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Bias in evaluating the effects of marine protected areas: the importance of baseline data for the Galapagos Marine Reserve

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SUMMARY

Analysis of ecological baseline data collected for key resource species within the Galapagos Marine Reserve indicates that variation in animal density associated with the location of fully protected zones can be comparable to protected area effects. Even with a high level of interspersion between conservation, tourism and fishing management zones, major differences in densities of economically important species were evident between zone types prior to enforcement of fishing restrictions. Densities of the most valuable fishery resource, sea cucumbers, were three times higher in zones that remained open to fishing compared to 'no-take' conservation zones, and densities of sharks were five times higher in tourism zones than fishing or conservation zones. These results highlight bias in the socio-political processes that can accompany selection of marine protected areas, where fishers attempt to minimize perceived impacts on their livelihood by locating large protected zones in resource-poor areas, and tourism operators and sport divers argue for protection of areas containing atypically-interesting features. Bias in the location of fully protected zones can seriously confound 'control-impact' field investigations when data prior to prohibitions on fishing are lacking, including meta-analyses, which are dominated by such potentially systematically biased studies.

Keywords: *Isostichopus fuscus*, meta-analysis, *Mycteroperca olfax*, sea cucumber, shark, spiny lobsters

INTRODUCTION

Largely as a consequence of widespread declines in inshore biodiversity and diminishing confidence with traditional single-species approaches to fisheries management, a growing number of fully protected or 'no-take' marine reserves are being proclaimed worldwide (Roberts & Hawkins 2000). Concurrently, research on marine reserves is accelerating rapidly (Schrope 2001; Lubchenco *et al*. 2003), with a more than 10-fold increase in publication output between 1991 and 2001 (Willis *et al*. 2003). Scientific benefits generated from marine reserve studies include knowledge gained about the unfished state of ecosystems, and also improved ecological theory through the opportunity to undertake manipulative predator (human) exclusion experiments at vast, and ecologically meaningful, spatial scales (Walters & Holling 1990).

Despite scientific field studies overwhelmingly identifying positive features of marine reserves (Russ & Alcala 1996; Edgar & Barrett 1999; McClanahan & Mangi 2000; Roberts *et al*. 2001; Kelly *et al*. 2002), many fishers remain sceptical of claims of benefits (Ward *et al*. 2001). This scepticism derives partly from the poor empirical foundation of the science of marine reserves, coupled with inconsistent mathematical models (Sumaila 1998; Gerber *et al*. 2002; Doyena & Béné 2003; Norse *et al*. 2003), and a general primacy of theory over factual detail.

The quality of field studies of marine reserves also is highly variable (Willis *et al*. 2003). To date, no definitive experiment has been performed that includes adequate experimental design ('before-after control-impact'), habitat comparability, replication (taxa, samples and sites), fishing mortality estimates (inside and outside), mid-to-long-term (5–20 years) monitoring, and regional replication for generality (Russ 2002). The majority of investigations have involved 'control-impact' comparisons of sites in reserves with those nearby.

The extent to which 'control-impact' studies dominate the marine reserve literature is indicated by a recent meta-analysis (Halpern & Warner 2002; Halpern 2003), which included 89 independent studies of marine reserve effects, nearly all of which were 'control-impact' type. Only 17 studies included 'before-after' measurements, only nine studies included both 'before-after' and 'control-impact' data, and only seven studies included multiple measurements of change through time. The small proportion of marine reserve studies that include a temporal component contrasts with increasing

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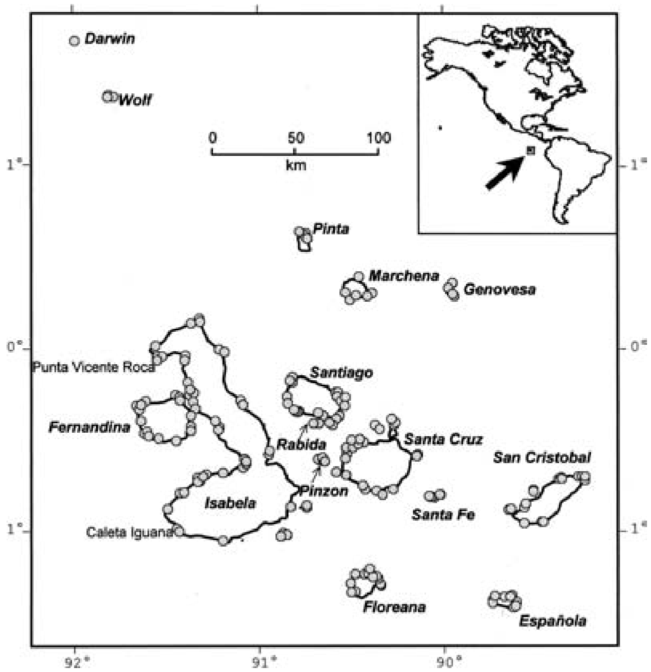

Figure 1 Sites within the Galapagos Marine Reserve, where we censused fish and macroinvertebrates densities during 2000 and 2001. The majority of sites are overlapping and so not distinguished.

recognition amongst designers of other types of environmental impact studies that baseline information can prove critically important (Osenberg *et al.* 1994; Underwood 2000).

In the present study we assess the importance of baseline information for evaluation of protected area effects within the Galapagos Marine Reserve (GMR), a large oceanic marine protected area that spans nearly 133 000 km^2 in the eastern tropical Pacific (Fig. 1). Following a consensus-based participatory process (Heylings & Cruz 1998), a zoning scheme was introduced within the GMR in 2000 with the aims to: (1) reduce conflicts between uses, principally tourism, fishing and scientific research, (2) protect marine biodiversity, and (3) promote sustainable uses (Heylings *et al.* 2002). Four coastal zone types are recognized: (1) strict no-take areas, where only scientific use is allowed (conservation); (2) no-take areas where tourism, recreation and education are permitted (tourism); (3) extraction areas under traditional fisheries management regimes (fishing); and (4) mixed areas with rotating closures or under special management in the vicinity of ports and harbours.

Agreement on zones was achieved amongst a core group of stakeholders and managers, working around two basic principles: substantive and active participation and adaptive management. Permanent representatives of four major groups of stakeholders participated in negotiations: (1) local artisanal fishers, (2) tourism operators, (3) science, conservation and education experts, and (4) management authorities. Discussions were guided by professionals in facilitation and conflict resolution over a period of two years at a series of workshops and field excursions where the main groups presented, defended and negotiated proposals for their preferred zoning schemes (Heylings *et al.* 2002).

Selection and siting of the conservation zones was largely based on expert opinions within the science and conservation group (i.e. a 'Delphic' approach). The main aim was to protect a range of sites of different sizes and distances apart that were representative of different shallow habitats in each of five locally-recognized biogeographic zones (Harris 1969; Heylings *et al.* 2002); however, useful technical data on shallow benthic biodiversity were limited, particularly when compared to information on pre-existing fisheries and tourism usage. Most tourism sites were already in place, either as designated sites or those traditionally used by the industry. Regulated fishing (by gear, season, quotas and minimum sizes) occurred throughout the whole archipelago until 2000.

Agreement was eventually reached by consensus on the boundaries of a total of 130 management zones, comprising 14 separate conservation zones (no fishing, no tourism), 62 tourism zones (no fishing, tourism), 45 fishing zones (fishing, no tourism) and 9 mixed management zones. Interspersion of these zones across the archipelago was considerable; the 15 largest islands shown in Figure 1 all include tourism and fishing zones, and 10 also include conservation zones. The wide distribution of zones should provide near ideal experimental conditions for assessing reserve effects. Conservation, tourism, fishing and mixed management zones encompass 8%, 9%, 77% and 5% of the total coast, with mean coastline lengths per zone of 9.3, 2.7, 28.5 and 9.4 km, respectively (Heylings *et al.* 2002). Individual zones range in size from small offshore islets to a 70 km span of coast.

Broad-scale ecological surveys of plant and animal densities on shallow reefs were undertaken across the GMR in 2000 and 2001, with a partial aim to provide a baseline data set for assessment of changes in different zone types through the long term, and also to assess whether conservation zones were located optimally, or should be changed when the provisional zoning scheme becomes permanent (Danulat & Edgar 2002). Although fishing for sea cucumbers and spiny lobsters became illegal in protected zones towards the start of the period when our baseline surveys were conducted (May and September 2000, respectively), many fishers were unaware of boundaries and numerous zone infractions occurred (Altamirano & Aguiñaga 2002). For example, analysis of GPS data logged by observers while onboard boats actively fishing during the 2001 sea cucumber season indicated that *c.* 10% of sites fished lay within conservation zones (Murillo *et al.* 2002). Because of the frequency of infractions, we consider that data described here represent baseline conditions.

We use the baseline data set to describe potential bias associated with protected area location for species of greatest economic significance in Galapagos. For the dive tourism industry, the most important species are requiem sharks (particularly *Carcharhinus galapagensis* and *Triaenodon obesus*), hammerhead sharks (*Sphyrna lewini*) and whale sharks (*Rhincodon typus*) (Zarate 2002). For the fishing industry,

Table 1 Mean density of sea cucumbers (number per 100 m^2) recorded in metre width transects in different management zones of the Galapagos Marine Reserve for the western sector and elsewhere. The standard error of the mean (SE) and number of management zones surveyed in each sector are also shown.

Zone type	*Western sector*			*Northern and eastern sectors*		
	Density	*SE*	*Number of zones*	*Density*	*SE*	*Number of zones*
Conservation	14.0	4.2	5	1.31	0.35	6
Tourism	47.2	13.0	7	1.22	0.24	33
Fishing	42.2	10.9	6	1.47	0.19	25

the most important species are (1) sea cucumber (*pepino de mar*; *Isostichopus fuscus*), (2) spiny lobster (*langosta*; *Panulirus penicillatus, Panulirus gracilis* and *Scyllarides astori*) and (3) a serranid grouper locally called *bacalao* (*Mycteroperca olfax*), comprising approximately 55%, 30% and 5% of the total annual Galapagos catch by value, respectively (Murillo *et al.* 2002; Nicolaides *et al.* 2002). Shark fishing has been prohibited throughout the archipelago since 1989.

METHODS

Densities of fishes and invertebrates were quantified using underwater visual transect methods between May 2000 and November 2001 during research cruises described by Edgar *et al.* (2004*a*). Transect lines were surveyed by diver along defined depth contours between 2 and 20 m depth at 50 islands and islets distributed across the archipelago (Fig. 1). Generally, two different depth contours were surveyed at a single site. For some sites, the two depth strata surveyed were parallel and immediately adjacent to each other, while in other areas depth strata were offset by up to 300 m when divers were working from different boats. Overall, a total of 579 and 569 depth strata were surveyed for fish and macroinvertebrates, respectively. The total number of different management zones censused was 11, 40 and 31 for conservation, tourism and fishing zones, respectively.

A diver initially swam beside a 50 m transect line at a distance of 2.5 m, recording on a waterproof notepad the abundance of fishes in a 5 m wide lane. This process was then repeated on return along the other side of the transect line, with data from the two adjoining sides of the transect added together for each 500 m^2 census block. For the majority (59%) of depth strata, two replicate 500 m^2 m blocks were surveyed and mean data for that depth stratum were used in analyses; however, on 41% of occasions the census block was not duplicated.

Fish census data are affected by a range of biases, including observer error and behavioural responses of fish to divers (DeMartini & Roberts 1982; Thompson & Mapstone 1997; Kulbicki & Sarramega 1999). Such biases were investigated and discussed for the transect methods used here by Edgar *et al.* (2004*b*). Despite the existence of census biases, we consider them to be largely systematic and not greatly confound interpretation of patterns described because data have been used for relative comparisons between different management zones only, and divers each obtained data in the three zone types.

Sea cucumbers, spiny lobsters and other large macroinvertebrates were censused along the same transect lines following fish counts. Divers counted abundances within 100 m^2 blocks (i.e. the 1 m wide lane on both sides of the 50 m transect line). As with fishes, the majority of depth strata were duplicated, and the mean value for the two blocks used in analyses.

Data were analysed using ANOVA after $\log(x+1)$ data transformation and data aggregation to reduce heteroscedasticity. In order to avoid spatial confounding through biased distribution of sites, data were aggregated as the mean density value for each of the 11 conservation zones investigated and for fishing and tourism zones in nearest proximity. A set of mean density values for three adjacent management zone types comprised a regional block. Region was included as a blocking factor in the ANOVA model, with management zone type (three levels: conservation, tourism, fishing) the primary factor of interest. Data from ‘mixed management’ zones within the GMR were not analysed because permitted activities within those areas remain to be defined. The null hypothesis tested was that no difference in density existed between management zone types.

In the case of lobsters and sharks, no animals were observed in some regions; hence those regions were deleted from analyses. In the case of sea cucumbers, the heavily fished western sector of Galapagos (Isla Fernandina and Isla Isabela from Punta Vicente Roca to Caleta Iguana; Fig. 1) was analysed separately. This sector, which yielded 88% of the total sea cucumber catch in 2001 (Murillo *et al.* 2002), possesses cooler water and higher algal productivity than elsewhere in the archipelago as a consequence of upwelling of the Equatorial Undercurrent (Chavez & Brusca 1991; Edgar *et al.* 2004*a*).

RESULTS

With respect to the most valuable fishery species, sea cucumber, observed baseline densities were three times higher in zones open to fishing than conservation zones for the western Galapagos sector of high population densities (Table 1). Differences between zone types were highly significant ($p < 0.001$), as was the regional blocking factor (Table 2). By comparison, non-significant ($p > 0.05$) variation in sea cucumber density existed between zones with low

Table 2 Results of ANOVA for log $(x + 1)$ density of different taxa blocked by region. df = degrees of freedom; MS = mean square; $F = F$-value; $^{***}p < 0.001$, $^{**}0.001 < p < 0.01$, $^{*}0.01 < p < 0.05$.

Taxa	*Factor*	*df*	*MS*	*F*
Sea cucumbers	Zone	2	3.590	24.58***
(western sector)	Region	4	2.400	16.44***
	Error	8	0.150	
Sea cucumbers	Zone	2	0.156	1.36
(other sectors)	Region	5	0.470	4.10*
	Error	10	0.115	
Lobsters	Zone	2	0.023	0.59
	Region	4	0.078	2.02
	Error	8	0.038	
Bacalao	Zone	2	0.165	0.58
	Region	10	1.314	4.63**
	Error	20	0.284	
Sharks	Zone	2	1.272	4.72*
	Region	4	0.368	1.36
	Error	8	0.270	

animal density elsewhere in the Galapagos Marine Reserve (Table 2).

The other important Galapagos fishery resource, spiny lobster, showed a similar pattern, with 2.7 times greater abundance in fished zones compared to conservation zones (Table 3); however, data were highly clumped and some regions were excluded because of an absence of sightings, so the power of the statistical test was low. The difference between zone types was not significant (Table 2). Nor was there a significant difference detected between zones for bacalao (Table 2), a species with almost identical mean densities in different zones (≈ 2.8 per 500 m^2; Table 3). Densities of sharks were five-fold higher in tourism zones than other zones (Table 3), a statistically significant difference ($p < 0.05$; Table 2).

DISCUSSION

The null hypothesis that no difference existed in density of resource species between management zone types prior to prohibition of fishing was rejected for two of the four species examined. In the case of sea cucumbers, the magnitude of baseline differences between zone types would be even greater than measured if fishers were respecting conservation zones because relative densities would have increased within conservation zones during the period between statutory protection and field survey.

A comparable effect size was noted for lobsters; however, in this case the power of the statistical test was inadequate to separate an almost threefold difference between conservation and fishing zones from the null model of no difference. Lobsters were more patchily distributed than sea cucumbers, with animals aggregating in particular crevices, adding to statistical variability and reducing power of tests.

Without baseline surveys, future comparisons of protected versus fished locations in the Galapagos Marine Reserve would be misleading, both as underestimated (sea cucumbers) and overestimated (sharks) assessment of change. For example, in the hypothetical case that a future survey shows no difference in sea cucumber density between conservation and fishing zones in the western sector, then we would logically conclude, in the absence of baseline information, that conservation zones provide little benefit for sea cucumbers. In fact, relative densities would have risen threefold in conservation zones.

Given the high level of interspersion of management zones, the substantial baseline differences in densities for sea cucumber and shark species were unlikely to be caused by random processes. During stakeholder negotiations over zones, fishers acted to minimize large conservation zones being placed in areas with high densities of the most valuable fishery species. Dive tourism operators also successfully negotiated for protection of sites with steep drop-offs and concentrations of pelagic species, where large sharks, which provide the focus for dive tourism trips, are commonly observed. Species of lesser fishery importance, from bacalao down, and sea cucumbers in regions where they occur in low density, were apparently afforded little weight in stakeholder discussions.

The paucity of sites with high sea cucumber density in conservation zones within the Galapagos Marine Reserve invokes the question: 'Do conservation zones, as selected through socio-political negotiations involving stakeholders, protect the full range of habitat types?' The answer will depend in part on the definition of habitat, particularly whether 'shallow reef' represents a single habitat type or is subdivided into finer categories such as reefs with sheer drop-offs (which are attractive to sharks), reefs with local upwelling (which are attractive to sea cucumbers), and reefs dominated by urchin barrens. For Galapagos, the answer will depend on the extent to which patterns of distribution for other plant and

Table 3 Mean number of rock lobsters sighted in 100 m^2 transect blocks, and bacalao (*Mycteroperca olfax*), and requiem and hammerhead sharks in 500 m^2 transect blocks, within different management zones of the Galapagos Marine Reserve. The standard error of the mean (SE) is also shown.

Zone type	*Lobster*		*Bacalao*		*Sharks*	
	Density	*SE*	*Density*	*SE*	*Density*	*SE*
Conservation	0.072	0.033	2.97	1.16	0.06	0.02
Tourism	0.109	0.032	2.86	1.09	0.27	0.16
Fishing	0.195	0.081	2.60	0.32	0.04	0.02

animal species correspond with those for sea cucumbers and sharks. Particular taxa may respond to the same environmental conditions as the important resource species, or be affected by direct or indirect interactions with those species. In these cases, populations are likely to be concentrated either inside or outside protected zones.

We further suggest that a non-random geographic distribution of 'no-take' conservation zones is not specific to Galapagos. Rather, small reserves are often declared around scenically interesting sites following lobbying by divers and tourism operators, whereas large marine reserves tend to be located in resource-poor areas following demands by fishers to minimize perceived impacts on their livelihood. Assuming that the magnitude of baseline effects in the Galapagos Marine Reserve is a useful guide, location bias should be recognized as sufficiently extreme to invalidate some studies lacking 'before' data.

Systematic bias associated with baseline differences in reserve location may explain, at least in part, the surprising finding of Halpern & Warner (2002) in their meta-analysis that marine reserves are effective almost immediately (< 2 yr) and generate effects that persist with negligible change through time. Numerous individual studies contradict this conclusion (for example Halpern & Warner 2002, fig. 3, where the longest two studies show fivefold increases in reserve effects after eight years compared to two years), albeit with substantial variation between species and locations (Russ & Alcala 2003, 2004). In fact, reserve effects that manifest themselves over long timescales may ultimately prove the most interesting, given that an initial build-up of large predators within reserves can lead to unpredictable trophic cascades (Shears & Babcock 2002, 2003; Parsons *et al.* 2004).

A second explanation for Halpern and Warner's (2002) conclusion is that their meta-analysis was affected by the general phenomenon of neutral and negative results tending to be less reported in the scientific literature than positive results (Browman 1999; Kotiaho & Tomkins 2002). Personal experience (G. Edgar) indicates that such 'publication bias' can be substantial, as when publishing results of long-term studies on Tasmanian marine reserves (Edgar & Barrett 1997, 1999). Tasmanian species reported were primarily commercially exploited taxa that exhibited clear trends through time, whereas indistinct trends shown by the majority of species were not mentioned. A similar comment applies to this paper.

The magnitude of differences in overarching conclusions that can be reached in meta-analyses with different data sets, particularly the mix of studies of exploited and non-exploited species, was recognized by Côté *et al.* (2001). They found a non-significant 25% overall increase in fish density in marine reserves in one meta-analysis, whereas an earlier study had indicated a 3.7-fold overall increase (Mosquera *et al.* 2000). By comparison, Halpern (2003) found an approximate doubling in mean population density of animals in reserves. Regardless of which of these three meta-analyses is the more accurate, the range in overall estimates indicates that the magnitude of reserve effects is comparable to the magnitude of baseline differences for important resource species in the Galapagos Marine Reserve.

Although we here question some claims of meta-analyses based on studies that are potentially systematically confounded (and also consider that our scientific interest should have progressed from assessing whether marine reserves have a net enhancement function to issues such as the distribution of responses amongst species), our criticism in no way negates potential usefulness of these analyses when intrinsic constraints and biases in data are taken into account. Similarly, our criticism does not detract from likely conservation management and fisheries benefits of marine reserves. On the contrary, if resource-rich regions are under-represented in marine reserve networks, as was the case with Galapagos sea cucumbers, then meta-analyses based on a predominance of 'control-impact' studies will underestimate the magnitude of resource recovery within reserves.

Neither should our conclusions be regarded as criticism of the process used to separate conflicting uses when deciding management zones for the Galapagos Marine Reserve. While not optimum from a resource conservation perspective in the light of new ecological data, the Galapagos zoning scheme required a balance between social and economic as well as biological factors. The final outcome, namely 18% of the coastal zone agreed by consensus amongst all stakeholders to be protected in interspersed 'no-take' zones, represents a model that is arguably world best practice to date.

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