Testing Mechanisms By Which Marine Protected Areas Export Fish To Adjacent Habitats: The Soufriere Experiment In Reef Fisheries Sustainability (SERFS)

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ABSTRACT

Marine Protected Areas (MPAs) are increasingly employed to manage resource use in the coastal zones of Caribbean countries, and are being promoted as effective tools for the management of coral reef fisheries. A fundamental tenet of reserve-based fisheries management is that these refuges from fishing mortality export fish from within the MPA to adjacent fished areas. An expectation is that the yield outside a refuge will increase enough to offset the catch forsaken by the fishery as a result of relinquished access to the MPA. If this does not occur within an economically viable period, fishermen will experience a net loss in income, which may inhibit compliance with management regulations. Documented increases in reef fish abundance and individual size within well-managed MPAs suggest two mechanisms of export to fisheries: 1) Emigration of catchable fish across refuge boundaries in response to increased densities of conspecifics, competitors or predators within refuges, and 2) Dispersal of larvae produced at high rates by the increased abundance of large fish within the refuge. The first mechanism assumes higher rates of recruitment or survival within the refuge to sustain exported production, while the second assumes that increased larval production enhances recruitment in adjacent areas (*i.e.* a local stock-recruitment relationship). Neither assumption is well-supported by current knowledge of coral reef fish ecology, and there are no robust demonstrations that Caribbean MPAs actually produce increased yields of catchable fish. Well-designed experiments conducted over complete histories of MPA creation are required to test for the existence of these mechanisms, and to quantify their contribution to the catches of fishermen who participate in reserve-based management. A collaborative research effort in the Soufriere Marine Management Area of St. Lucia, involving the national Fisheries Department, local NGOs and marine scientists from two universities is attempting to quantify the effect of a newly declared set of marine reserves and fishing priority areas stretching along 11 km of fringing reef. Spatially and temporally replicated mark-recapture and recruitment experiments will be conducted in partnership with local fishermen. Here we present a detailed experimental design, and estimate the power of different monitoring options to unequivocally identify the effects of MPAs and their causes.

Keywords: Coral Reef Fish, Experimental Design, Marine Protected Areas, St. Lucia.

INTRODUCTION

Brochures promoting Caribbean tourism rightly enthuse about marine parks, emphasizing the positive effects of associated conservation and management practices within their marine protected areas (MPAs) have on their living resources. It is safe to conclude from experience elsewhere, and from initial studies of the Caribbean's established MPAs that non-extractive uses of marine resources (*i.e.* recreation, education) by both residents and visitors are enhanced if protection and management is effective (Roberts and Polunin, 1993; Bohnsack, 1994; Russ, 1994). Significant benefits often accrue directly to those who service these non-extractive uses (*e.g.* guides, boat operators, hoteliers, etc), and indirectly to others in the local community.

One claim sometimes made explicitly (and often assumed implicitly) is that MPAs will also directly benefit extractive users of marine resources (*e.g.* Bohnsack,1994). Specifically, improved quality of benthic habitat and increased diversity, abundance and individual size of fish in MPAs is expected to replenish and improve catchable fish stocks, and hence the livelihoods of fishermen. This appears to be a "win-win" situation: the very users who contribute to the severe depletion of resources that often prompts the creation of MPAs (*e.g.* over fishing of reef fish by coastal fishermen exacerbates the destruction of fringing reefs, Hughes, 1994), will benefit, rather than lose as result of their exclusion from them. How valid is this claim? What assumptions and data is it based upon? To what extent is it being used to enlist the support of fishermen in the creation and management of MPAs? The answers are crucial to the success of Caribbean MPAs because the cooperation and self-regulation of fishermen is essential to effective reduction of fish mortality within them.

Prior to undertaking a major research program, we review the basis of marine fishery reserve function in terms of ecological mechanisms, effects on fisheries and the knowledge requirements for management. The ability of various biological sampling programs to unambiguously test hypotheses about MPA function is compared. From this we develop an experimental design for assessing the effectiveness of marine protected areas as fisheries management tools in a recently zoned marine management area.

THE ASSUMPTIONS

The first assumption linking MPAs and fisheries is that they are effective spatial refuges for fish from fishing mortality. The existence of natural spatial refugia (*e.g.* seabed or waters too rough for gear deployment), and their potential to influence fisheries yields has long been recognized in fisheries science (*e.g.* Beverton and Holt, 1957). The refuge is expected to support a more productive population of any protected species than the surrounding area, exporting both emigrants and reproductive products (*i.e.* viable gametes and larvae) to adjacent (fished) areas with lower abundances. Simple, single-species models exist to estimate this export, but they do not incorporate species interactions or partial refugia, and few empirical measures of the effect exist (but see Russ *et al*, 1994). When the refuge is man-made, and the fishery multi-specific and multi-gear, the specificity and degree of protection must be constantly reassessed. For example, some of the coral reef MPAs in the Caribbean are not effective as fish refuges because certain forms of fishing (*e.g.* spear fishing, lobster potting), are not excluded (due to prior access rights or inadequate surveillance and enforcement). It appears to take only a small amount of targeted fishing in a reef MPA to remove the rare, large species which produce the most obvious within-refuge effects (Bohnsack, 1982). Thus, an obvious pre-requisite for a significant contribution from a MPA to fisheries yields is that real and effective exclusion of fishing mortality occurs within it. This criterion is not met in many of the parks encompassing coral reefs of the Caribbean, and is one of the most problematic aspects of reserve-based fisheries management (Bohnsack, 1994). There are implications for experimentation as well, because treatment effects will not be as large as expected if illegal fishing persists in reserves after declaration, and because recaptures of tagged fish in reserves are unlikely to be reported. Quantifying the relationship between form and degree of protection and export of fish from MPAs is clearly a research priority.

If we accept that effective refuges from fishing mortality can be created and maintained over ecological time scales, three sequential stages can be identified in the causal link between MPAs and fisheries:

1. The production of fish populations in the MPA must exceed that in the surrounding area.

This production can take the form of more fish per unit area (recruitment minus mortality) or larger fish (growth). Over time it may lead to increases in standing stock biomass and reproductive output of fish in the MPA. The first effect is well documented in about 10 empirical, quantitative studies of MPAs world-wide, with species-specific increases of up to 31 (mean about 5) times the abundance and up to 2 times the mean size of fish in adjacent areas 1.5 to 8 y after creation of an MPA (see Roberts and Polunin, 1993; Rowley, 1994 for reviews). Note however that an increase in biomass does not necessarily mean a sustained increase in production. Fish could migrate into an MPA from surrounding areas, and the accumulated biomass could turn over more slowly than the original standing stock (*i.e.* reduced productivity as the as the stock abundance nears habitat carrying capacity). The second (reproductive) effect is assumed on the basis of the exponential relationship between fish size and fecundity. It exists in theory only, there being no comparative measures of fecundity, reproductive success or larval settlement of reef fish inside and outside of reserves.

Increased production of fish in MPAs may come about because of increased rates of recruitment, growth, fecundity or survival (reduced mortality). A better quality of habitat (*e.g.* greater live coral cover or substrate rugosity) within MPAs may attract disproportionately high densities of settlers from the plankton, and may enhance the survival of those that do settle. MPAs centered on fish spawning areas will clearly exhibit high reproductive output, but not necessarily higher recruitment of juveniles. Great temporal and spatial variability characterize the recruitment of reef fish (Doherty, 1991), potentially masking MPA effects and making the interpretation of temporal changes in fish abundance inside and outside of MPAs difficult. Conversely, the greater abundance of fish (and other animals) characteristic of MPAs may hinder the survival or growth of new recruits through predation or competition (Jones, 1991). The relative importance of these mechanisms undoubtedly varies among species and ecosystems (Rowley,1994), and has not been partitioned in any study. The evidence to date, however, suggests that increased survival of catchable fish due to reduced fishing mortality is the primary cause of increased fish biomass in coral reef MPAs (Bohnsack, 1982; Alcala and Russ, 1990; Roberts and Polunin, 1991). Whether that translates into greater (and sustained) production of catchable fish is far from demonstrated in the Caribbean.

2. Fish production in the MPA must be exported to adjacent fished areas.

Fish that do survive to catchable size may migrate from a refuge, perhaps as food or shelter become scarce due to increased density in an MPA. As the transition from refuge to surrounding habitat may represent gradients of fish density, habitat quality, food availability and both natural and anthropogenic predation, fish species with different life histories, adaptations and catchabilities can be expected to respond according to the nature and steepness of these gradients (*e.g.* Ogden and Quinn, 1984). For example, large predatory fish which are highly catchable and have large resource demands may be most sensitive to MPA gradients. The few movement studies of reef fish suggest, however, that their ambits are smaller or of the same order as the few square kilometres scale of most MPAs (Ogden and Quinn, 1984; Roberts and Polunin, 1991). To date, there is no good evidence that any of the generally site-attached fish species of coral reefs exhibit a net emigration from MPAs as adults (*e.g.* Rakatin, 1994), but some of the more highly motile, schooling species may do so when a refuge is established in an area of intense fishing (*e.g.* Russ *et al*, 1994). Most studies of fish movement focus on the life history stages of single species, but no single-species model can be used to predict the net export of catchable fish from a refuge to the multi-species, multi-gear demersal fisheries characteristic of the Caribbean region.

Fish that remain within a refuge have a higher probability of reaching a large size and age than those which move outside into fished areas. The greater fecundity of large fish, coupled with high abundance, suggests that (in the absence of strong density-dependent effects) much larger numbers of fish larvae will be produced in MPAs compared with unprotected reef areas (Bohnsack,1994). Long larval periods characteristic of tropical fish relative to the rapid flushing of shallow reef habitats (Leis,1991) ensure that virtually all of these larvae will be exported from typical size MPAs, and indeed beyond immediately adjacent areas as well. Over the long term, it can be hoped that a network of effective MPAs throughout the Caribbean could be maintained as source areas, maintaining an input of larvae to the basin-scale pool that is adequate to ensure some recruitment even in over fished areas. This ideal poses many intractable questions of the appropriate time and space scales for MPAs (Rowley,1994).

On a more immediate level, the fundamental question is whether the combined, net export of new recruits and catchable fish from MPAs to adjacent fished areas is high enough to compensate for the loss of catch fishermen suffer from long-term closure of a previously-fished area, and the reduced recruitment due to the over fishing or habitat deterioration that results from the proportionally increased fishing intensity in the remaining area available for extractive use. So, an important assumption from the fisherman's point of view is:

3. The sustained catches of fish in the areas adjacent to MPAs must increase by an amount at least equal to the loss of catch resource users suffer as a result of forgone access to MPAs.

Comparative measures of fisheries performance (catch, effort) inside and outside of an MPA prior to and following its creation are required to test this hypothesis. There is only one study in the world that comes close to this goal. A 20 year old reserve occupying about 25% of the total area of a heavily fished reef in the Philippines was closed to all forms of fishing for ten years, and then opened and closed for shorter periods to different forms of fishing in the following decade. The yield per recruit of the most important fished species, the total catch per unit effort for the multi- species, multi-gear fishery, and the total fisheries yield from the entire reef were all highest when the reserve was operational, and decreased significantly when fishing was permitted in the reserve (Russ *et al*, 1994). In this case, the fishery as a whole, and the average catches by individual fishermen were demonstrably improved by the MPA. Is this result transferrable to the Caribbean situation? The intensity of the fishing at Sumilon (ca. 100 fishermen working 0.5 km^2 of reef area) is considerably higher than most regions of the Caribbean, and more destructive fishing methods (*e.g.* muro-ami, dynamite) are used. This suggests that the effects of the Philippine MPA are greater than might be expected in most Caribbean reef fisheries, but the question is open.

A Rigorous Basis for Testing Reserve Effects

Assessing the effect of MPA's on fish communities and fisheries can be likened to an environmental impact assessment (Eberhardt and Thomas, 1991; Peterson, 1993). The creation of a reserve represents a spatially and temporally discrete anthropogenic change in a major ecological process (mortality), of a relatively large magnitude and scale. The putative impact of the reserve must be assessed on the fish communities both within and outside the MPA. The logistics, costs and socio-economics of MPA design, implementation and management mean that few reserves are created in any given ecosystem: usually only one. This lack of replication, coupled with the spatial scale of the treatment and the great natural variability of reef communities poses a severe challenge to the determination of whether change occurs, and whether reduced fishing mortality in the MPA caused that change (*i.e.* whether there was an impact, see Stewart-Oaten *et al*, 1992). There are many ways of dealing with these problems, but only by testing falsifiable hypotheses using parametric statistics with sufficient power (probability of detecting a real effect) can unequivocal results be obtained (Toft and Shea, 1983; Peterman, 1989; Underwood, 1990). Table 1 outlines the structure of hypothesis testing for the effect of marine fishery reserves, and the implications of various outcomes for management. While both Type I (false positive) and Type II (false negative) errors can lead to inappropriate management decisions, the conclusion that a fishery reserve does not export fish when indeed it does (Type II error) is the more serious, given the other apparent benefits of MPA's. The challenge in designing an MPA experiment then is to optimize the sampling regime so as to maximize the power of the tests, and hence the strength of the inferences made about causality (Millard and Lettenmaier, 1986; Peterman, 1989).

The most common experimental design for assessing the effects of large scale manipulations like fisheries closures is the Before-After, Control-Impact (BACI) comparison, analyzed with univariate or multivariate analysis of variance (ANOVA), (Green, 1979). Figure 1 shows a schematic of the spectrum of BACI designs for testing the effect of MPA's, with a simplified comparison of standardized estimates of power. In its simplest form, BACI involves comparing a single putatively affected area with a single putatively unaffected area (the reference or control treatment), once before and once after the event supposed to cause the change (impact). The tests have such low power that they cannot unequivocally identify whether a change in the response variate occurred, much less what caused it. Considerable effort has recently been put into improving BACI designs so that real effects of anthropogenic perturbations can be clearly identified in natural communities (*e.g.* Peterson, 1993, Underwood, 1991,1993;

Table 1. A hypothesis-testing framework for assessing the effects of Marine Fishery Reserves (adapted from Toft & Shea, 1983). The null hypothesis (Ho) states that the reserve has no effect on the adjacent reef fishery as measured in terms of response variables such as fish recruitment, abundance, biomass, diversity, yield or export across boundaries. Decisions are classified according to the true state of nature (whether the reserve produces a change in the response variable) and the result of the statistical test of the null hypothesis. Probabilities of each outcome are described and the most commonly used significance levels for each probability are shown in brackets. The conclusions and possible management decisions are outlined. Failure to reject the null hypothesis does not mean that it is true unless the probability of making a Type II error is acceptably low (*i.e.* the test has sufficient power).

	True state of nature	
Result of Test	Reserve has no effect H0 True	Reserve has an effect H0 False
Retain H0	**Correct** - Do not reject (accept) true Ho - probability of not detecting an effect when there is none. $= 1 - \alpha$ (0.95, 0.99, 0.999) - conclude that reserve does not work when it does not. - do not use reserve for fisheries management.	**Type II error** - Fail to reject false Ho - probability of not detecting an effect when there is one (false negative) $= \beta$ (0.5, 0.2, 0.05) - conclude that reserve doesn't work when it does. - do not use reserve-based management when you should.
Reject Ho	**Type I error** - Reject true Ho - probability of detecting an effect when there is none (false positive) $= \alpha$ (0.05, 0.01, 0.001) - conclude that reserve works when it does not. - promise increased catch to fishers, who are misled.	**Correct** - Reject false Ho - probability of detecting an effect when there is one: $=1-\beta$ = **POWER** (0.5, 0.8, 0.95) - conclude that reserve works when it does. - realize promise of increased catch for fishers when rules of reserve respected.

Table adapted from: Taft and Shea, 1983

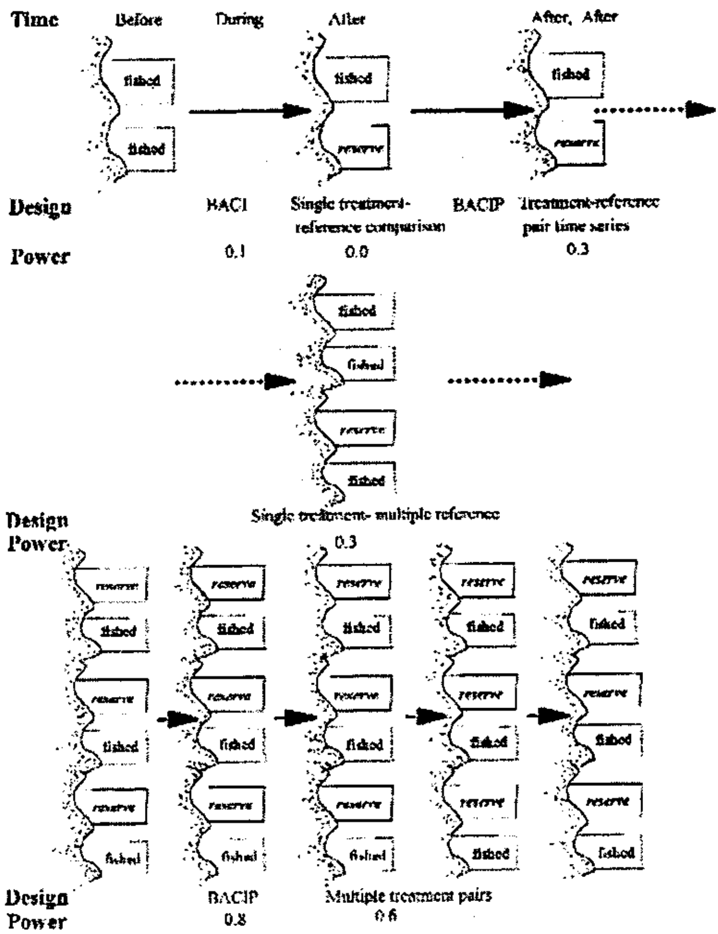

Figure 1. A diagrammatic representation of various experimental designs for assessing the effects of Marine Fishery Reserves. Various sampling designs based on analysis of variance (ANOVA) are shown with increasing degrees of spatial and temporal replication of reserve and fished (reference) treatments. The power of each design (ability to correctly reject a false null hypothesis) is calculated according to the formula of Millard & Lettenmaier (1986), assuming an alpha (probability of Type I error) of 0.05, a normally distributed response variable with a coefficient of variation of 20%, and a step-function effect of magnitude 25% of the per-impact mean. The unsuitability of simple designs, and the advantages of treatment replication and long time series are multiple sample times is clear.

Walters and Sainsbury, 1990). Because impact and reference treatments are rarely assigned randomly to sites, and once assigned remain so throughout the experimental sampling period, repeated measures of the same treatment areas (rather than re-randomized treatments of areas through time) are used almost exclusively in BACI designs (Green, 1993). This is appropriate because our main interest is in change and its causes in the specific areas of reef that have been zoned for protection or fishing, not in generalizations about spatial-temporal variability in all coral reef areas.

The primary effect to be tested in repeated measures designs is whether the change through time of unique sites subjected to the treatment (no-fishing) differs significantly from the change in different sites not so subjected (reference sites). Thus, it is the treatment by time interaction which is tested for significance against the sites by time interaction (using an F-ratio) in order to detect an effect due to the zoning treatment. The power of the test increases with both the number of sites and times used in any comparison, because this increases the degrees of freedom in the denominator of the F-ratio (the error term). Power is also affected by the ratio of the effect size (*i.e.* the magnitude of the difference between the treatment and reference sites due to the impact) to the error variance (Peterman, 1990). As the error variance is the within sites by time interaction, careful selection of similar treatment and reference sites can enhance power. One common approach is to followed paired treatment and reference sites through time (BACIP, *e.g.* Stewart-Oaten *et al*, 1986). Finally, it is important to note that increasing the number of spatial sub-samples (statistical replicates) within treatment areas ("pseudoreplication", Hurlbert, 1984) does not improve the power of tests in BACI designs.

A time series of measurements in several ("replicate") refuge and fished areas from before closure to fishing to well after any change due to zoning is likely to occur is thus the optimal experimental design for assessing the effectiveness of MPA's in reef fisheries management. Because the change in most fish and fishery response variables after a refuge is created will be gradual (months to years), rather than abrupt (*e.g.* catch can be expected to drop immediately), experimental designs which maximize temporal sampling intensity are preferred (Peterman, 1990; Green, 1993). Analysis of statistical power indicates that even with substantial spatial replication of reserve and fishing priority areas (*i.e.* at least three sites), at minimum of five sets of measurements through time are required to yield an acceptable probability of avoiding Type II error (Fig. 1).

Measurement variables should include benthic community structure, fish community biomass and diversity, population size structure, reproductive status and fecundity of commercially or ecologically important fish species, advection rates of larvae and migration rates of tagged fish across refuge boundaries, settlement rates of fish to benthic substrata (recruitment), natural and fishing mortality rates of catchable fish, catch, effort and income of fishermen, and community perceptions of and compliance with MPA management. It is unlikely that all of these variables would be included in any experiment, and the selection will be based on the most pressing needs of a particular management situation. In the case of Caribbean coral reefs fished by artisanal fishermen, variates which quantify the yield of catchable fish from areas immediately adjacent to MPAs should take precedence.

Site Selection

A solid background of natural history, theoretical and empirical ecology exists in which to frame the type of experiments proposed here, and the necessary facilities (including functioning MPAs) are available in several countries throughout the Caribbean (Table 2). The latter is a particular strength: both because the ambit of most tropical fish larvae spans this small ocean, and because the full spectrum of reef fishing intensity can be found within the region. Comparative measurements across a range of fishing pressures is highly desirable because MPAs are likely to enhance fisheries in some ecosystems but not others. The concept of a network of MPAs spanning the Caribbean provides an attractive framework for experiments to test the function of refuges from fishing. The results will be of both local (fishery specific) and regional (shared stocks) significance.

Experimental, multi-disciplinary approaches are clearly called for if we are to rigorously assess the contribution of MPAs to fisheries in the Caribbean. There are of course social and economic as well as biological aspects to costs and benefits of MPAs. The processes outlined in this paper involve multiple

Table 2. (opposite) An assessment of the suitability of existing and planned Marine Protected Areas within the CARICOM nations of the Caribbean for experimental assessment of the effects of Marine Fishery Reserves on coral reef fish and fisheries. The areas considered were the Southeast Peninsula in St. Christopher (SKN-SEP), Scott's Head-Soufriere Bay Marine Reserve in Dominica (DOM-SHB), Soufriere Marine Management Area in St.Lucia (SLU-SMMA), Tobago Cays National Marine Park in St. Vincent and the Grenadines (SVG-TCNP), Folkstone Marine Park in Barbados (BAR-FMP), Buccoo Reef Marine Reserve Area in Tobago (T&T-BRMR), Montego Bay Marine Park and Discovery Bay in Jamaica (JAM-MBMP & JAM-DB), Hol Chan Marine Reserve and Glover's Reef Marine Reserve in Belize (BEL-HCMR & BEL-GRMR). The selection criteria were chosen to maximize the power of statistical tests and the probability of successful completion of the experimental monitoring.

Criteria:	1	2	3	4	5	6	7	8	9	10
RESERVE	Contig. Reef	Treat. Repltn.	Effect. Refuge	Subst. Fishing	Reserve History	Environ. Quality	Commty. Support	Complty. Research	Logistic Support	Overall Rating
SKN-SEP	Fair	Posbl	Fair	Yes	Nil	Good	Fair	Fair	Fair	Fair
DOM-SHB	Good	Posbl	Good	Yes	Nil	Good	Good	Fair	Fair	Good
SLU-SMMA	Excel	Yes	Good	Yes	Now	Good	Excel	Excel	Excel	VGood
SVG-TCNP	Excel	Posbl	Poor	Some	Nil	Good	Poor	Poor	Poor	Poor
BAR-FMP	Poor	No	Fair	Yes	3 yr.	Fair	Fair	Excel	Excel	Good
T&T-BRMR	Good	No	Poor	Yes	2 yr.	Poor	Fair	Good	Fair	Fair
JAM-MBMP	Fair	No	Fair	High	3 yr.	Fair	Good	Good	Fair	Fair
JAM-DB	Excel	Posbl	Fair	High	Nil	Poor	Good	Excel	Excel	Fair
BEL-HCMR	Good	No	Excel	Yes	8 yr.	Good	Good	Good	Poor	Good
BEL-GRMR	Excel	Posbl	Good	Low	1 yr.	Excel	Good	Good	Poor	Good

Criteria:

1 - **Contiguous**, uniform area of **Reef** which are intersected by the boundaries of a reserve.
2 - reserve - non-reserve **Treatment Replication** (at least three)
3 - reserve conditions which provide **Effective Refuges** from fishing mortality.
4 - **Substantial** and measurable **Fishing** mortality in areas adjacent to reserves.
5 - a **Reserve History** of protection which includes "before" measurements and approximates reef fish generation ttime (at least 2 years).
6 - **Environmental Quality** (little degredation) in reserve and adjacent reef areas.
7 - a high degree of **Community Support** and cooperation in reserve management & research
8 - **Complementary** programs of monitoring and **Research**
9 - proximity, degree economy of **Logistic Support** available.

environmental factors, fish species and human behaviors across a broad range of spatial scales. No one set of experiments in a particular management area will answer the general question of how MPAs affect fisheries in the Caribbean. The results of multiple studies must be compared and synthesized to accomplish this task, and formal analytical methods are being developed to do so (*e.g.* Arnquist and Wooster, 1995). The effectiveness of such analysis however will be greatly improved if the individual studies are consistently and rigorously experimental in approach.

Ambitious programs of marine research in the Caribbean require coordinated effort by many individuals and agencies because of the large number of countries and states (ca. 40) sharing the resources (*e.g.* Ogden and Gladfelter, 1986). The CARICOM Fisheries resource Assessment and Management Program (CFRAMP) serves fisheries departments in the CARICOM countries with training, scientific expertise, financial and material support, and the coordination of regional fisheries research. Standardized methods and systems of catch, effort, and biological data collection have been established in 12 countries, which serve to improve the comparability of results from national research activities. Recognizing the growing commitment by the regions' fisheries departments to reserve-based management of reef fisheries, the CFRAMP is supporting experiments to measure the export of fish production from MPAs and its capture in adjacent fished areas.

After determining the statistical basis for the research, the next step was to review the current status of MPAs in the CARICOM countries with a view to selecting a location meeting as many criteria as possible for acceptable experimental power and benefit to cost ratios (Table 2). Visits were made to all countries, discussions were held with fisheries department staff and representatives of involved NGOs, and first-hand examination of sites was undertaken where possible. The nine criteria reflect both the statistical and logistic requirements of field research. Community support for the MPA was given a high ranking because of the need to involve fishermen as partners in the research program. The results demonstrate that eight of the twelve countries have embraced the use of MPAs in marine resource management, and that a range of well-established to tentatively planned reserve zonings exists. Unfortunately, many of these suffer the chronic problems of inadequate compliance by resource users (Roberts and Polunin, 1993; Bohnsack, 1994), and at the time of review only one has the multiplicity of zoned MPAs required for rigorous experimentation. On these bases, the Soufriere Marine Management Area (SMMA) in Saint Lucia was selected as the first site for research. It is hoped that current initiatives in several of the countries will lead to comparative programs of research in the future.

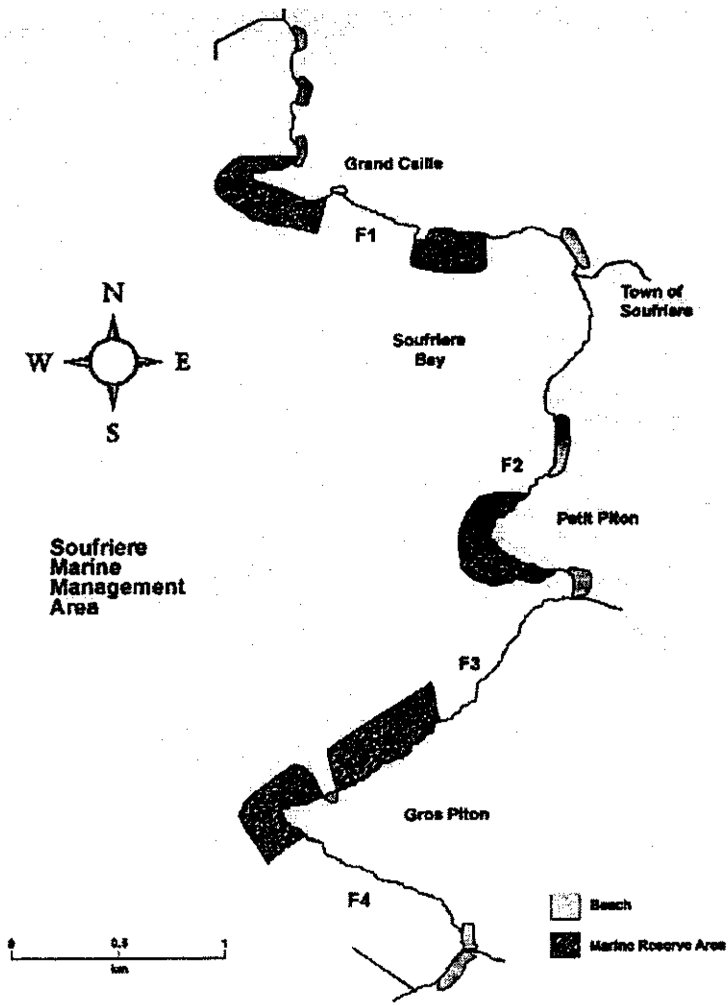

Figure 2. Map of Soufriere Marine Management Area on the central west coast of Saint Lucia, showing the five zoned Marine Reserve Areas, surrounded by areas where fishing is permitted. Beaches and rivers, which partially isolate sections of fringing reef along the volcanic shore are also indicated. The four reserve-fished pairs selected for the experiments are coded Reserve and Fished.

The Soufriere Experiment in Reef Fisheries Sustainability (SERFS)

In the SMMA protective zoning banned all forms of fishing in five marine reserves spread over 11 km of coastline on 1 August, 1995 (SRDF, 1994). There, the alternating spatial layout of MPAs and Fishing Priority Areas (Fig. 2), the timing of MPA creation under the Fisheries Act, and the level of community involvement in management by the Fisheries Department and the Soufriere Regional Development Foundation (Nichols and George, this volume) provide ideal conditions for experimentation. The contiguous, zoned marine habitats are narrow fringing reefs of high live coral and sponge cover on steep volcanic slopes, interspersed with nine areas of coarse sediment adjacent to beaches and small river mouths. The reefs occupy a narrow, boulder-strewn ledge to about 8 m depth, then drop precipitously to depths exceeding 50 m within 200 m of the shore. The five Marine Reserve zones are centered on coral reef habitats, and range in length from 0.7 to 1.1 km (*i.e.* about 14 to 22 Ha in area). The total area of reef protected by Marine Reserve zoning ("look but don't touch or take") is about 66 Ha., or 30% of the total management area. The minimum distance separating reserves is less than 100 m, while the maximum distance is 2.4 km. Sandy substrata and areas of fresh water input occur in these inter-reserve areas, which could inhibit fish migration and larval transport between reserves. All five reserves are bounded on both sides by zones where fishing is permitted, and at least one of the boundaries dissects contiguous reef habitat, such that there is no natural impediment to fish migration and transport between unfished and fished areas.

Our team approach to the research capitalizes on knowledge, expertise, personnel and existing data from the Saint Lucia Fisheries Department and two universities.

We have taken advantage of the spatial juxtaposition of fished and unfished zones in the experimental design (Table 3). Up to four pairs of reserve and adjacent fished areas (sites) will be used to provide spatial replication of the two levels of treatment (reserved and fished). Response variates will be followed through time as repeated measures. The level of within-site replication will depend on the response variate being measured. For example, visual census of abundance will have 2 to 5 replicates (sub-sites) per site per sample time, while measures of migration from sites will be a single estimate per site per time. (As discussed above, statistical replication within sites does not contribute to the power of tests of the main hypothesis of MPA effect). Response variates will be followed through time as repeated measures at each site (or sub-site). Mark-recapture methods (*e.g.* Rexstad *et al*, 1990) will be adapted to the Soufriere reefs using both visual surveys (*e.g.* Buxton and Smale, 1989, Matthews and Reavis, 1990) and trapping in traditional fish pots (*e.g.* Ratakin, 1994) by both researchers (in reserves) and fishermen (in fishing zones). Net migration rates will be estimated from simple, 1-d horizontal dispersion models parameterized

Table 3. Summary of experimental design, ANOVA table and power analysis for the Soufriere Experiment in Reef Fisheries Sustainability. The model assumes independence of main factors, and repeated, single, contemporaneous measures of response variables in each of the paired treatment sites through time. The power of statistical tests of the treatment by time interaction is calculated analyzed as in Figure 1, except that a noncentrality parameter for gradual rather than abrupt impacts (Mar *et al*, 1985) is used.

Response Variables:

- Fish density (visual census & CPUE)
- Net migration and mortality rate of large juvenile & adults (mark-recapture by visual census & fishery)
- Larval fish abundance (light traps)
- Settlement and post settlement survival (monitor recruitment to standardized substratum)
- 9 species of reef fish: 3 sedentary, 3 mobile & 3 itinerant.

Experimental Factors:

Factor	Code	Type	Levels
Reserve vs. Fished	R*vs*F	Fixed	2 ...r
Reef	Block	Fixed	4 ...b
Sites (w/in Treat)	S(R*vs*F)	Random	4 ...s
Times	T	Fixed (R.M.)	4(7)*...t

ANOVA Table:

Source of Variation	df		F-ration df	Power
Among sites:				
Reserve *vs* Fished	r-1	1	F[1,21]	
Among Reefs	b-1	3	F[3,21]	
Sites (R*vs*F)	2(s-1)	6	F[16,18]	
Reefs x R*vs*F	(b-1)(r-1)	3	F[3,18]	
Reefs x Sites(R*vs*F)	(b-1)2(s-1)	18	Error	
Within sites:				
Times	t-1	3 (6)*	F[3.72]	
Times x R*vs*F	(t-1)(r-1)	3 (6)*	F[3.72] (F[6,144])	0.48 (0.81)
Times x Reefs	(t-1)(b-1)	9 (18)*	F[9,72]	
Times x Sites(R*vs*F)	(t-1)2(s-1)	18 (36)*	F[18,54] (F[36,108])	0.35 (0.75)
Times x Reefs x Sites (R*vs*F)	(t-1)(b-1)2(s-1)	54 (108)*	Error	

with the spatial time series of fish locations after release at the centre of each site. The mark-release-recapture experiments will be conducted at each reserve and fished site within a single week, at intervals of approximately six months. Both mass tagging and unique individual tagging methods will be used. The actual day of release of tagged fish at any given site will be assigned randomly, so all sites will be assumed to be sampled at the same time (Underwood, 1991). The likely non-independence of fish dispersion variates among times within sites (autocorrelation) is accounted for in the repeated measures model.

Time and resources permitting, we expect to establish light trap sampling regimes for reef fish larvae (*e.g.* Doherty, 1987), and fixed benthic recruitment monitoring stations (*e.g.* Victor, 1986) in fished and unfished areas. These crucial data would allow tests of the effects of MPAs of larval abundance and settlement.

In the SERFS there will be little opportunity to collect a good time series of measurements before the exclusion of fishing activities within the reserves because of the concurrence of zoning and our filed work. This short-coming of the design is ameliorated by the fact that it takes a considerable period after reserve creation for fish populations in reserves to build up to measurably enhanced densities which are likely to be a major factor affecting recruitment and migration (Alcala and Russ, 1988; Roberts and Polunin, 1993). For mechanistic rate variables like migration and recruitment then, we will have to see a substantial diversion of the temporal trends in reserves versus fished areas if we are to detect a significant effect of the MPA's. Power analysis shows for example that net migration rates will have to be measured on seven occasions before the probability of a Type II error will be less than 0.2 (Table 3). If tag-release experiments are conducted twice per year, it will be over three years before the null hypothesis can be confidently rejected (minimum of 7 time samples for a power greater than 0.8). For descriptive variables like fish abundance, mean individual size, catch per unit effort and yield per unit area, we are fortunate to have access to at least one year's data prior to zoning (Roberts *et al*, 1995; Anonymous, 1995). Detailed interviews with fishermen will be used to quantify the fishing intensities and yields per unit area prior and following MPA enforcement. In this way the spatial scales of the fishery will be matched to those of the habitat zoning (*e.g.* Hatcher *et al*, 1990).

CONCLUSIONS

The question of whether marine protected areas "work" as fisheries management tools is crucial to their future in the Caribbean. Fishermen are the dominant extractive resource users, and their activities are known to profoundly affect coral reef communities. Other, non-extractive users may also affect the function of MPAs in the fisheries context. The mechanisms and rates of reef fish export from Caribbean marine protected areas are unknowns, knowledge of which is essential for sound management. Assessing the effects of MPAs on fisheries in adjacent reef areas requires experimental approaches having enough spatial and temporal replication to allow powerful tests of hypotheses. Of the many MPA initiatives in the CARICOM countries, only the SMMA currently meets these rigorous criteria for experimentation. The SERFS capitalizes on good fisheries data, multiple MPA zoning, and established co-management structures. Power analyses of various experimental designs indicates that over two years of sampling after MPA creation will be required to obtain unequivocal results.

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