A Framework for Assessing Impacts of Marine Protected Areas in Moorea (French Polynesia)[1]

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Abstract: Marine Protected Areas (MPAs) have been promoted as effective management tools to protect biodiversity at local and global scales, but there remains considerable scientific uncertainty about effects of MPAs on species abundances and biodiversity. Commonly used assessment designs typically fail to provide irrefutable evidence of positive effects. In contrast, Before-After-Control-Impact (BACI) designs potentially remedy many of these problems by explicitly dealing with both spatial and temporal variation. Here, we document the historical context of implementation and the scientific assessment of MPAs recently established at eight sites around the island of Moorea, French Polynesia. In 2004, we designed and implemented a monitoring plan that uses a BACI-Paired Series (BACIPS) design to quantify the effect of the MPAs. Twice per year, we monitor fish, corals, and other benthic invertebrates at 13 sites (eight within MPAs and five outside MPAs) around Moorea, in three distinct reef habitats (fringing, barrier reef, and outer slope). We present statistical analyses of data collected during five surveys (July 2004 to July 2006), before the initiation of enforcement. We also assessed the potential of our program to detect future responses to the established MPA network. Our estimates of biomass for five categories of fishes (Acanthuridae, Chaetodontidae, Serranidae, Scaridae, and fisheries target species) within MPA sites generally track estimates in paired Control sites through time. Estimated statistical power to detect MPA effects (a 192% biomass increase within the MPA) was high at the MPA network scale but varied among taxonomic categories and reef habitats: power was high on the reef outer slope and lower in the lagoon, and generally high for acanthurids and chaetodontids. It did not vary significantly between sites. We discuss limitations of our approach (shared by all MPA assessments to date) and describe solutions and unique opportunities to redress these limitations in French Polynesia.

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Attempts to restore marine systems through the establishment of marine protected areas (MPAs) have been well documented, and assessments of MPAs typically highlight positive effects (e.g., increased species richness or increased density, size, and biomass of key species or increased fisheries yield outside reserves): for example, Russ and Alcala (1996, 2003), Allison et al. (1998), Palumbi (2000), Roberts et al. (2001), Halpern and Warner (2002), Russ (2002), Halpern (2003), Lubchenco et al. (2003), Norse et al. (2003), Russ et al. (2004). Indeed, MPAs are generally expected to have (1) local benefits within the boundaries of the MPA; and (2) positive regional effects that extend beyond the MPA boundaries and therefore help restore degraded areas that are not protected but may nonetheless benefit from spillover from the reserve. These cases not withstanding, there remains a considerable need for improved tools to document and estimate the local and regional effects of MPAs, because limitations of common assessment designs described in MPA papers published to date still leave the results open to differing interpretations (Osenberg et al. 2006).

The most common statistical designs used to evaluate MPAs are Control-Impact designs, which contrast systems inside and outside the MPA and therefore confound a putative effect of MPAs with natural spatial variation resulting from other processes (e.g., preexisting site differences). Before-After designs address this problem but may confound MPA effects with other sources of temporal variance. Before-After-Control-Impact Paired Series (BACIPS) assessments (e.g., Stewart-Oaten et al. 1986, Stewart-Oaten and Bence 2001, Osenberg et al. 2006) overcome many of these limitations. In studies utilizing a BACIPS design to assess the effects of MPAs, data are collected at one or more MPA sites and one or more Control areas, Before and After the impact of interest (e.g., before the establishment of an MPA[s]) (Figure 1). On each date in the Before period, the difference between the Impact and Control sites provides an estimate of the spatial differences between these sites. The average difference from the Before period therefore gives an estimate of the difference that should exist in the After period if the impact has "no effect." The magnitude of change in the differences from Before to After gives an estimate of the effect of the MPA, assuming the MPA has no effect on the Control areas (see Stewart-Oaten and Bence [2001] for a more detailed discussion of BACIPS and Osenberg et al. [2006] for a discussion of BACIPS in the context of MPAs).

In this paper, we discuss our ongoing study of an MPA network in Moorea, French Polynesia, that uses the BACIPS approach. We describe (1) the historical context that led to the establishment of the MPA network; (2) sampling methods; and (3) preliminary analyses we use to estimate and evaluate the statistical power of our assessment design. We conclude with a discussion of the limitations of our design, particularly in the light of spillover (and nonindependence of the MPA and Control areas).

Historical Context

The fish communities of Moorea have been studied extensively for nearly three decades at Tiahura, off the island's northwest coast (Galzin 1979) (Figure 2). In general, overall fish density and species richness on the outer slope have been increasing (Figure 3*a*) since several severe cyclones struck Moorea in the early 1980s. These events induced great reductions of fish density and species richness by disturbing their habitats (Galzin 1987, Harmelin-Vivien 1994). Similar increases for many species have been observed in nearby barrier and fringing reefs habitats. In contrast, the density of commercial fishes has declined over this same time period (Figure 3*b*) and the average abundance/biomass and trophic structure of commercial fishes have been greatly altered at several sites around Moorea (Lison de Loma 2005). In addition, the density and biomass of harvested species has decreased more in Tahiti and Moorea (which are more heavily fished) than in Maupiti and Raiatea, which are less heavily fished (Lison de Loma 2005). Together, these data suggest that certain fishes have been overharvested and that fishing mortality has pre-

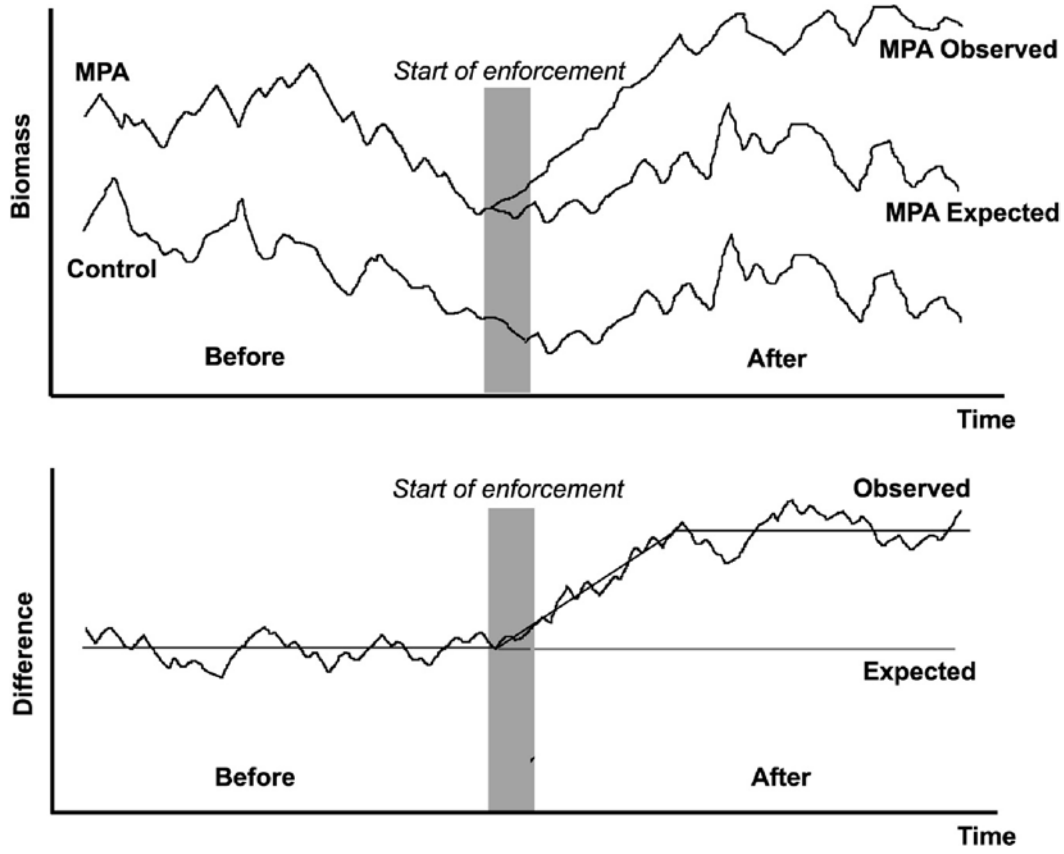


Figure 1. Schematic of the BACIPS assessment design applied to an MPA. *Top panel:* The response variable (in this example, the biomass of the focal group) fluctuates through time in an MPA and a Control area, Before and After enforcement (the vertical bar indicates the initiation of enforcement). *Bottom panel:* The difference in biomass between the MPA and Control. The expected difference in the After period is the mean from the Before period. Thus, a deviation between the Before and After differences indicates an effect of the MPA on local biomass. The expected biomass at the MPA in the After period (top panel) is the biomass at the Control area in the After period plus the difference from the Before period.

vented commercial fishes from recovering following the cyclones of the 1980s. Concerns about overfishing have led to the implementation of a comprehensive marine management plan. The Plan de Gestion de l'Espace Maritime (PGEM, JOPF 22/10/04) for Moorea encompasses the entire lagoon and all waters beyond the reef crest out to a depth of 70 m on the outer reef slope. This plan took more than 10 yr of effort and involved several planning meetings attended by representatives of local communities, territorial services (Fisheries, Environment, Urbanism), scientific research institutions, local politicians, and various user groups (e.g., hotels, tour and dive boat operators). The plan was developed with the goal of having local stakeholders deeply involved in the decision-making processes, particularly with the geographical siting of MPAs (no-take areas).

The PGEM includes a network of eight MPAs on the island of Moorea. In 2004, the Fisheries Service of French Polynesia contracted the Centre de Recherches Insulaires et Observatoire de l'Environnement

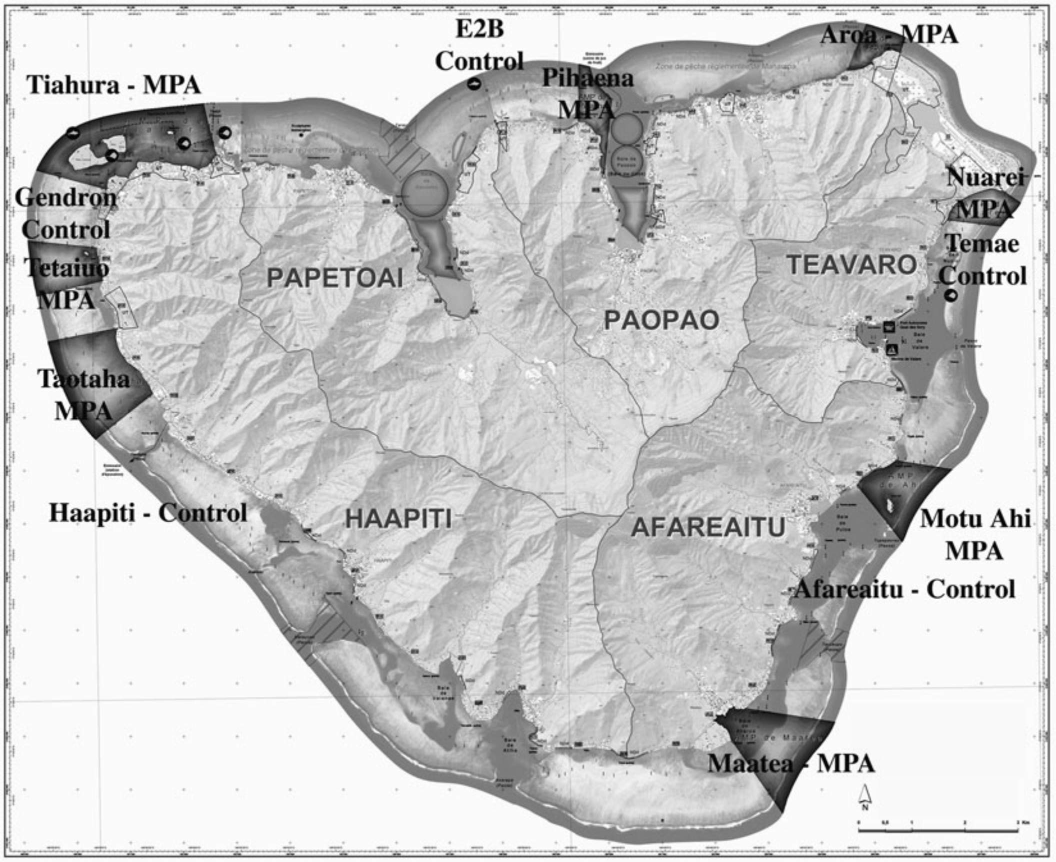


FIGURE 2. Marine Protected Areas (MPAs) and Control areas in Moorea. A total of eight MPAs was defined by the Plan de Gestion de l'Espace Maritime, and we selected five Control areas (modified from PGEM JOPF 22 October 2004).

(CRIOBE) in Moorea to design and implement a monitoring plan that would allow a statistically rigorous assessment of the biological effects of implementing the MPAs. CRIOBE consulted with other scientists, and a monitoring plan was designed by a consortium of scientists at the CRIOBE, University of California (Berkeley), the University of Florida, and Victoria University of Wellington. This group was joined in 2006 by additional marine scientists from the University of California, Santa Barbara, and the California State University, Northridge, following the establishment of the Moorea Coral Reef Long-Term Ecological Research (MCR LTER) site in Moorea by the U.S. National Science Foundation.

MATERIALS AND METHODS

Study Sites

A total of 13 sites was selected for monitoring around Moorea (eight MPAs and five Control areas [C]) (Figure 2). Four of the MPA sites were uniquely paired with four Controls based on their proximity and geomorphology; two MPA sites (Ahi and Maatea) shared a single, matched Control (Afareaitu) site; two MPA sites (Tiahura and Aroa) were fairly

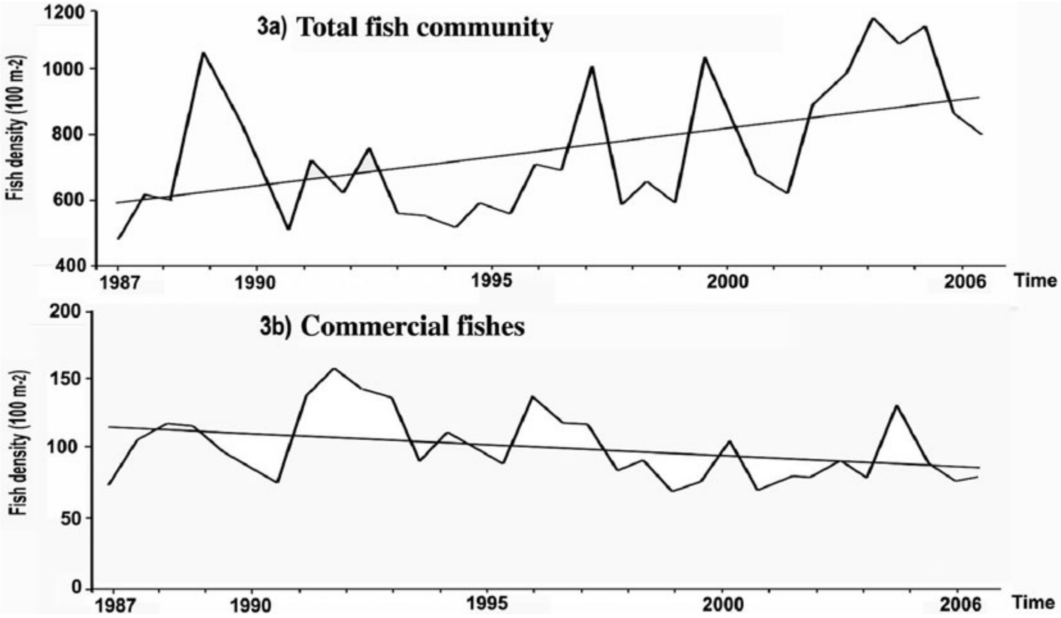


Figure 3. Density of total fish fauna (*a*) and commercial fishes (*b*) on the outer slope at Tiahura (NW Moorea) between 1987 and 2006 (modified from Galzin et al. 2004).

unique in their geomorphology. For the purposes of this paper, we paired these two MPA sites with the nearest and geomorphologically most similar Control (E2B), although we suspected that these pairings may provide less power to detect significant MPA effects than other pairings in our power analyses (see section on Data Analyses). Each MPA site extends from the shore to beyond the reef crest and out to the 70 m isobath on the outer reef slope. We study three distinct reef habitats at each site: the fringing reef, the barrier reef, and the outer slope. Three stations are surveyed per reef habitat, yielding a total of 117 stations: 13 sites (eight MPAs, five Controls) × three habitats × three stations per habitat. Each station is located using a handheld global positioning system (GPS) receiver because there are no fixed markers on the reef. Within each site, the three reef habitats are sampled (a) on the border of the fringing reef close to the channel, or when there is no channel, at the boundary of the barrier reef and the fringing reef; (b) on the barrier reef at 200 m shoreward from the reef crest; (c) on the outer slope at 10 m depth. At each station, a transect line 25 m long is randomly placed on the bottom, and fishes, invertebrates, and benthic substrates are enumerated.

Sampling Methods

All transects within each site were sampled on the same day. Initially (first campaign of sampling), all surveys were performed by two divers. Beginning with the second campaign, sampling was conducted by two teams of divers at each site; one team sampling the outer slope and the second team sampling the fringing and barrier reef habitats. Surveys typically were conducted over a period of 10 days in each of the two principal seasons: one during the cooler, dry season (July–August) and the other during the hotter, wet season (January–February), starting 5 days before the full moon to account for potential seasonal and/or lunar variation (Galzin 1987).

TABLE 1

Categories of Benthic Substrates

Category	Description
Live coral	All hard living coral including *Millepora* sp. Coral is identified and recorded at the generic level. Broken, living fragments (e.g., branches of *Acropora* sp.) larger than 15 cm are counted.
Dead coral	Skeletons of recently dead coral (death < 1 yr) still standing or recently broken. The polyp structure must be visible. Algal cover must be slight.
Macroalgae	All the noncalcareous algae of large size that are easily identified visually. We distinguish seven genera: *Turbinaria*, *Sargassum*, *Halimeda*, *Padina*, *Boodlea*, *Dictyota*, and *Caulerpa*. We also count Cyanophycea. Another category consists of the large turf (>5 mm in height) within territories of *Stegastes nigricans*. Genera that are difficult to identify are lumped into a single unidentified category.
Pavement	Hard, compacted substrate, even when covered with fine turf (smaller than 5 mm) or encrusting algae. Old dead coral (>1 yr) is included.
Rubble	Small fragments of biogenic calcium carbonate (shells and coral rubble) between 0.2 and 15 cm.
Sand	Sediment with particles < 0.2 cm and that do not stay suspended when disturbed.
Mud	Fine sediment that remains in suspension and obstructs visibility when disturbed.
Other	All other organisms (anemones, sponges, etc.) not included in other categories.

All transects were aligned parallel to shore in the case of the lagoon habitats or parallel to the reef crest on the outer slope. When the outer slope was characterized by deep and large spurs and grooves, the three transects were arranged in a triangle over a single spur (e.g., MPA or Control of Pihaena E2B, Tiahura, Aroa). In these cases, the transects may vary slightly in depth (7–12 m). Along each transect, data were collected on percentage cover of the various components of the benthic substrate, abundance of selected benthic invertebrates, and abundance and size structure of the fish community. Observations were always made between 0800 and 1630 hours (local time), to minimize any heterogeneity caused by diel variation in fish behavior (Galzin 1987). Each transect line was surveyed three times: once for benthic cover, once for invertebrate abundances by one diver, and once for fish by the other diver.

Benthic Substrate Monitoring

Eight categories of substrate cover were quantified using a line intercept transect (LIT) method. The substrate was assessed at its shallowest point every 50 cm and placed into one of eight mutually exclusive categories (Table 1). Substrates within two of these categories (live coral and macroalgae) were further identified to genus, giving a total of approximately 35 categories.

Monitoring of Benthic Invertebrates

The densities of 12 target invertebrates were quantified using 25 by 4 m belt transects. Four mollusks (giant clam, *Tridacna maxima;* conch, *Turbo marmoratus;* seven fingers, *Lambis truncata;* and troca, *Trochus niloticus*) and eight echinoderms (crown-of-thorns starfish, *Acanthaster planci;* dotted sea cucumber, *Bohadschia argus;* black sea cucumber, *Halodeima atra;* synapta sea cucumber, *Synapta* sp.; spiny sea cucumber, *Telenota ananas;* white-spined sea urchin, *Tripneustes gratilla;* diadema sea urchin, *Diadema* sp.; and big-spined sea urchin, *Echinothrix diadema*) are included.

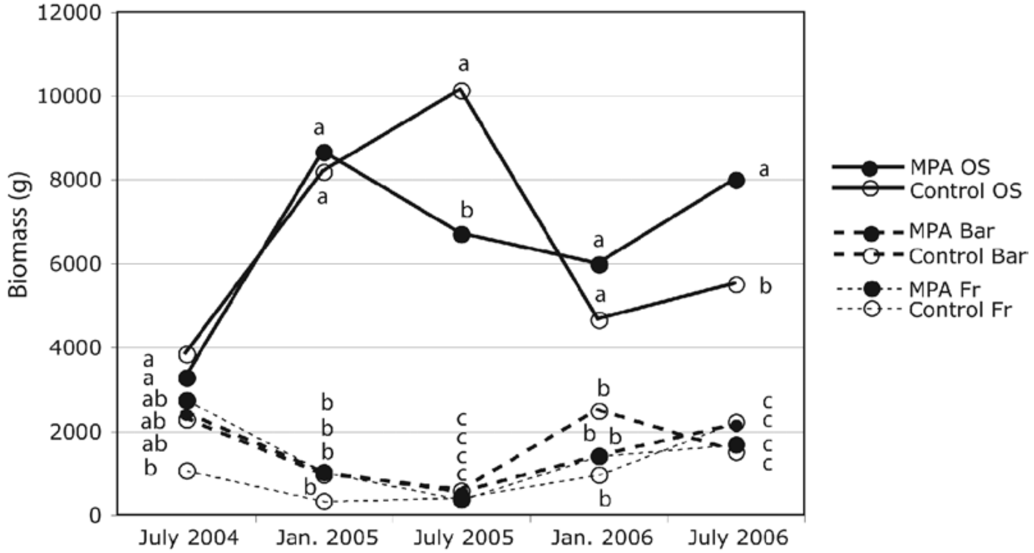
Fish Surveys

Fishes were surveyed using 25 by 2 m belt transects that extended through the entire depth of the water column. All fishes observed were identified to the species level, enumerated, and an estimate of body length to the nearest centimeter was recorded (counts and average body lengths were recorded for schools of fishes). The entire 25 m transect line was surveyed continuously for the occurrence of very large individuals (e.g., sharks, rays, terminal-phase parrot fishes, etc.) or members of highly mobile species (e.g., carangids). In the case of smaller individuals or more territorial species, each transect line was subdivided into 5 m subsections and only individuals within a given subsection were counted. When all of the fishes within a subsection had been recorded, the diver moved on to the next 5 m subsection and counted the individuals within that subsection. This process was repeated five times until the entire 25 m transect had been sampled. This method ensured that each portion of the transect was observed for an approximately equal amount of time. In the transects where the territorial damselfish *Stegastes nigricans* and/or the surgeonfish *Ctenochaetus striatus* were particularly abundant, individuals of these species were counted by swimming back along the transect line after all other observations had been completed.

Data Analyses

We present a preliminary analysis of data on fishes collected during the first five campaigns of our BACIPS assessment, all of which come from the Before period. Our aim is to estimate the statistical power of our assessment and how our power to detect MPA effects may vary among habitats, taxonomic categories, and/or MPA sites. Focal campaigns were completed between July 2004 and July 2006. All counts and fish lengths were converted to biomass using specific length-weight relationships for Pacific reef fishes (from Kulbicki et al. 2005). For our analyses we selected a subset of 96 fish species (27,981 individuals) that we grouped into five taxonomic or functional groups: Acanthuridae (21 species, 17,472 individuals), Chaetodontidae (18 species, 3,216 individuals), Serranidae (7 species, 736 individuals), Scaridae (17 species, 3,539 individuals), and other targeted fisheries species (comprising 2 species of Siganidae, 1 Carangidae, 11 Holocentridae, 5 Lethrinidae, 4 Lutjanidae, 8 Mullidae, 1 Sphyraenidae, 1 Ephippidae; a total of 3,014 individuals). Species were included in the analyzed data set if they were (1) present in most of the transects from a specific habitat, and (2) hypothesized to respond to MPA establishment due to elimination of harvesting or the improvement of habitat quality.

Differences in mean total fish biomass were tested between habitats and sites (grouped among MPAs or Controls) for each campaign of the survey using a one-way analysis of variance (ANOVA), followed by an a posteriori Student-Newman-Keuls (SNK) test. To perform power analyses, we first averaged biomass within each of our five defined groups across replicate transects and then calculated Δ values for each group of species in all 24 zones (eight MPAs × three habitats) over the five campaigns: $\Delta = \ln(\text{MPA biomass} + 1) - \ln(\text{Control biomass} + 1)$. To calculate statistical power, we had to specify several additional parameters. The most subjective of these was the effect size: the true magnitude of difference that we would like to be able to detect given our current design. We used an effect size based on Halpern's (2003) meta-analysis of 89 MPA studies, which found that on average, MPA establishment increased biomass by 192% (which corresponds to a change in Δ from the Before to After periods of ~ 1.07 (i.e., $1.07 = \ln(2.92/1)$, ignoring the minor influence of adding 1 in both terms of Δ). In summary, we performed power analyses for a two-sample t-test assuming: (1) $\alpha = 0.05$; (2) five surveys in both the Before and After periods; (3) identical variation in Δ during the Before and After periods, and equal to the observed variation among the five existing campaigns; (4) an effect size (i.e., $\Delta_{\text{After}} - \Delta_{\text{Before}}$) equal to 1.07 (i.e., a 192% increase in biomass inside the MPA); and (5) a two-tailed test (a conservative assumption, because for most of our taxa we expect positive responses to MPA establishment). Power was calculated for each of the five groups of species in each habitat for all MPA-Control pairs based on these assumptions and an online Java applet (Lenth 2006). We also calculated power for the combined data set (i.e., based on biomasses for the aggregate fish bio-



Campaign	1	2	3	4	5
ANOVA results	$F = 2.68$ $p < 0.05$ df = 5	$F = 32.2$ $p < 0.001$ df = 5	$F = 14.9$ $p < 0.001$ df = 5	$F = 10.6$ $p < 0.001$ df = 5	$F = 14.3$ $p < 0.001$ df = 5

FIGURE 4. Variation in the mean total fish biomass in each habitat (Fr, fringing reef; Bar, barrier reef; OS, outer slope) of the MPA and Control sites during the five campaigns in the Before period. Points with a letter in common are not significantly different (post hoc SNK test, ANOVA results).

mass averaged across all MPA and Control sites in each habitat).

RESULTS

Mean total biomass was significantly higher on the outer slopes of both MPAs and Control sites than in lagoon habitats (Figure 4) in most campaigns of the survey. Such differences in biomass and species composition (not shown) between habitats demonstrate the need to analyze outer slope and lagoon habitats separately. At the island scale, biomass at the Control sites tracked the biomass at the MPA sites through time in each respective habitat. Tracking should lead to higher power in BACIPS designs and indicated good matching of Control and Impact sites (Osenberg et al. 2006). Power to detect a 192% increase in biomass inside the MPAs (based on Halpern's [2003] meta-analysis) was very high for the aggregated data set (all fish groups and sites combined): the probability of detecting such an increase was 99.7% on the outer slope, 99.1% on the barrier reef, and 66.8% on the fringing reef.

Power based on data from the paired sites and for the five groups of fishes separately was generally lower and variable (Table 2), with a mean of 32.5 ± 29.5%. A three-way factorial ANOVA (factors: Site, Habitat, and Fish group) on this data set showed significant power differences among habitats ($F = 19.2$; df = 2, 13; $P < .001$) and fish groups ($F = 9.3$; df = 4, 13; $P < .001$) but failed to exhibit significant differences among individual MPA sites ($F = 0.26$; df = 7, 13; $P = .97$). Power was not obviously reduced for the MPA sites (Tiahura and Aroa) that were not originally paired with Controls. If all groups of species are pooled, power was greater on the outer slope compared with

TABLE 2

Power (Probability of Detecting a Change in Δ Equal to 1.07 [i.e., a 192% Increase in Biomass (Halpern 2003)]) in Response to MPA Establishment for Five Fish Groups in Three Different Habitats in Moorea, French Polynesia

Habitat	MPA Site	Acanthurids	Chaetodontids	Groupers	Scarids	Other Harvested Species
Barrier reef	Aroa	12.9	12.6	7.6	6.5	15.3
	Maatea	22.8	15.3	8.9	12.7	9.0
	Motu Ahi	9.8	23.8	19.1	8.5	12.4
	Nuarei	18.2	32.5	14.6	14.9	7.0
	Pihaena	69.6	16.8	8.7	6.3	44.3
	Taotaha	19.8	9.9	10.5	9.6	10.5
	Tetaiuo	11.5	41.8	9.8	10.1	6.3
	Tiahura	99.9	22.0	7.4	6.8	10.4
Fringing reef	Aroa	44.3	56.5	7.4	8.9	18.7
	Maatea	60.2	22.0	12.1	17.1	53.1
	Motu Ahi	71.0	53.1	10.9	10.9	21.2
	Nuarei	9.0	9.7	11.3	17.6	11.7
	Pihaena	79.8	97.2	9.8	8.9	29.5
	Taotaha	22.0	21.2	19.1	9.6	15.7
	Tetaiuo	98.7	31.0	9.2	10.9	8.5
	Tiahura	10.4	16.6	14.2	11.7	14.9
Outer slope	Aroa	56.5	88.2	56.5	8.2	12.4
	Maatea	60.2	88.2	68.2	15.0	8.3
	Motu Ahi	68.2	79.8	75.4	8.9	18.7
	Nuarei	53.1	53.1	29.5	97.2	60.2
	Pihaena	53.1	41.8	29.5	17.6	8.6
	Taotaha	99.9	64.1	97.2	29.5	24.8
	Tetaiuo	100.0	97.2	15.0	100.0	27.0
	Tiahura	70.0	41.2	99.0	84.1	8.2

Note: Power is based on observed spatiotemporal variation in biomasses from five surveys in the Before period and assuming five additional surveys in the After period.

the fringing and barrier reefs: $52.8 \pm 32.2\%$, $26.6 \pm 25.0\%$, and $17.9 \pm 18.1\%$, respectively ($n = 40$; one-way ANOVA: $F = 19.9$; $df = 2, 117$; $P < .001$). Acanthuridae and Chaetodontidae showed significantly higher power than other groups of species, with respective means of $50.9 \pm 32.1\%$ and $43.2 \pm 29.1\%$ (no site or habitat distinction made; $n = 24$; one-way ANOVA: $F = 6.19$; $df = 4, 115$; $P < .001$).

DISCUSSION

Previous studies of MPAs have been limited by the lack of sound designs, including the absence of Before data. Our BACIPS study of MPAs in Moorea potentially overcomes these limitations. However, even a BACIPS study can lead to low statistical power and therefore squander valuable resources and political capital. Power in a BACIPS study is primarily affected by two issues: the number of surveys available from the Before Period, and the variability in the time series of differences, Δ (Osenberg et al. 1994). The number of Before surveys is usually constrained by the ability to initiate a scientific program before establishment of the MPAs and is the reason why most studies include only After data (Halpern 2003, Osenberg et al. 2006). We were able to conduct five biannual surveys before enforcement began. This is better than most MPA studies published to date but is still small based on other power analyses with BACIPS data (e.g., Osenberg et al. 1994). Well-matched MPA and Control sites (i.e., they track one another through time and respond similarly to large-scale external processes [Stewart-Oaten et al. 1986, Osenberg et al. 2006]) should give rise to lower variation in Δs and can yield high power despite limited numbers of surveys. In our study, power was high for the aggregated data set. Thus, assuming that enforcement continues and effects are similar to those estimated by Halpern (2003), our study should yield a powerful assessment of effects of the MPAs on fish biomass.

Of course, we expect effects of MPAs to vary among habitats and species. Power values were higher in the outer slope habitat, suggesting that effects would be better detected in this habitat. This is probably due to the less-variable geomorphology, and hence fish communities, on outer slopes in Moorea compared with fringing and barrier reef habitats (Galzin 1987). Acanthuridae and Chaetodontidae showed higher statistical power than other groups of species, possibly because they are more abundant and more reliably censused. Harvested fishes, which are less abundant and poorly detected using belt-transect visual censuses, yielded lower estimates of power.

Our power analyses are based on a single effect size. Smaller effects will, of course, be harder to detect. Several steps could be taken to improve our power. First, we have paired Control and MPA sites based primarily on geographic proximity and/or geomorphologic similarity, but a more formal analysis of temporal coherence might suggest more appropriate controls for particular MPAs. Second, fixed transects could reduce the observed variation in Δ (by reducing sampling error induced by sampling different microhabitats during different campaigns). However, such a change at this time (after seven campaigns of survey) would probably be unwise. Third, species might be aggregated in ways that yield less-variable time series (e.g., if groups were more stable in their dynamics than individual species). The aggregation method we used in the analyses presented here was family-based, and more-rigorous approaches could be tried (e.g., based on a functional group approach). Despite these limitations, the results of the initial power analyses presented here are encouraging.

The current BACIPS design is suited to detect local effects of MPAs (inside MPAs versus outside MPAs), but it does not allow a good estimation of the magnitude of the *regional* effects of an MPA network via spillover (Osenberg et al. 2006). Sampling of a nearby and geomorphologically similar island would allow the assessment of this phenomenon, via a BACIPS design in which Moorea (the MPA network site) was matched with a Control island (see Osenberg et al. 2006). Such an approach has been implied (Roberts et al. 2001) but never implemented in a comprehensive design. We have some additional data from other islands in the Society Islands that may prove useful in this context, but the studies were not planned as part of an integrated assessment of MPAs. Given the importance of spillover effects to management and restoration goals of MPAs, we argue that implementation of such comprehensive designs should be a high priority for scientists and funding providers. With marine management areas being planned for many of its islands and given its scientific capacity, French Polynesia provides an excellent opportunity for addressing the reality of spillover effects, a crucial question of general importance to marine conservation science.

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