comparisons (Figure 23). Venus tuskfish *Choerodon venustus* are also highly prized target species, and higher median counts in green zones were detected when data was pooled for the southern banks, but the opposite pattern was evident for the Pompeys reef bases. No significant differences in median counts were detected elsewhere between zones (Figure 24).

Bycatch species also showed regional differences in distribution and abundance amongst zones. Grey reef sharks *Carcharhinus amblyrhynchos* are often hooked as bycatch, and this species is retained, unhooked and released, or breaks away with the hooks still remaining in place. It frequently attacks other hooked fish, and sometimes ingests hooks in this manner. Highest counts were detected in green zones when data was pooled for some of the regions, but the species was rare in the northern shoals (Figure 25). Consistently higher counts of collared sea bream *Gymnocranius audleyi* (also a bycatch species) were detected in blue zones, open to fishing, when data was pooled for most of the southern regions, but the species was rare on the northern shoals (Figure 26).

The abundant starry triggerfish *Abalistes stellatus* avidly attacks baits, but is seldom caught as bycatch because of its very small mouth. It is much maligned by fishers as a bait-stealer before more desirable fish can gain access to baited hooks. All other conventions as in Figure 15. Differences amongst zones were inconsistent for this common species, with the exception that significantly more starry triggerfish were present in green zones off Townsville (Figure 27).

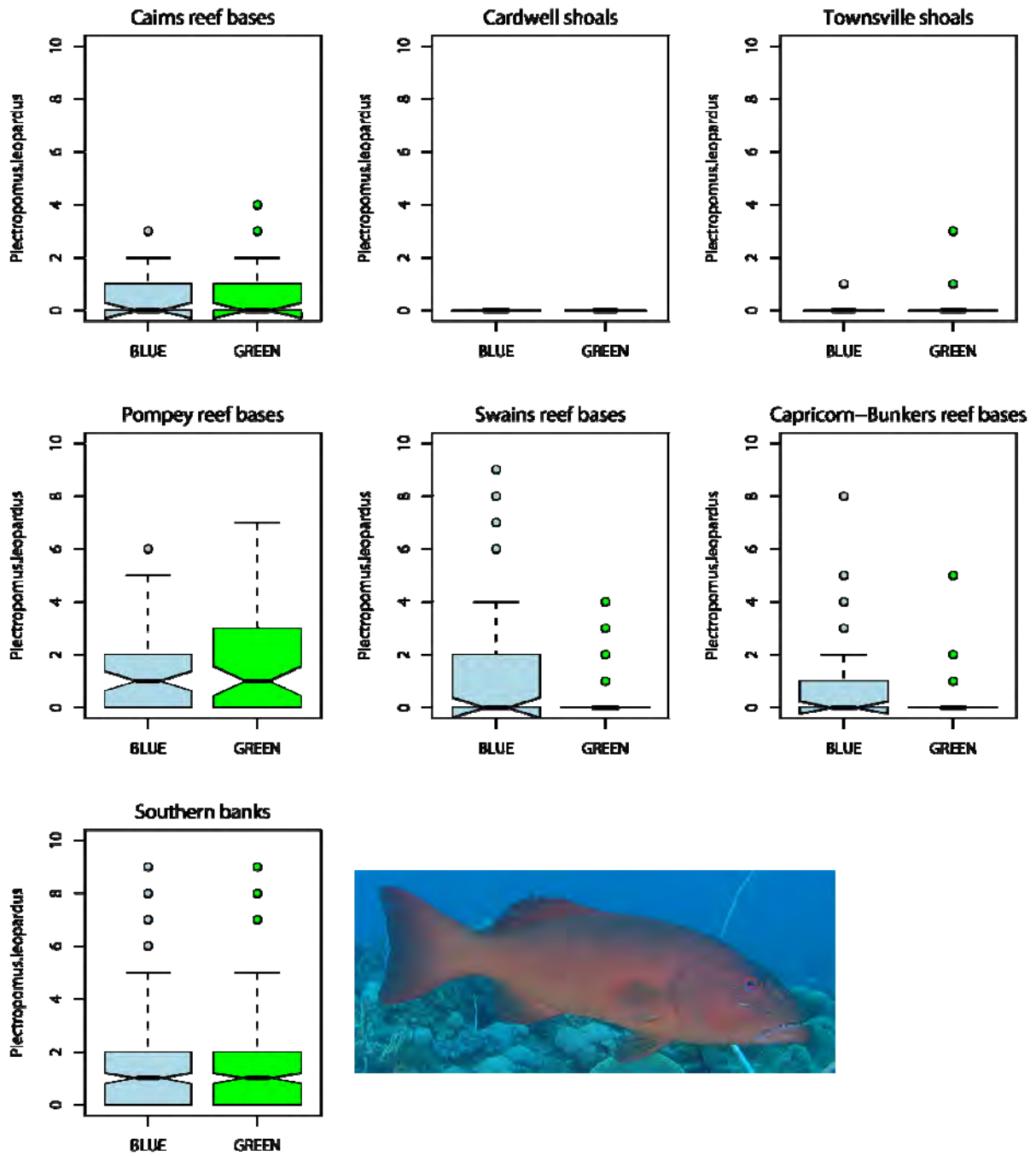


Figure 21. Comparisons of the median counts (*MaxN*) of prized coral trout on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. Differences between zones were not detected when data was pooled for the different regions.

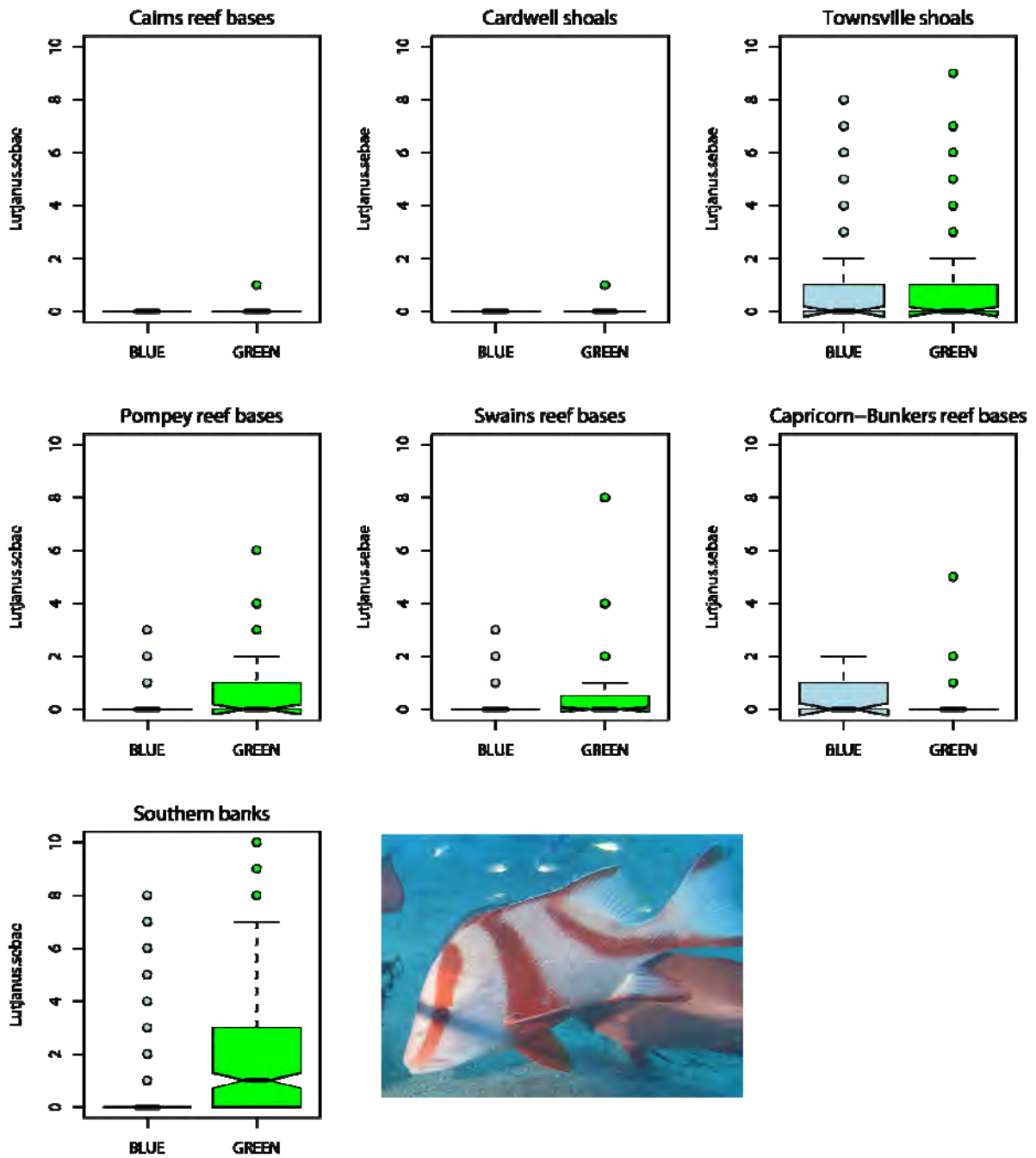


Figure 22. Comparisons of the median counts (*MaxM*) of prized red emperor *Lutjanus sebae* on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. Higher median counts in green zones were detected when data was pooled for the southern banks, and for the Pompeys reef bases, but small numbers elsewhere gave inconsistent comparisons.

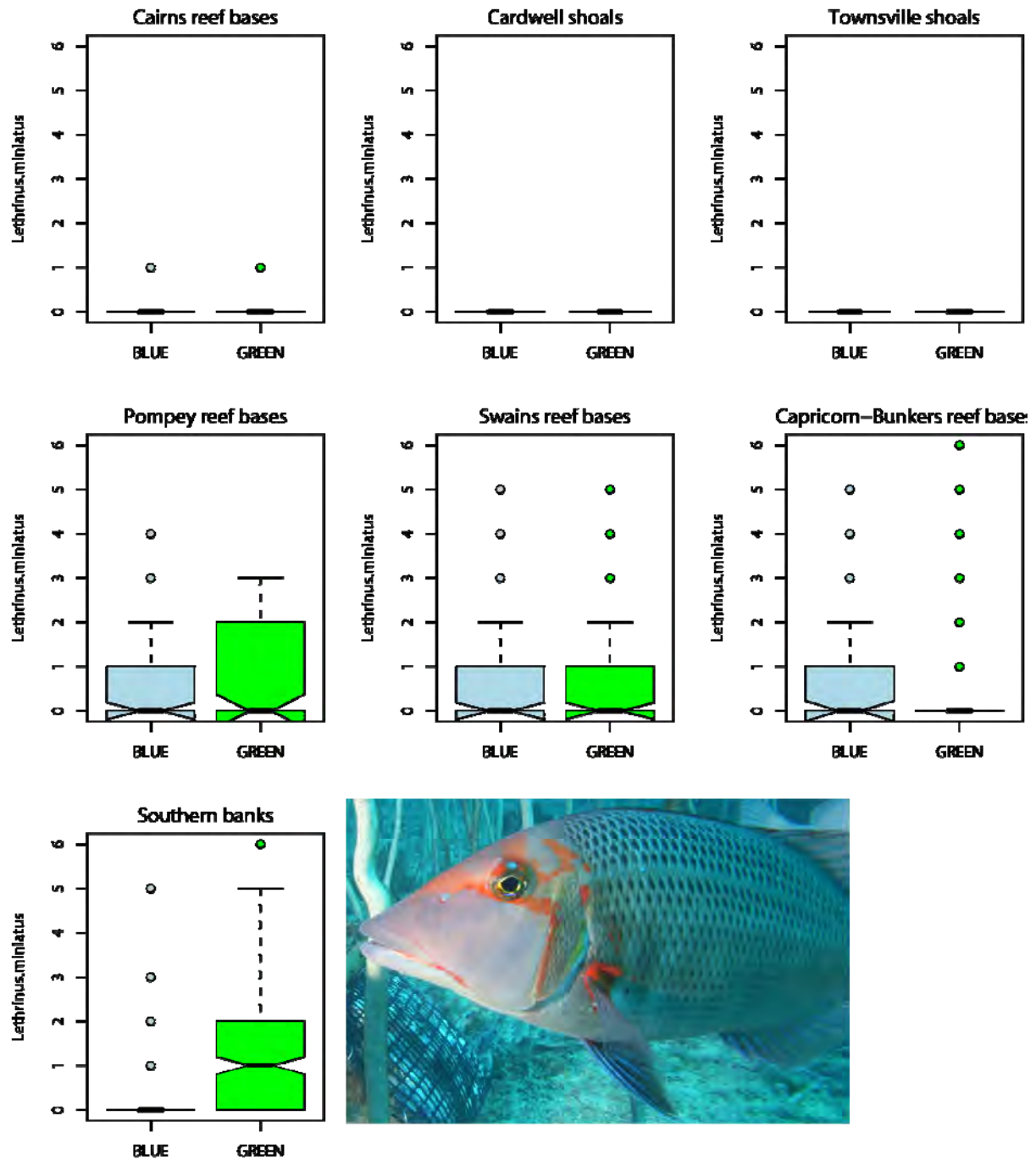


Figure 23. Comparisons of the median counts (*MaxN*) of prized red-throat emperor *Lethrinus miniatus* on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. Higher median counts in green zones were detected when data was pooled for the southern banks, but small numbers elsewhere gave inconsistent comparisons.

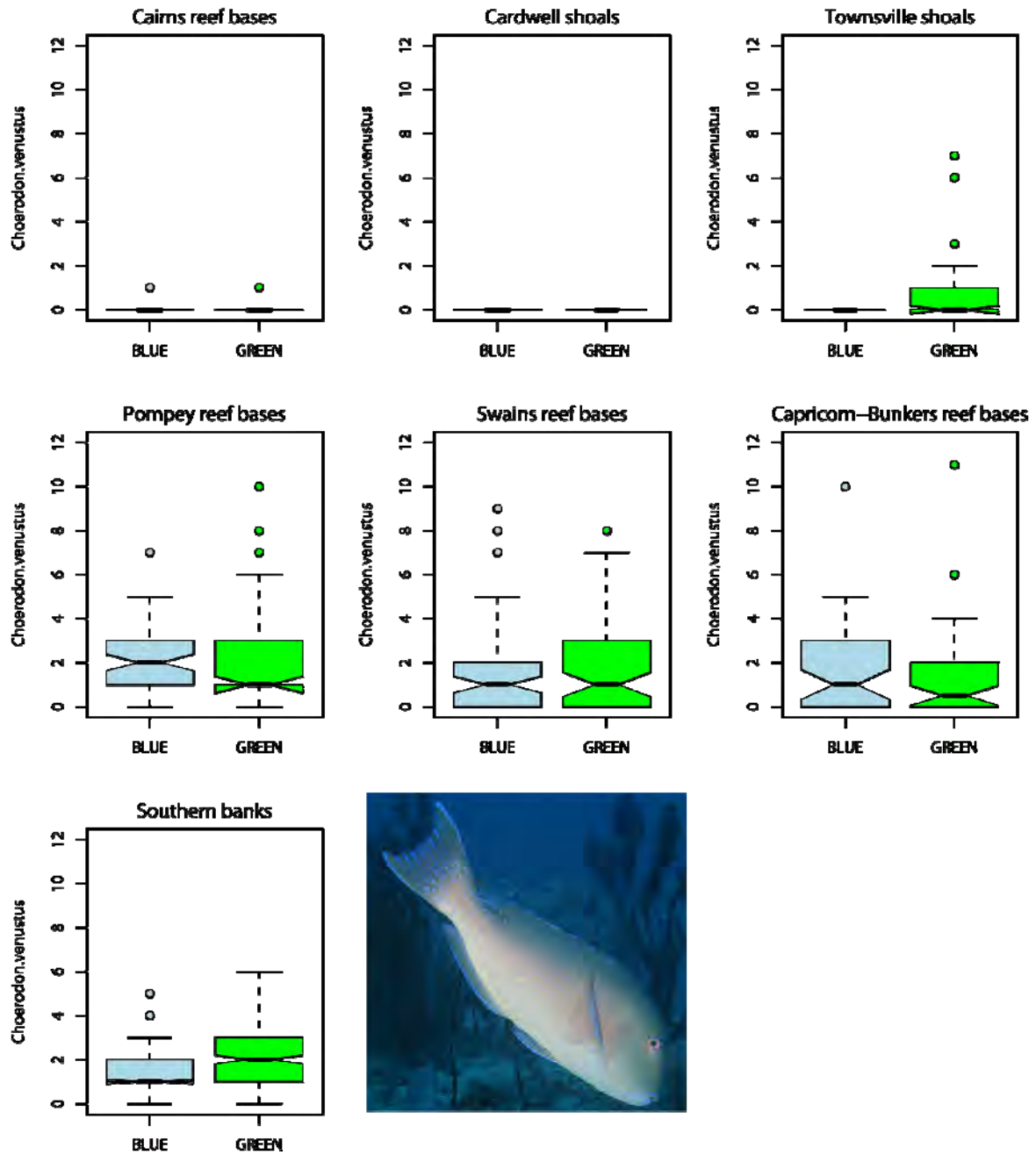


Figure 24. Comparisons of the median counts (*MaxN*) of the prized Venus tuskfish *Choerodon venustus* on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. All other conventions as in Figure 15. Higher median counts in green zones were detected when data was pooled for the southern banks, but the opposite pattern was evident for the Pompeys reef bases. No differences were detected elsewhere.

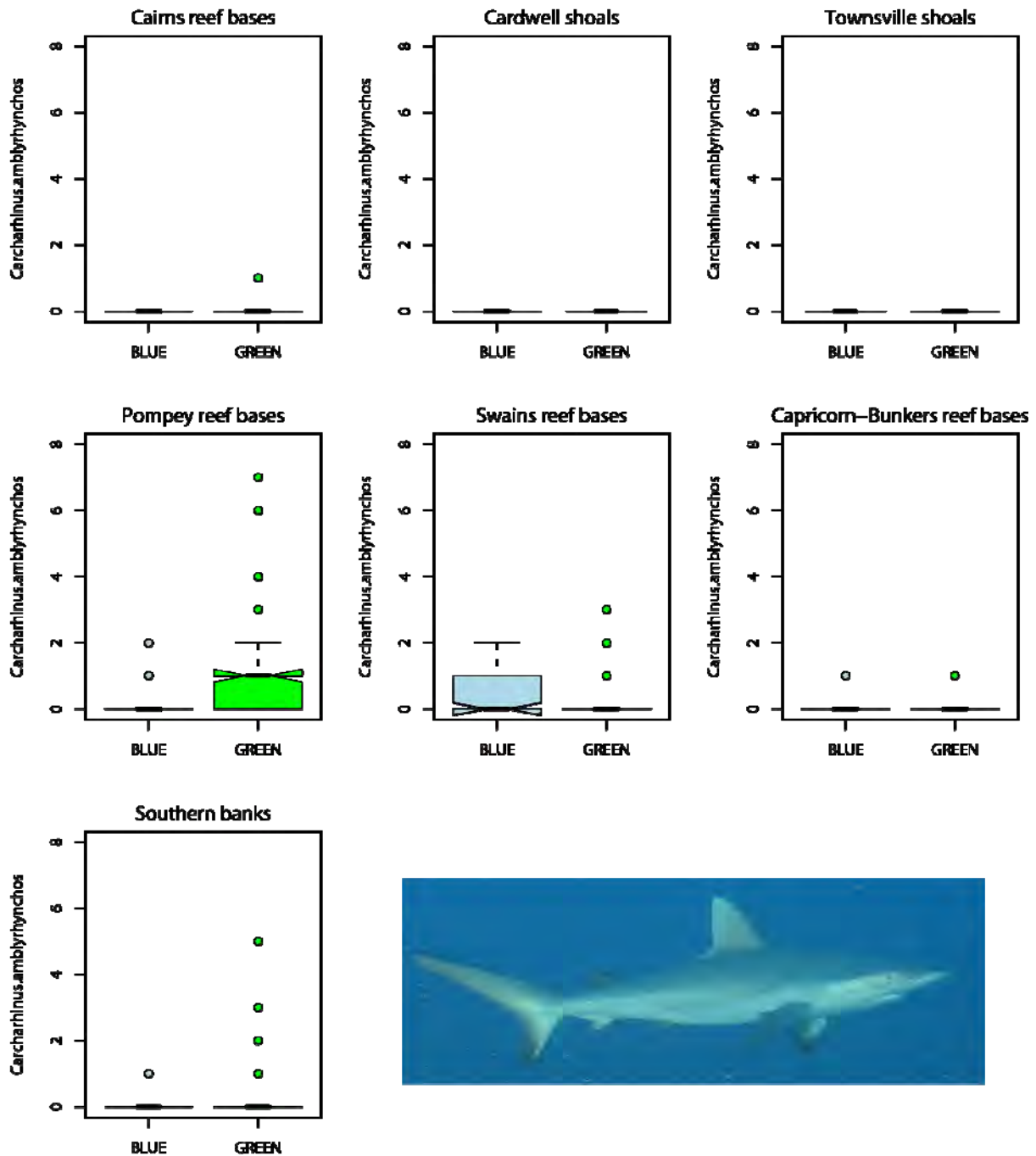


Figure 25. Comparisons of the median counts (*MaxN*) of the grey reef shark *Carcharhinus amblyrhynchos* on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. This species is often hooked as bycatch, and is retained, unhooked and released, or breaks away with the hooks still remaining in place. It frequently attacks other hooked fish, and sometimes ingests hooks in this manner. All other conventions as in Figure 15. Highest counts were detected in green zones when data was pooled for some of the regions, but the species was rare in the northern shoals.

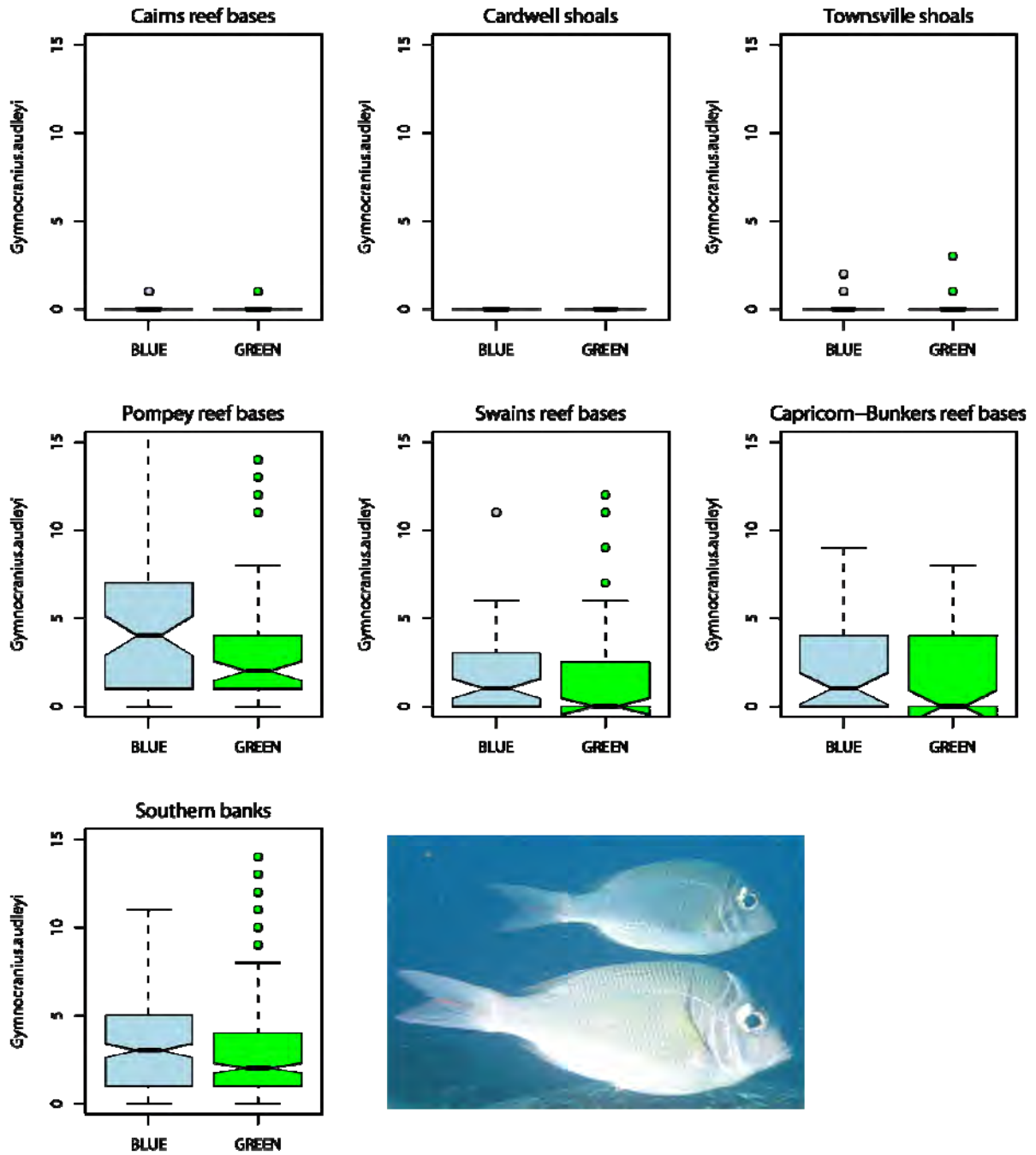


Figure 26. Comparisons of the median counts (*MaxN*) of the collared sea bream *Gymnocranius audleyi* on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. This species takes a hook, but is seldom caught as bycatch because of its small size. All other conventions as in Figure 15. Consistently higher counts were detected in blue zones, open to fishing, when data was pooled for most of the southern regions, but the species was rare on the northern shoals.

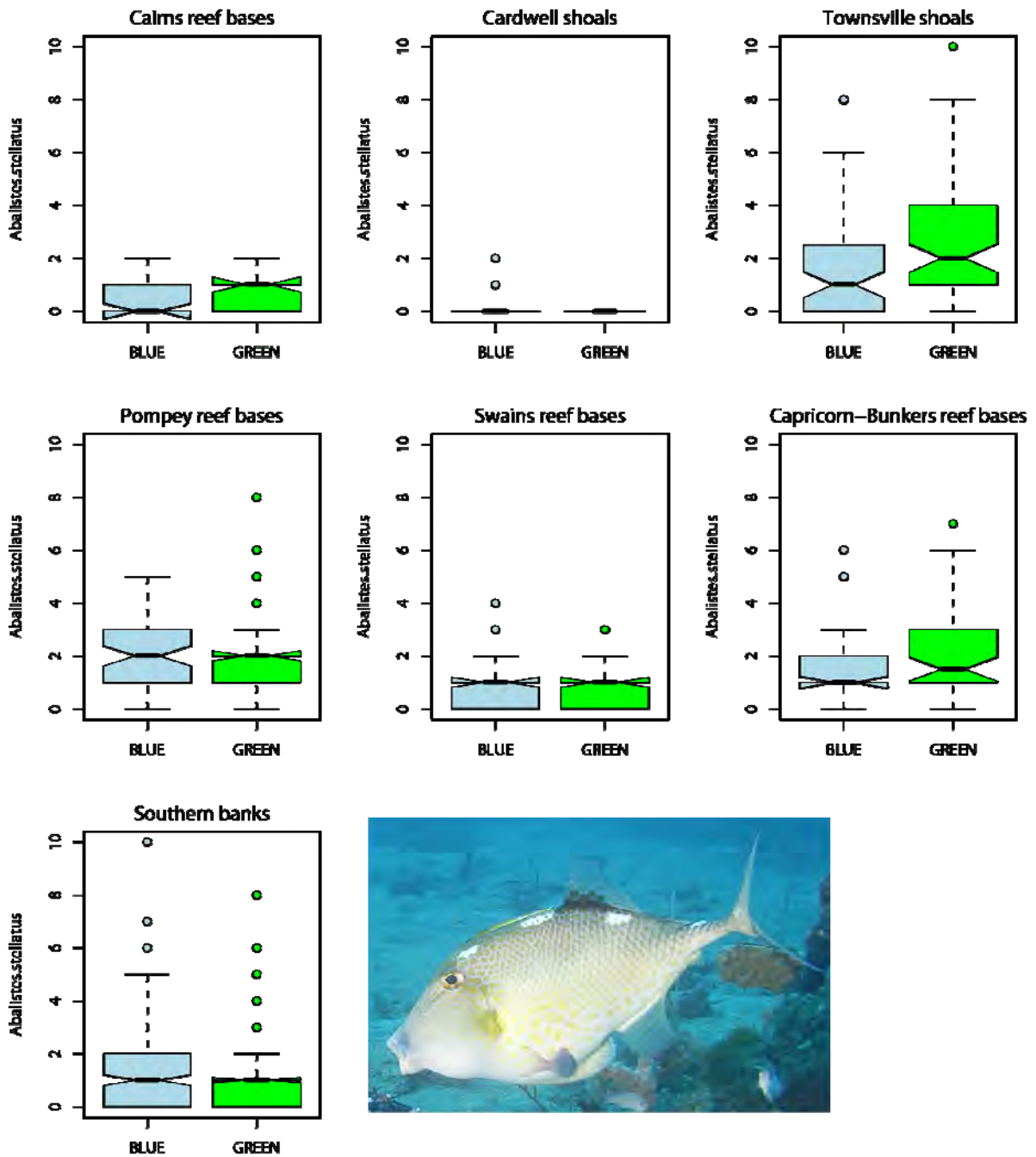


Figure 27. Comparisons of the median counts (*MaxN*) of the starry triggerfish *Abalistes stellatus* on BRUVS set between zones on shoals within 7 regions of the GBRMP from north to south. This species avidly attacks baits, but is seldom caught as bycatch because of its very small mouth. It is much maligned by fishers as a bait-stealer before more desirable fish can gain access to baited hooks. All other conventions as in Figure 15. Differences amongst zones were inconsistent for this common species, with the exception that significantly more starry triggerfish were present in green zones off Townsville.

A summary of mean abundances of key species between zones within regions of the GBRMP

Plots of the means for the eight key target, bycatch and unfisher species between the management zones within each of the seven regions are presented in Figure 28 to Figure 34. There were clear differences in the fauna between the “type” of shoal and its location north or south of Townsville.

Red emperor *Lutjanus sebae* were ubiquitous amongst regions and shoal types, but were most common on the southern banks. The large-mouth and small-mouth nannygais (*L. malabaricus*, *L. erythropterus*) were common as adults only on the diffuse shoals off Townsville, and were rare elsewhere – although the juvenile/sub-adult stages were very abundant on the small, discrete shoals and wrecks off Cardwell and in Halifax Bay. Red-throat emperor *Lethrinus miniatus*, Grey reef sharks *Carcharhinus amblyrhynchos* and collared sea bream *Gymnocranius audleyi* were all rare on the shoals and reef bases north of Townsville. These species are mainly associated with reefs and reef bases. The unfisher starry triggerfish *Abalistes stellatus* was commonly recorded in all regions and all shoal types.

There were some notable differences within the seven regions:

- the mean number of coral trout was nearly twice as high around the bases of the Cairns reefs closed to fishing in 2004
- the mean number of large-mouth and small-mouth nannygai on Brook shoal (closed to fishing) vastly exceeded the numbers on the nearby shoals open to fishing
- the pattern off Townsville was in the opposite direction – the mean number of large-mouth and small-mouth nannygai on diffuse shoals *open* to fishing off Townsville vastly exceeded the numbers on the diffuse shoals *closed* to fishing in 2004
- only one “bycatch” species appeared to show strong differences amongst the Pompeys reef bases. The collared sea bream was more abundant in the “blue” zones there
- there appeared to be about 1.5 times *less* coral trout around the reef bases of the Swains group closed to fishing in 2004
- numbers were generally very small in the Capricorn-Bunkers comparisons, but there appeared to be *less* target species, on average, around the reef bases in “green zones”
- a general trend line showed strong, significant differences in abundance of several key target species on the southern banks closed to fishing in 2004.

This use of global means hides the significant differences detected when microhabitats were taken into account in comparisons (see Stowar *et al.* 2008, Cappo *et al.* 2009a), but does serve to illustrate the point that there is no single, simple trend in the effect of the RAP 2004 zoning on “shoals”.

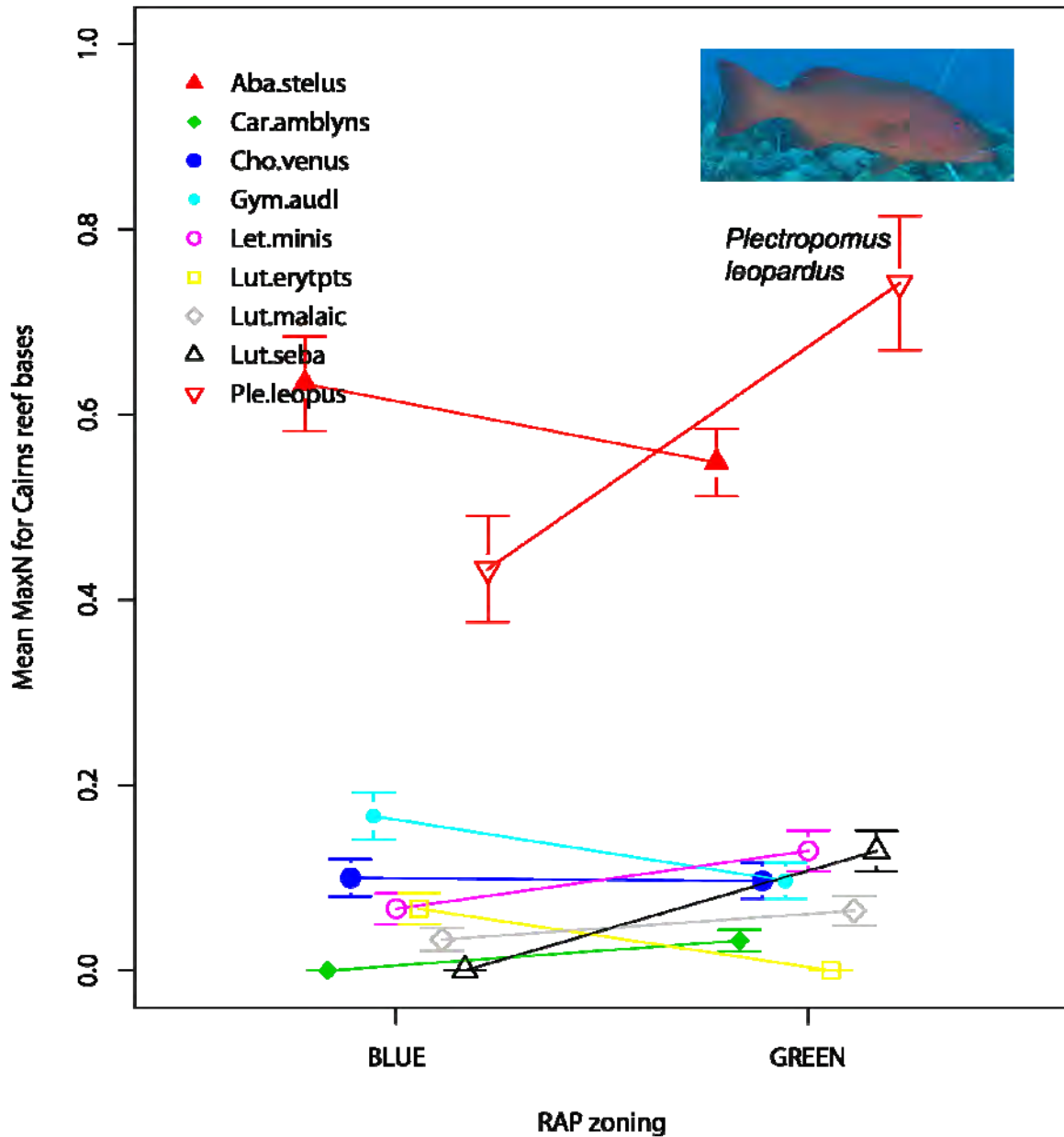


Figure 28. Plots of the means, with 95% Confidence Intervals, for the key target species (red emperor, large-mouth and small-mouth nannygais (Lut.seba: *Lutjanus sebae*, Lut.malaic: *L. malabaricus* and Lut.erytpts: *L. erythropterus*) and reef species (coral trout Ple.leopus: *Plectropomus leopardus* and red-throat emperor Let.minis: *Lethrinus miniatus*), bycatch species (Car.amblyns: grey reef sharks *Carcharhinus amblyrhynchos* and collared sea bream Gym.audl: *Gymnocranius audleyi*), and unfished species (starry triggerfish Aba.stelus: *Abalistes stellatus*) sighted in the single sampling expedition to the Cairns reef bases in 2007 (see Speare *et al.* 2008). The mean number of coral trout was nearly twice as high around the bases of the Cairns reefs closed to fishing in 2004.

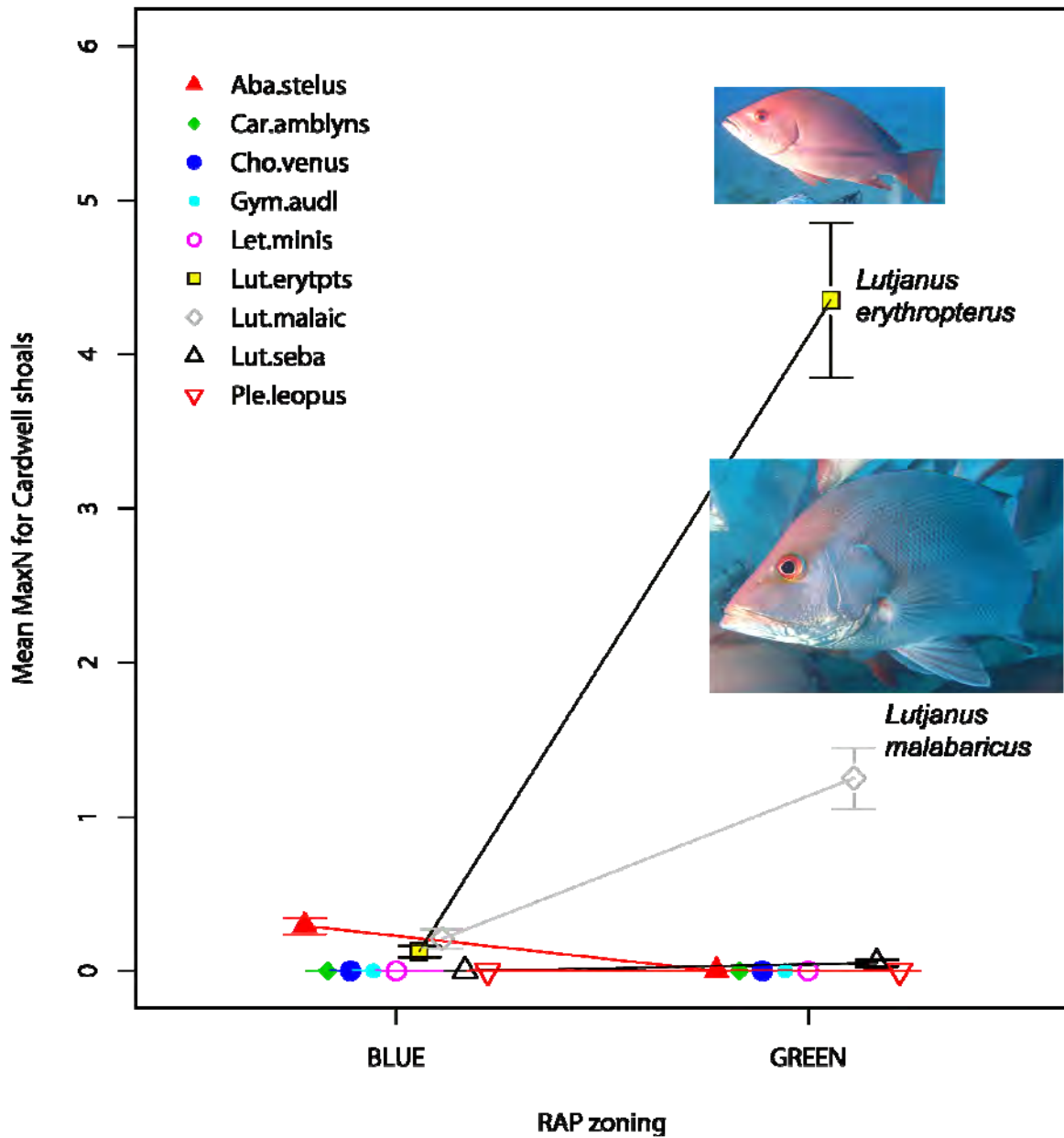


Figure 29. Plots of the means, with 95% Confidence Intervals, for the key target and bycatch species sighted in all the sampling conducted on the small, discrete shoals of the Cardwell region (see Speare *et al.* 2008). The mean number of large-mouth and small-mouth nannygai on Brook shoal closed to fishing in 2004 vastly exceeded the numbers on the nearby shoals open to fishing. All other conventions follow Figure 28.

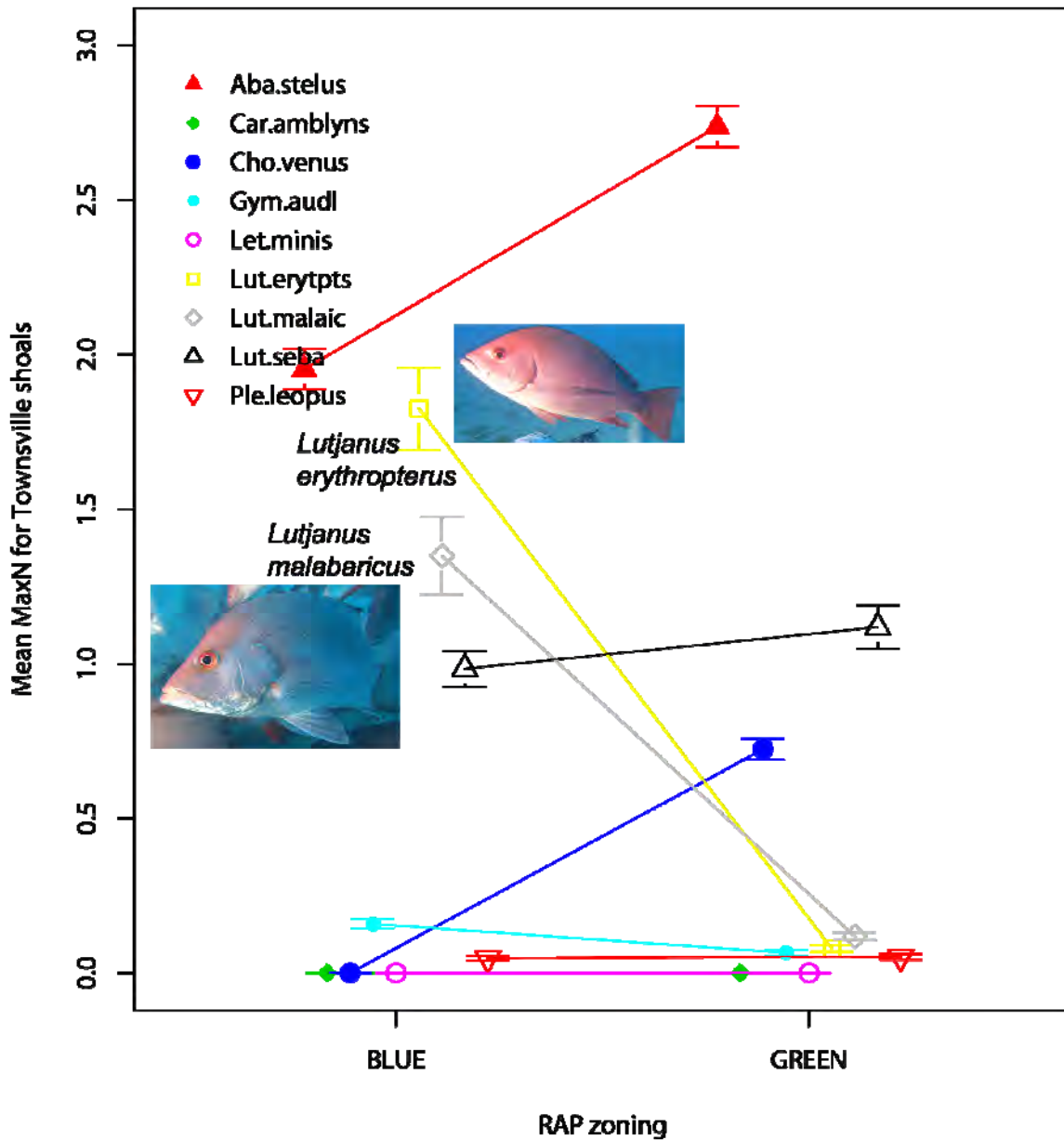


Figure 30. Plots of the means, with 95% Confidence Intervals, for the key target and bycatch species sighted in all the sampling conducted in the diffuse, low-relief shoals of the Townsville region (see Speare *et al.* 2008). The mean number of large-mouth and small-mouth nannygai on diffuse shoals open to fishing vastly exceeded the numbers on the diffuse shoals closed to fishing in 2004. Only the undesirable starry triggerfish were more abundant in the “green” zones there. All other conventions follow Figure 28.

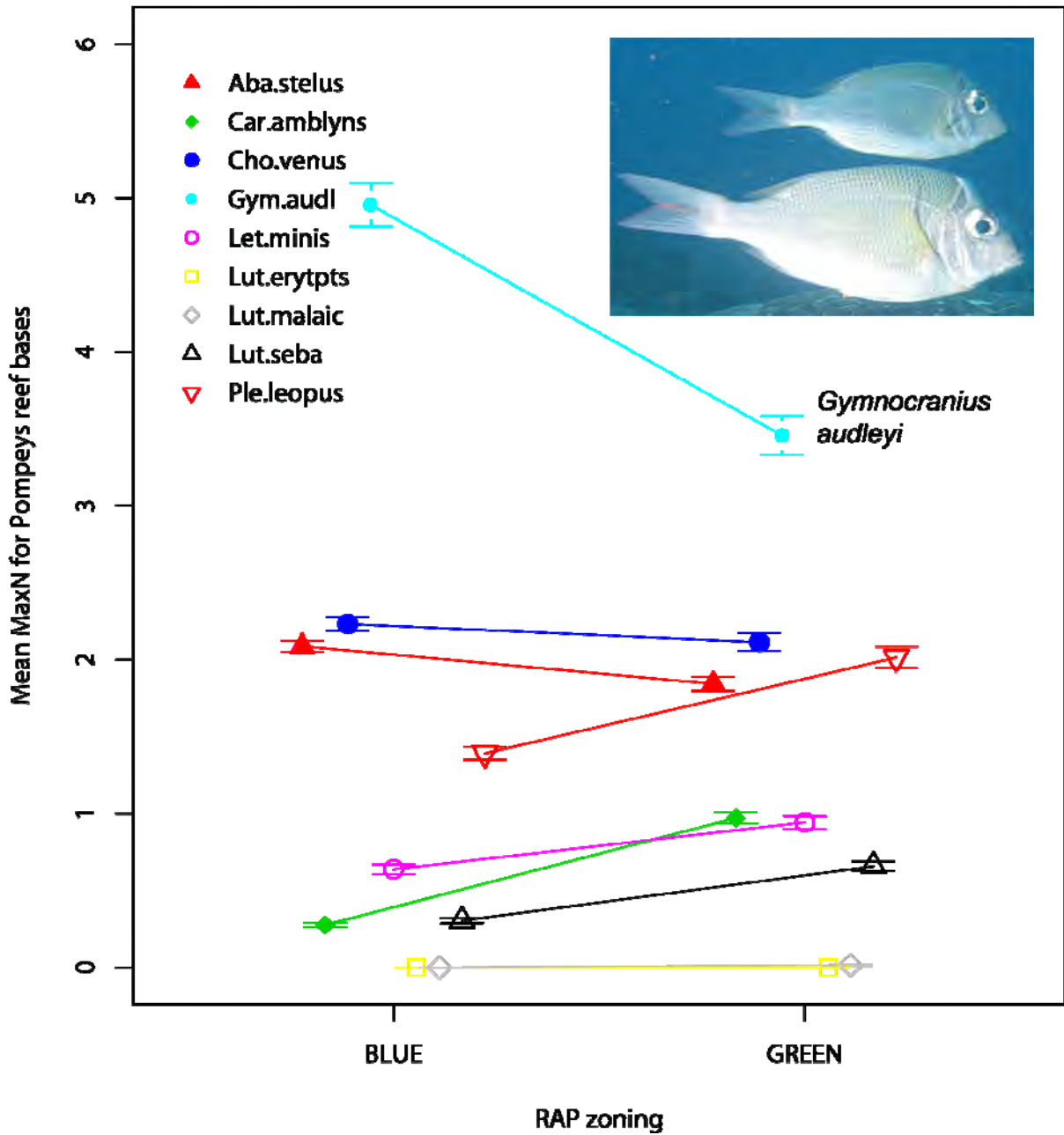


Figure 31. Plots of the means, with 95% Confidence Intervals, for the key target and bycatch species sighted in the single sampling expedition to the 6 pairs of reef bases in the Pompeys group (see Cappo *et al.* 2009a). Numbers were small, but there appeared to be about 1.5 times more key target species around the reef bases closed to fishing in 2004. Only one “bycatch” species seemed more abundant in the “blue” zones there. These averages hide the significant differences detected when microhabitats were taken into account (see Cappo *et al.* 2009a). All other conventions follow Figure 28.

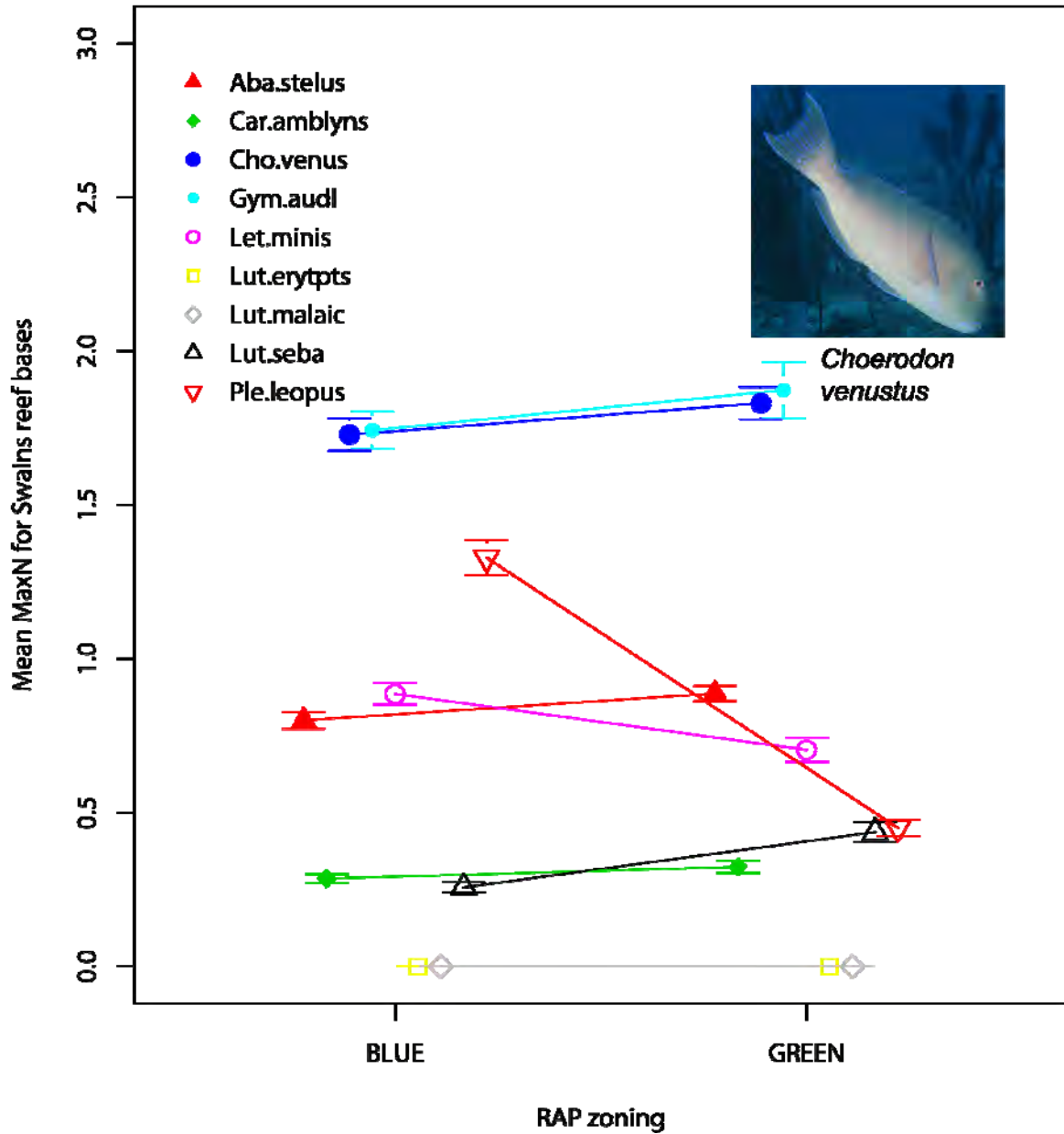


Figure 32. Plots of the means, with 95% Confidence Intervals, for the key target and bycatch species sighted in the single sampling expedition to the 6 pairs of reef bases in the remote Swains group (see Cappo *et al.* 2009a). Numbers were small, but there appeared to be about 1.5 times less coral trout around the reef bases closed to fishing in 2004. These averages hide the significant differences detected when microhabitats were taken into account (see Cappo *et al.* 2009a). All other conventions follow Figure 28.

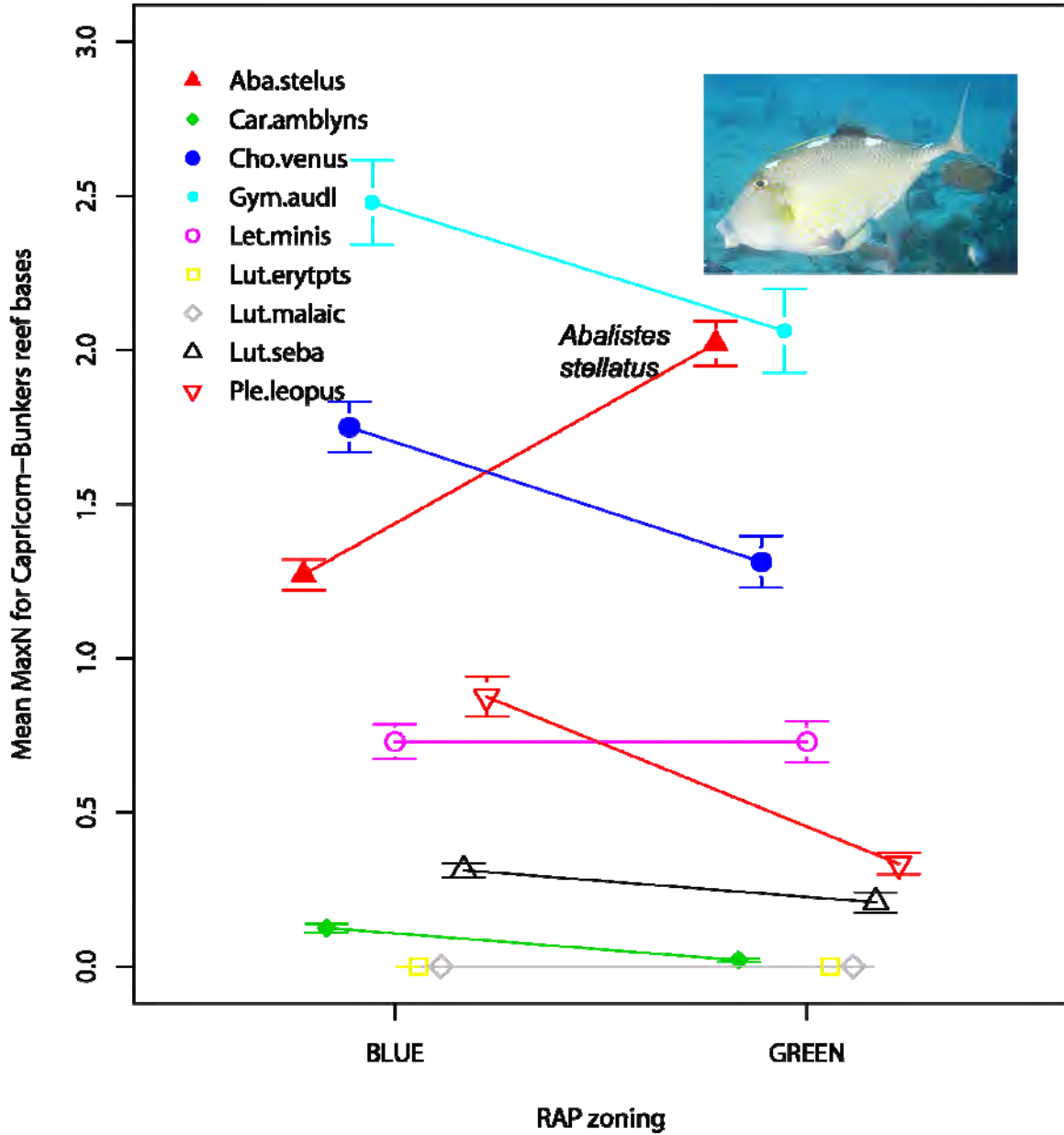


Figure 33. Plots of the means, with 95% Confidence Intervals, for the key target and bycatch species sighted in the single sampling expedition to the 4 pairs of reef bases on the sandy shelf of the Capricorn-Bunker group (see Cappo *et al.* 2009a). Numbers were very small, but there appeared to be less target species, on average, around the reef bases closed to fishing in 2004. These averages hide the significant differences detected when the availability of coral-dominated microhabitats were taken into account (see Cappo *et al.* 2009a). All other conventions follow Figure 28.

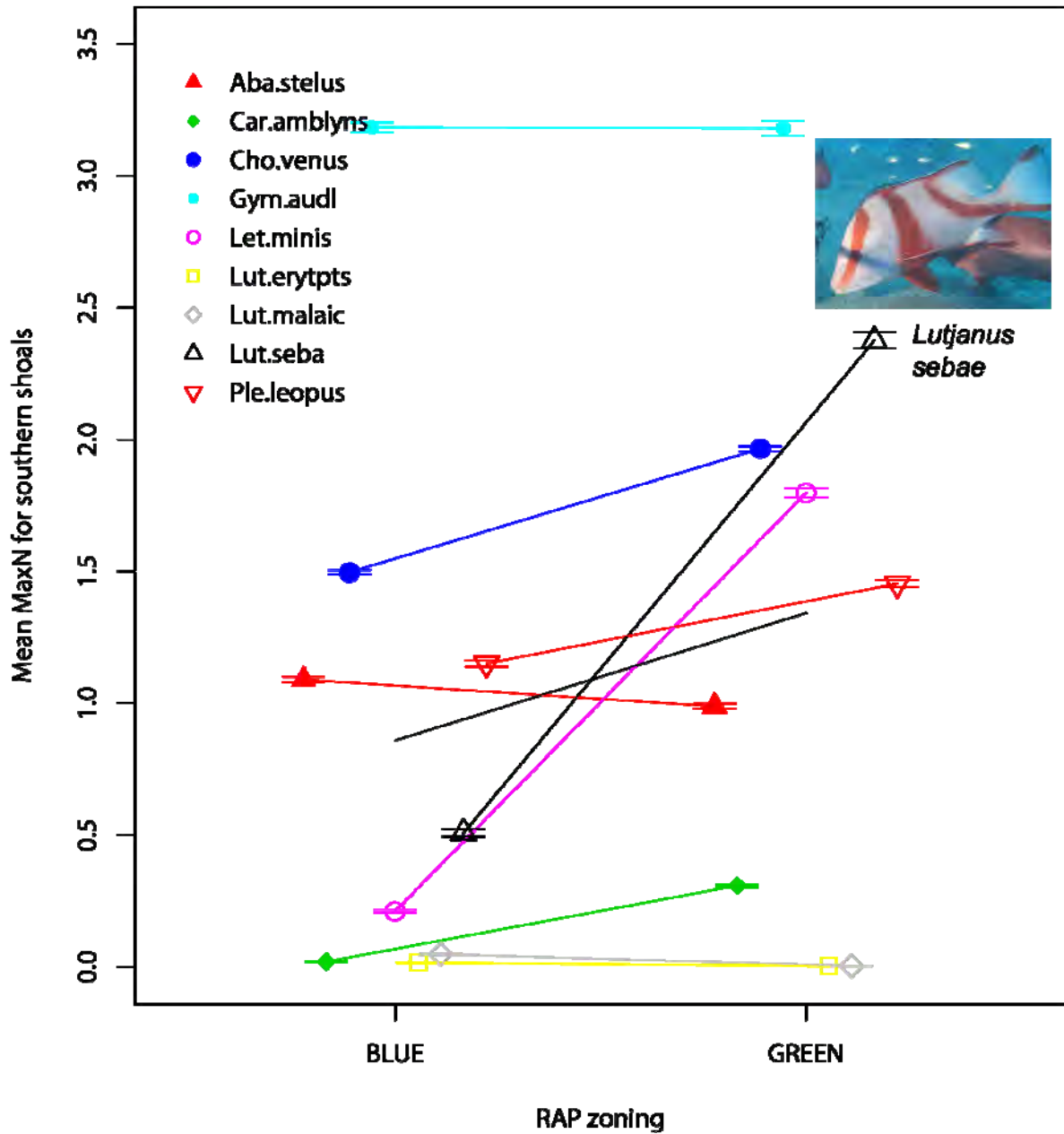


Figure 34. Plots of the means, with 95% Confidence Intervals, for the key target and bycatch species sighted in the repeated sampling expedition to the 2 pairs of discrete banks in the Capricornia region (see Stowar *et al.* 2008). A general trend line is shown in the centre of the plot. There were strong, significant differences in abundance of several key target species on the banks closed to fishing in 2004. These differences prevailed when the availability of coral-dominated and “megabenthos garden” microhabitats were taken into account. All other conventions follow Figure 28.

Comparison of length compositions on southern banks from stereo-video measurement

Many fewer fish were available for some target groups on shoals open to fishing, but maximum sizes were generally seen in "green" zones (Table 4).

Table 4. Summaries of the median and quantiles in the *N* measurements of the six species divided by zoning (open or closed to fishing), and year. There were insufficient red-throat emperor (*Lethrinus miniatus*) sighted on SBRUVS in 2007 to make comparisons.

species	Year	Zone	Min.	2nd Qu.	Median	3rd Qu.	Max.	N
<i>P. leopardus</i>	2007	Open	270.9	377.2	434.9	529.3	665.5	83
	2009	Open	348.4	442.4	480.9	598.1	652.4	39
	2007	Closed	197.8	311.5	418.8	479.5	710.6	84
	2009	Closed	307.9	435.1	507.4	555.1	730.1	126
<i>L. miniatus</i>	2009	Open	249.2	276.3	306.6	407.2	456.6	34
	2009	Closed	233.6	350.8	388.9	426.9	564.9	136
<i>L. sebae</i>	2007	Open	350.2	466.3	480.2	607.5	839.1	37
	2009	Open	341.7	488.4	516.1	529.0	554.7	55
	2007	Closed	171.6	415.6	487.7	565.3	918.5	227
	2009	Closed	264.2	439.1	487.5	559.9	771.4	406
<i>C. venustus</i>	2007	Open	132.4	270.0	295.1	320.0	411.1	63
	2009	Open	141.2	298.5	331.4	348.6	498.7	107
	2007	Closed	158.0	285.9	321.1	356.0	462.4	161
	2009	Closed	206.7	308.8	338.2	372.3	591.2	220
<i>A. stellatus</i>	2007	Open	205.2	293.2	310.9	330.2	444.0	41
	2009	Open	292.0	354.4	372.3	407.3	434.5	59
	2007	Closed	175.8	277.1	328.7	365.1	460.7	51
	2009	Closed	262.7	291.4	330.9	382.1	479.6	62
<i>G. audleyi</i>	2007	Open	186.7	247.8	261.9	277.8	322.2	158
	2009	Open	203.0	251.0	260.5	272.1	315.9	168
	2007	Closed	182.0	246.9	261.6	280.6	325.0	321
	2009	Closed	221.1	243.3	268.6	278.8	315.1	89

Length-frequency distributions

It was impossible to either avoid repeated measurements of the same individual fish, or to distinguish individuals on the basis of measurement times, lengths and associated errors. Instead the shapes of the length compositions in Figure 35 to Figure 40 can be compared between zones to detect differences. The number, location and shapes of the length modes gave us confidence that stereo-video measurements were a useful tool to examine effects of removal by fishing and other influences.

There were clear differences in the shape of the length compositions for the coral trout, red emperor, red-throat emperor and Venus tuskfish (Figure 35 to Figure 39). There were up to 9 clear length modes for coral trout that agreed well with knowledge of length-at-age (Begg *et al.* 2005). All these major target species were both larger and in higher proportions at lengths above the legal minimum size at first capture. An examination of the right-hand Y-axis on these plots shows much fewer fish were available for measurements in the shoals open to fishing (see summaries in Table 4). In contrast, the “non-target” starry triggerfish and collared sea bream showed no major displacement amongst modes between zones.

The differences in length compositions of “target” species cannot be wholly attributed to removals by line-fishing, because there may have been natural variability amongst zones in recruitment and fish growth. These natural influences may be density-dependent (e.g. Adams *et al.* 2000; Williams *et al.* 2007).

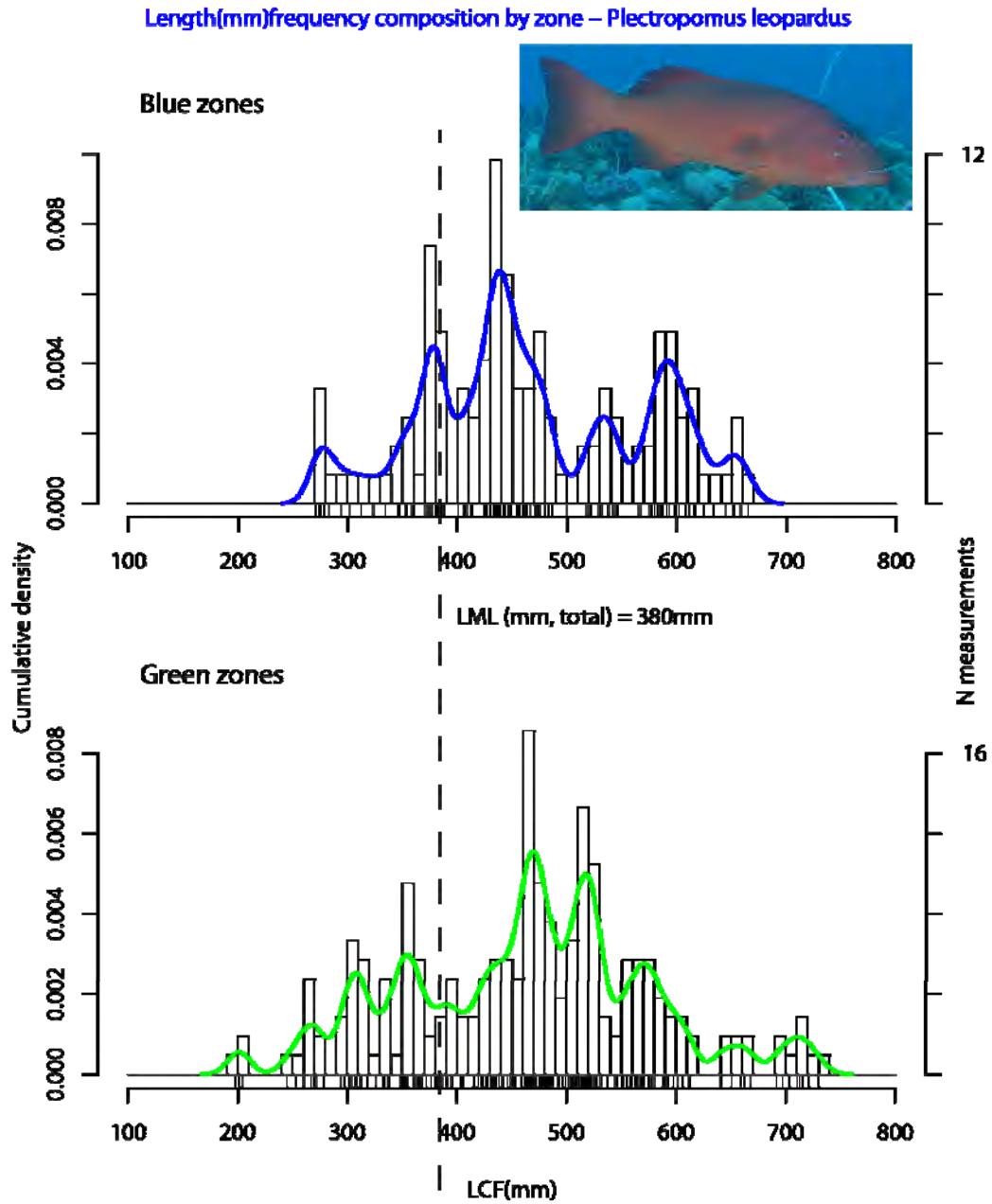


Figure 35. Histogram of stereo-video measurements (all shoals and years pooled) for the coral trout *Plectropomus leopardus* showing the legal size limit at first capture (LML=380 mm). The lines, coloured by zoning status, are empirical cumulative density functions (ECDF) that represent length modes. The rug on the x-axis shows individual measurements.

Length(mm)frequency composition by zone – *Lutjanus sebae*

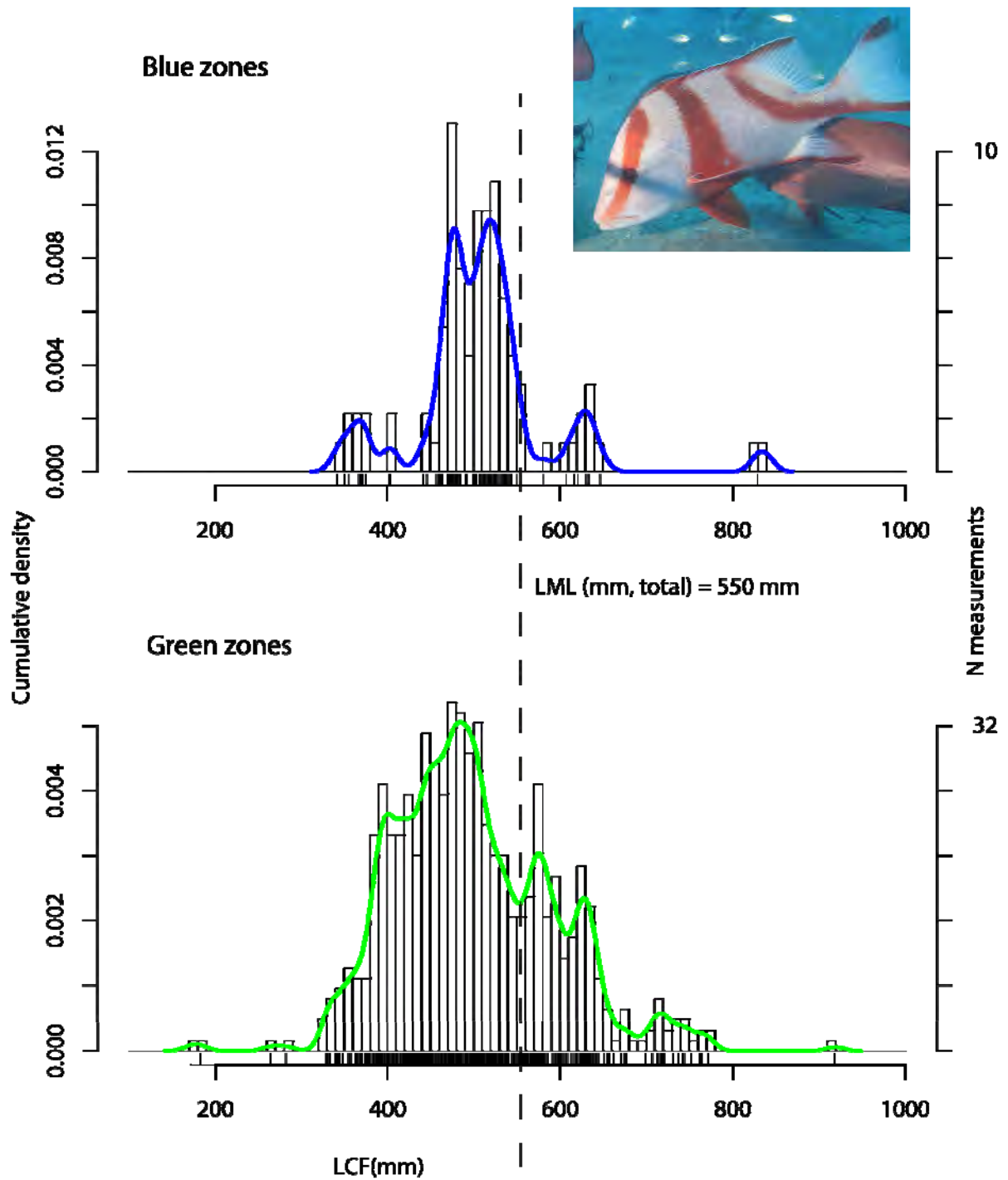


Figure 36. Histogram of stereo-video measurements for the red emperor *Lutjanus sebae* showing the legal size limit at first capture (LML=550 mm). All other conventions follow Figure 35.

Length(mm)frequency composition by zone – *Choerodon venustus*

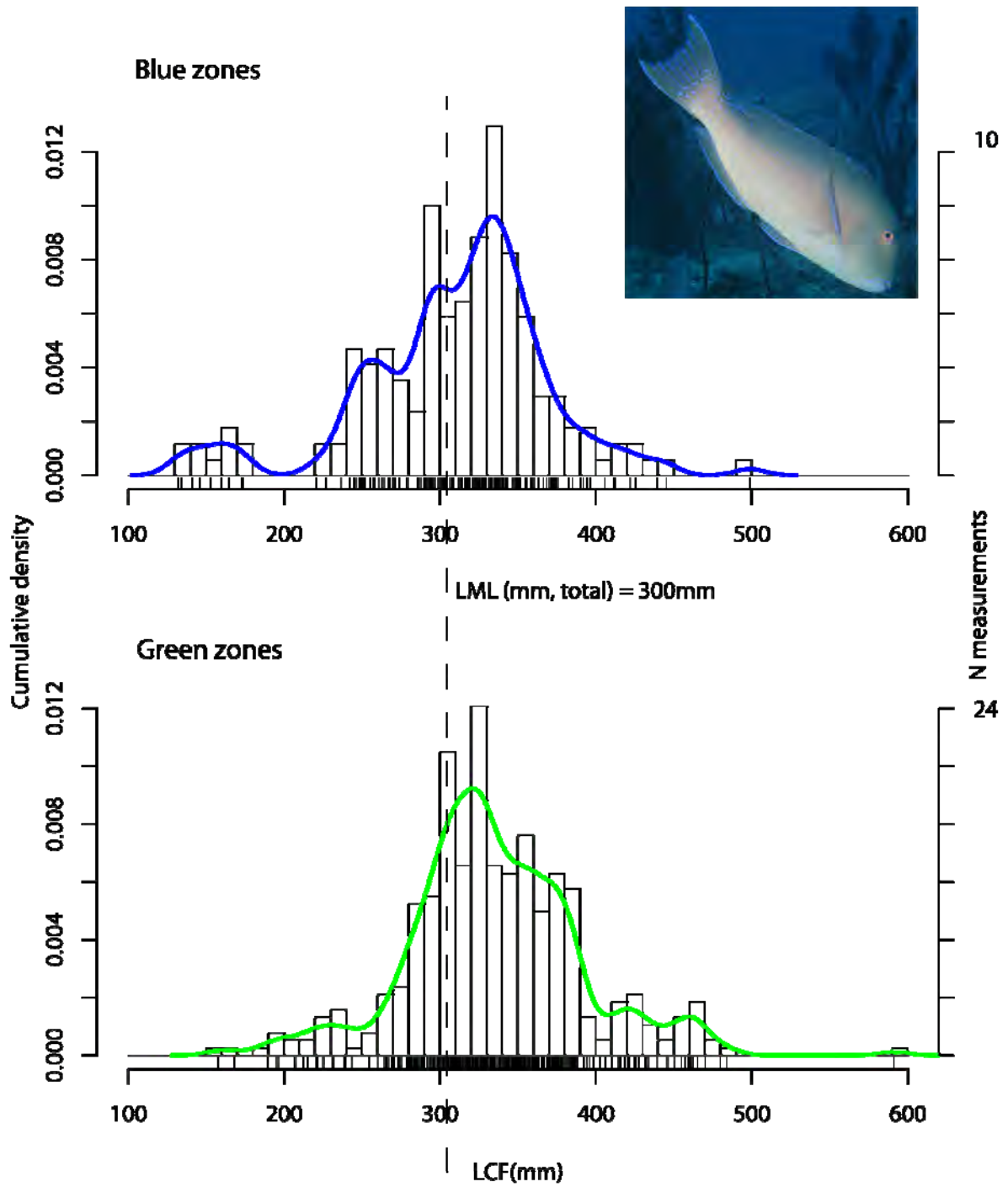


Figure 37. Histogram of stereo-video measurements for the Venus tuskfish *Choerodon venustus* showing the legal size limit at first capture (LML=300 mm). All other conventions follow Figure 35.

Length(mm)frequency composition by zone – *Lethrinus miniatus*

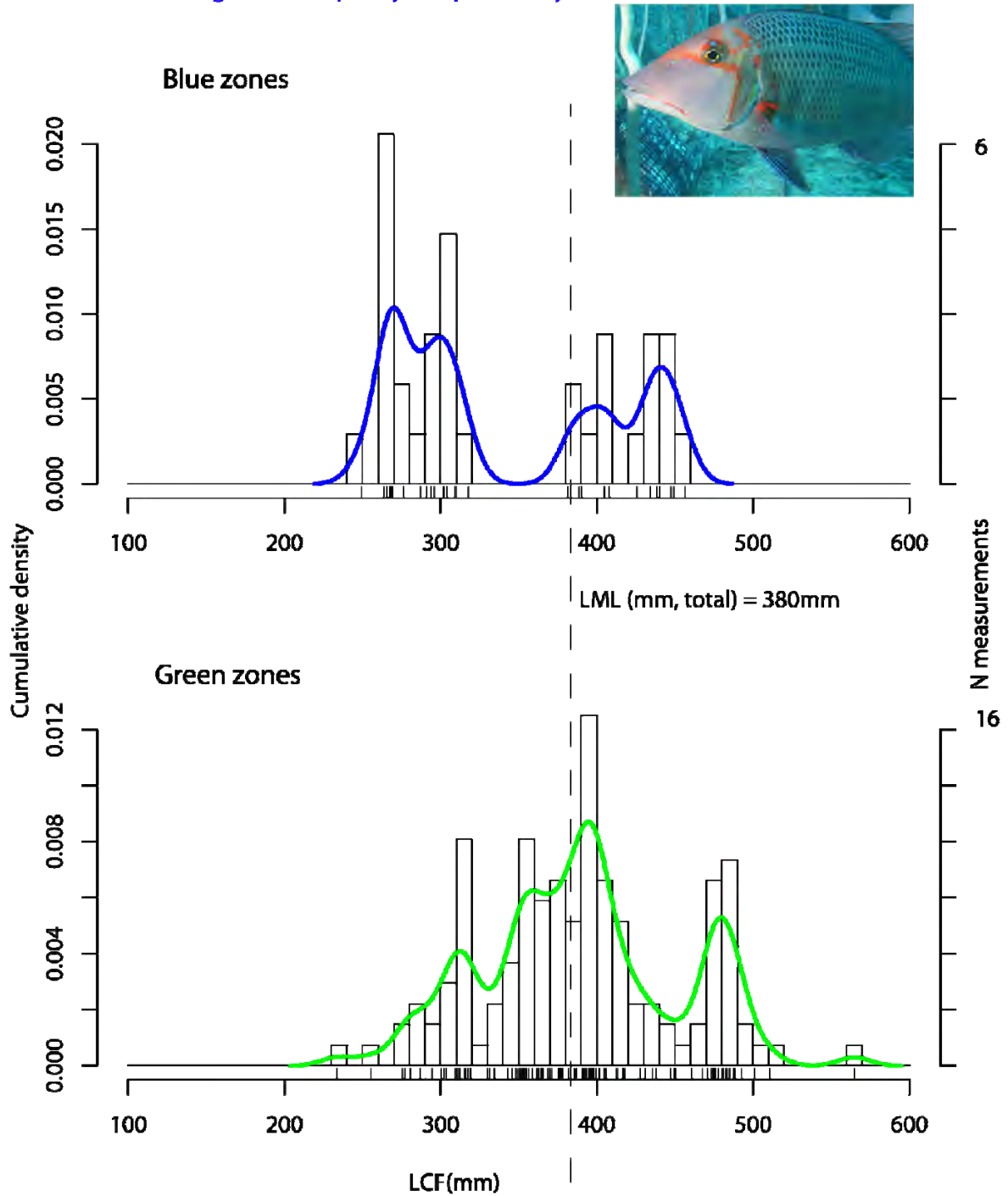


Figure 38. Histogram of stereo-video measurements for the red-throat emperor (*Lethrinus miniatus*), showing the legal size limit at first capture (LML=380 mm). All other conventions follow Figure 35.

Length(mm)frequency composition by zone – *Abalistes stellatus*

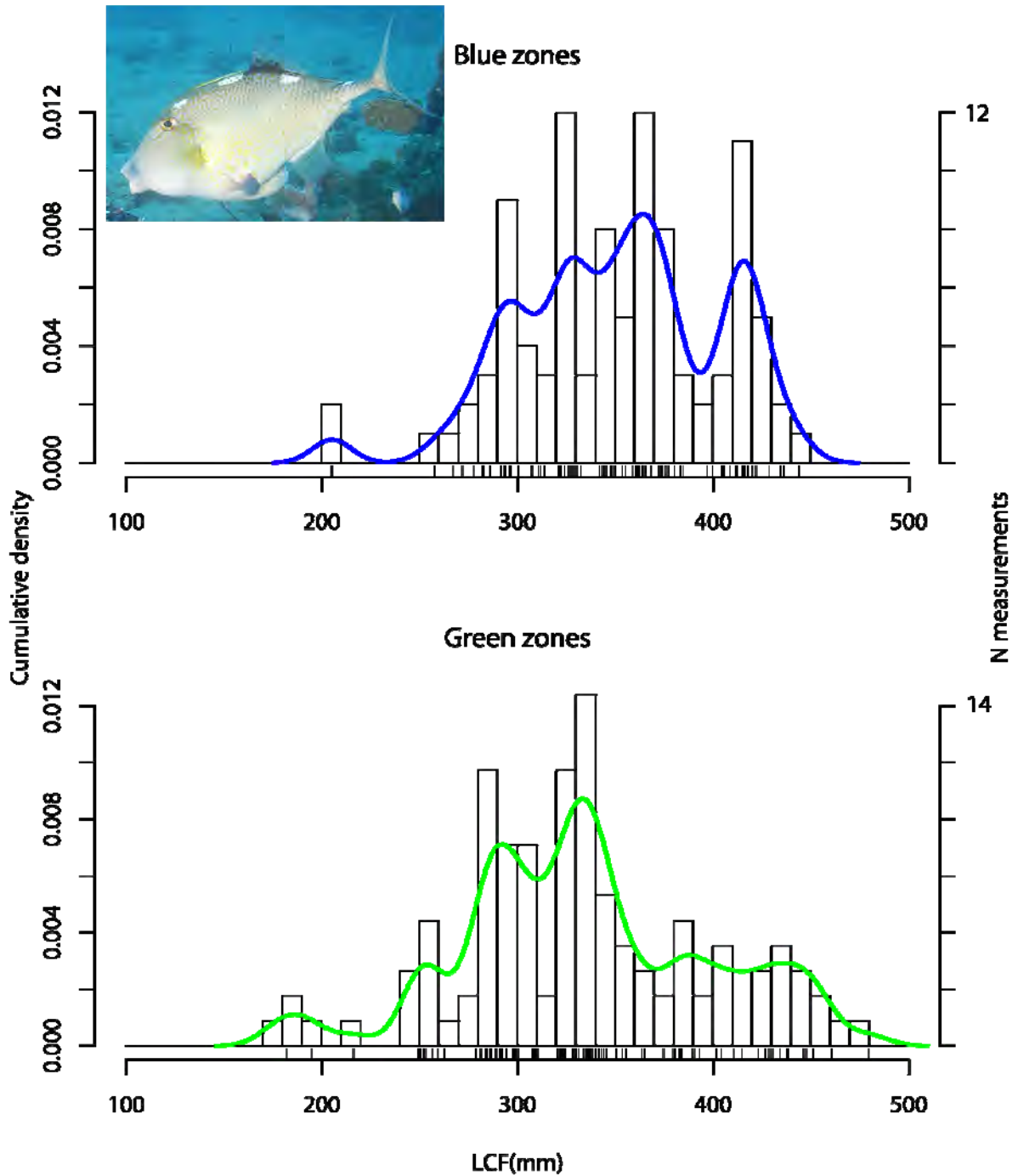


Figure 39. Histogram of stereo-video measurements (both techniques pooled) for the starry triggerfish (*Abalistes stellatus*). There is no legal size limit at first capture for this species, which is treated with extreme disdain by fishermen if caught. All other conventions follow Figure 35.

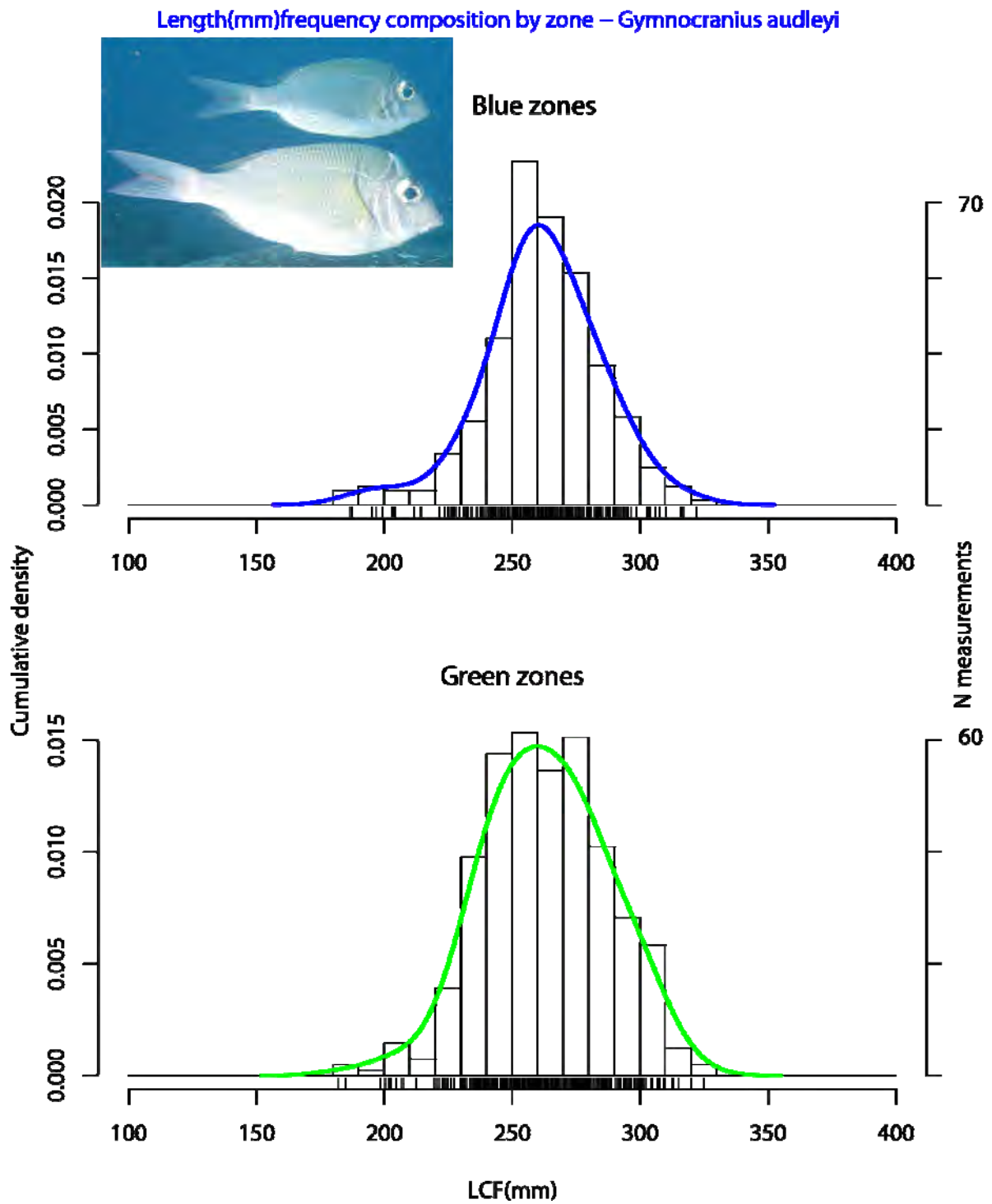


Figure 40. Histogram of stereo-video measurements for the collared sea bream (*Gymnocranius audleyi*). There is no legal size limit at first capture listed specifically for this species, which is not a favoured target, but an LML of 250mm applies to unspecified “sweetlips and emperors” in the GBRMP. All other conventions follow Figure 35.

Metadata records and communication activities

Metadata

The following metadata records have been mounted on the **e-atlas**

1. **EFFECTS OF CHANGES IN GREAT BARRIER REEF MARINE PARK ZONING PLANS ON DEEP SHOALS OFF CARDWELL (MTRSF PROJECT 4.8.2)**
<http://data.aims.gov.au/geonetwork/srv/en/metadata.show?uuid=fd9eeebc-9476-44d4-aeb5-c87423e604a1>
2. **EFFECTS OF CHANGES IN GREAT BARRIER REEF MARINE PARK ZONING PLANS ON DEEP SHOALS OFF CAIRNS (MTRSF PROJECT 4.8.2)**
<http://data.aims.gov.au/geonetwork/srv/en/metadata.show?uuid=1ccbf455-e826-4e13-852e-4ae20f3bfbe0>
3. **EFFECTS OF CHANGES IN GREAT BARRIER REEF MARINE PARK ZONING PLANS ON THE 'MAGNETIC SHOALS', OFF TOWNSVILLE (MTRSF PROJECT 4.8.2)**
<http://data.aims.gov.au/geonetwork/srv/en/metadata.show?uuid=df3b2e47-3e3c-4323-a376-38620f1418b4>
4. **EFFECTS OF CHANGES IN GREAT BARRIER REEF MARINE PARK ZONING PLANS ON SOUTHERN SHOALS - CAPRICORN-SWAINS-POMPEY GROUPS (MTRSF PROJECT 4.8.2)**
<http://data.aims.gov.au/geonetwork/srv/en/metadata.show?uuid=1b773e11-7d77-4da4-a04b-5bb627e376fa>
5. **EFFECTS OF CHANGES IN GREAT BARRIER REEF MARINE PARK ZONING PLANS ON MID-SHELF SHOALS (MTRSF PROJECT 4.8.2)**
<http://data.aims.gov.au/geonetwork/srv/en/metadata.show?uuid=6c3302ea-4955-470a-9922-ae5207f02f63>

Journal article

McCook LJ, Ayling T, **Cappo M**, Choat JH, Evans RD, Freitas DMDe, Heupel M, Hughes TP, Jones GP, Mapstone B, Marsh H, Mills M, Molloy F, Pitcher CR, Pressey RL, Russ GR, Sutton S, Sweatman H, Tobin R, Wachenfeld DR, Williamson DH (2010) Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. Proc Natl Acad Sci USA. PNAS published online before print February 22, 2010, doi:10.1073/pnas.0909335107

Link to PNAS website: <http://www.pnas.org/content/early/2010/02/18/0909335107.abstract>

Media

Newspaper article: "Courier Mail" (February 6, 2010) mounted on web at:

<http://www.couriermail.com.au/news/queensland/reefcam-captures-deep-sea-drama-as-shark-stalks-sea-snake/story-e6freoof-1225827264339>

Radio Interviews:

M. Cappo, BBC London World News (February 6, 2010),

M. Cappo, ABC "Drive" program (March 1, 2010) at:

http://blogs.abc.net.au/queensland/2010/03/what-lurks-below-on-the-great-barrier-reef.html?site=northqld&program=north_queensland_drive

Television Interview: M. Cappo, Channel 7 Regional News (February 10, 2010)

Public Presentations

M. Cappo: Townsville Region Local Marine Advisory Committee (LMAC) (March 11, 2010)

M. Cappo: Burdekin Volunteer Marine Rescue (June 9, 2010)

P. Doherty: CERF Meeting, Canberra (May, 2010)

Discussion

Repeated sampling of southern banks and Cardwell shoals

The previous comparison of the southern banks by Stowar *et al.* (2008) showed strong evidence that the abundance of the species prized most by recreational and commercial line fishers were, on average, approximately two times greater on the southern shoals closed to fishing (green zones) relative to those open to fishing (blue). Whilst the responses to zoning of the “target” species varied in magnitude, they all showed increases. Five of these species showed statistically significant increases at the 5% level when means were compared. The consistency of the response of these target fishes both individually and when aggregated strongly suggested an effect of zoning.

The repeated sampling reported here, at both very small spatial scales and wider, random placements of BRUVS, indicates that these two-fold differences have been maintained. In fact, the differences between “blue” and “green” shoals has widened between 2007 and 2009 on the Warregoes pair of southern banks, as populations have declined on the fished bank and increased on the closed bank.

The Cardwell shoals are very small, discrete rocky outcrops inhabited mainly by juvenile/sub-adult stages of lutjanid sea perches that migrate across-shelf to deeper adult habitats (see Mapleston *et al.* 2006). Repeated sampling in 2006, 2007 and 2010 showed an increase from year to year in the overall numbers of these “target” species on Brook shoal.

Regional differences in the effects of zoning reflect shoal type

The common expectation of marine protected areas is to produce increased numbers and biomass of species vulnerable to fishing (see Mapstone *et al.* 2005), yet the results presented here showed the opposite trend for several species and regions. The mean number of large-mouth and small-mouth nannygai on diffuse shoals *open* to fishing off Townsville vastly exceeded the numbers on the diffuse shoals *closed* to fishing in 2004. There appeared to be about 1.5 times *less* coral trout around the reef bases of the Swains group closed to fishing in 2004, and there appeared to be *less* target species, on average, around the reef bases in “green zones” of the Capricorn-Bunker group.

This use of global means hides the significant differences detected when microhabitats were taken into account in comparisons (see Stowar *et al.* 2008, Cappo *et al.* 2009a), but does serve to illustrate the point that there was no single, simple trend in the effect of the RAP 2004 zoning on “shoals”. In the case of the reef bases in the south, the recognition of microhabitat types in analyses showed that target species were, in fact, about 1.5 times more abundant in the coral-dominated habitats of all three reef groups.

A general trend line showed strong, significant differences in abundance of several key target species on the southern banks closed to fishing in 2004. These discrete, submerged banks are very large and have high cover of hard and soft corals on the tops and megabenthos (such as sea whips, gorgonians and sponges) around their bases. They are isolated from each other by large tracts of open, sandy seabed and can be confidently predicted to be ideal sites for pair-wise comparisons of the effects of zoning on fish populations.

However, they are most probably not a good representation of the small, diffuse “patches” of low-relief that are key “shoal” grounds for the three lutjanid “reds” species line-fished off Townsville and Cairns. Anglers suspect that these fish rove between such patches to feed and shelter, but the lack of catches on any particular “mark” cannot be distinguish between

an emigration of target species or lack of feeding activity and unwillingness to take a baited hook at a particular time.

The southern banks resemble the isolated reef “units” utilized in powerful experiments that manipulated fishing effort in the GBR line-fishery (see Mapstone *et al.* 2005), but they do not represent well the deep reef bases compared in ARP 2 and ARP 3. For example, the emergent reef flats and reef slopes of the 16 pairs of reefs in the Pompeys, Swains and Capricorn-Bunkers were easily recognizable as separate entities in the study by Russ *et al.* (2008), but we found in ARP3 that the reef bases were sometimes contiguous patches of rugose habitat that extended between reefs within blue-green pairs.

In some pairs, such as Wade Reef and 22084S in the Swains, “blue” and “green” reefs were separated only by narrow channels 10’s of metres wide. Elsewhere, in the Capricorn-Bunkers, one reef was “half green” and “half blue”. Whilst coral trout may remain sedentary at small spatial scales, it was almost certain that the “shoal” species (especially grey reef sharks and lethrinids) move freely between such reefs along suitable corridors of habitat.

Effects of zoning on length compositions

Our numerous measurements of target species using stereo-video showed that was a larger proportion of red emperor, coral trout, venus tuskfish and red-throat emperor above the legal minimum size at first capture on the southern banks closed to fishing. In addition, there was clear evidence that the larger, and largest, individuals (the “super spawners”) of these target species were accumulating on the “green” banks. A compelling account of the same effect of removals by fishing for *Plectropomus* and *Choerodon* in the marine park zones of the Abrolhos Islands of Western Australia was reported by Watson *et al.* (2007, 2009). Fish size has been shown by Begg *et al.* (2005) to be a major indicator of lower fishing mortality in MPAs.

In contrast, the “control species” starry triggerfish and collared sea bream showed no major displacement amongst modes between zones -- perhaps with the exception that triggerfish were larger, on average, in the green zones. We recommend that stereo-video techniques will be a powerful tool to detect effects of zoning in the GBRMP on the major target species, especially if they are repeated through time to account for recruitment and growth in analysis of length modes.

We expect future effects of zoning will manifest in the shape of length compositions at both juvenile and adult ends of the spectrum, as well as the height of peaks and proportion of individuals above the legal minimum size at first capture.

Future directions for research

The regional differences in the “effectiveness” of closure to fishing depends largely on two factors that should be addressed in future research.

Firstly, microhabitat types must be accounted for in models comparing mean abundances. This factor was identified in ARP3 (see Cappo *et al.* 2009a) who found that there is little merit in comparing fish populations on diffuse, low-relief shoals with discrete, submerged banks. BRUVS interrogation software has now been upgraded to incorporate useful measurements of habitat “cover” in the field of view, so it is desirable to re-visit earlier tapes from ARP1 and ARP 2 to make such rapid assessments of microhabitats and then incorporate them into models of the effects of zoning.

Secondly, the target species can be mobile – especially when the habitat is either contiguous stretches of reef base or diffuse widespread shoals. Tag returns from juvenile small-mouth and large-mouth nannygai have shown a strong cross-shelf movement from nursery habitats (see Mapleston *et al.* 2006) and it is probable that the adults also forage between “marks” in areas where shoals are diffuse. On the other hand, repeated recaptures (up to 5 times) have been made of red emperor on “good fish-holding structures” (pers. comm. Bill Sawynok AusTag).

The technology now exists to trace this movement within and between management zones (Meyer *et al.* 2010). The long-term movements of large predators can be tracked by implanting them with small transmitters and deploying underwater monitoring devices inside and outside MPA boundaries. For example, Meyer *et al.* (2010) found that a variety of reef fishes tagged inside an MPA swam back and forth across the boundary intersecting continuous reef, but a wide sandy channel functioned as a natural barrier to movements across park boundaries.

Conclusions

A number of explanations can be invoked for the different patterns and regions described in this report. Fish can move between zones, political influences near townships may have led to closure of “poorer” shoals, and there may be very low levels of fishing effort (within the bounds of natural disturbances) in remote areas such as the Swains. We had no access to useful statistics on fishing effort on the shoals, and levels of poaching were unknown. It was also possible that some “green” shoals in our pairwise comparisons were always better habitats and supported more fish than those open to fishing.

However, this project has clearly demonstrated that numbers and biomass do accumulate (through more, larger fish) in submerged shoal habitat in green zones. The lack of a consistent trend amongst regions, pairs of shoals, species groups, and individual species, should not be cited as some sort of failure of management or science – nor should each shoal be treated as a “special case”. Rather, the limits to pairwise comparisons of “shoals” should be recognized and incorporated into future research questions.

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Appendix

Appendix 1. Identity of “all target species”. “Prized target” species are highlighted in boldface type.

Family	Genus	Species
Labridae	<i>Bodianus</i>	<i>perditio</i>
	<i>Choerodon</i>	<i>cephalotes</i>
	<i>Choerodon</i>	<i>schoenleinii</i>
	Choerodon	venustus
Lethrinidae	<i>Lethrinus</i>	<i>laticaudis</i>
	Lethrinus	miniatus
	<i>Lethrinus</i>	<i>nebulosus</i>
Lutjanidae	<i>Aprion</i>	<i>virescens</i>
	Lutjanus	erythropterus
	Lutjanus	malabaricus
	Lutjanus	sebae
	<i>Pristipomoides</i>	<i>multidens</i>
Serranidae	<i>Epinephelus</i>	<i>coioides</i>
	<i>Epinephelus</i>	<i>undulatostratus</i>
	<i>Plectropomus</i>	<i>laevis</i>
	Plectropomus	leopardus
	<i>Plectropomus</i>	<i>maculatus</i>
	<i>Variola</i>	<i>albimarginata</i>
	<i>Variola</i>	<i>louti</i>
Sparidae	Pagrus	auratus

Appendix 2. Identity of major "bycatch species".

Family	Scientific Name
Carangidae	<i>Carangoides chrysophrys</i> <i>Carangoides fulvoguttatus</i> <i>Carangoides gymnostethus</i> <i>Caranx ignobilis</i> <i>Gnathanodon speciosus</i> <i>Pseudocaranx dentex</i>
Carcharhinidae	<i>Carcharhinus albimarginatus</i> <i>Carcharhinus amblyrhynchos</i> <i>Galeocerdo cuvier</i> <i>Triaenodon obesus</i>
Ginglymostomatidae	<i>Nebrius ferrugineus</i>
Hemiscylliidae	<i>Chiloscyllium punctatum</i>
Labridae	<i>Choerodon cyanodus</i> <i>Choerodon fasciatus</i>
Lethrinidae	<i>Gymnocranius audleyi</i> <i>Gymnocranius grandoculis</i> <i>Lethrinus genivittatus</i> <i>Lethrinus ravus</i> <i>Lethrinus rubrioperculatus</i> <i>Lethrinus semicinctus</i>
Lutjanidae	<i>Lutjanus adetii</i> <i>Lutjanus carponotatus</i> <i>Lutjanus vitta</i> <i>Symphorus nematophorus</i>
Rhynchobatidae	<i>Rhynchobatus djiddensis</i>
Scombridae	<i>Gymnosarda unicolor</i> <i>Scomberomorus commerson</i>
Serranidae	<i>Cephalopholis boenak</i> <i>Epinephelus fasciatus</i> <i>Epinephelus quoyanus</i>