APPLICATION OF SCIENTIFIC EXPERIMENTAL DESIGN IN MONITORING HARD BOTTOM HABITATS ASSOCIATED WITH AREAS OF BEACH NOURISHMENT

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ABSTRACT

The regulatory, engineering, and scientific communities are becoming increasingly aware of the potential impacts of beach nourishment. For example, the “70 Scientists’ Letter" (Environmental Defense, 2000) calls for a full assessment of the short-term and long-term impacts of beach nourishment on species that utilize nearshore habitats and potential cumulative impacts of beach nourishment across affected shelf areas. To adequately address the issue of potential impacts to nearshore reefs, scientific experimental design principles should be incorporated into monitoring programs to improve the monitoring of hard bottom habitats and add to the overall understanding of the potential impacts of beach nourishment on these habitats. These principles include clear definition of the monitoring objectives, clear specification of hypotheses, and sound sampling design incorporating appropriate stratification, randomization, and replication. Because of the site-specific nature of monitoring, generalizations of the results are difficult. We recommend adopting a strategy of designing beach nourishment monitoring projects for a future meta-analysis to examine potential impacts more generally with the hope of eventual quantitative predictions of impacts. Case studies of two ongoing programs reveal that changes can be made to the currently used monitoring approach that would improve the utility in a future meta-analysis. Finally, the implications of project funding and timing on the experimental design of monitoring projects are recognized.

INTRODUCTION

The initial question related to potential effects of beach nourishment on nearshore reefs is why be concerned about nearshore reef communities in the first place. Beach nourishment has suffered criticism as related to the health of nearshore reefs in the vicinity of the projects, as exemplified by the 70 Scientists’ Letter. Nearshore hard bottom provides substrate for colonization and habitat of numerous species adapted to the rigors of this very energetic environment. In addition, it serves as a habitat for early life stages of many important fish species that inhabit other areas of the continental shelf as older life stages (Gilmore et al., 1981; Lindeman and Snyder, 1999; Lindeman et al., 2000). Accordingly, the South Atlantic Fishery Management Council (SAFMC) recognizes nearshore hard bottom not only as essential fish habitat but also as a habitat area of particular concern (SAFMC, 1998). Another important value of this habitat is the algae living there, which provide a food source for juvenile turtles (Ehrhart et al., 1996; Holloway-Adkins, 2005).

Beach nourishment projects potentially result in burial of nearshore reefs (Nelson, 1989; Lindeman and Snyder, 1999; Bush et al., 2004). There are other potential direct and indirect impacts that could affect productivity on the continental shelf. To evaluate potential impacts, monitoring projects are frequently undertaken. The ability of these monitoring projects to address important questions related to the effects of beach nourishment on nearshore reef communities has been questioned with respect to scientific merit (Nelson, 1993; Peterson and Bishop, 2005). Much of this criticism is related to the basic principles of experimental design. If monitoring projects are to be improved to address the criticisms and eventually provide scientifically reliable answers to the questions raised concerning the impacts of beach nourishment projects on nearshore reefs, they must be soundly designed.

A second question is what good scientific design principles will add to monitoring projects. Use of these principles will eventually lead to better prediction of effects that may occur from beach nourishment projects. These predictions can then be incorporated into the determination of reasonable mitigation for impacts to nearshore reefs.

In this paper we initially discuss various aspects of experimental design as they are related to monitoring of nearshore hard bottom areas associated with beach nourishment projects. We describe a strategy that could contribute to the overall understanding of potential effects of beach nourishment on nearshore reefs. We then examine some basic experimental design principles that should be considered for monitoring projects. Following this discussion, two case studies are examined to see how they might be changed to more directly address the important questions related to the effects of beach nourishment projects.

OVERALL EXPERIMENTAL DESIGN CONSIDERATIONS

Future monitoring programs probably will have to be designed on a case-by-case basis due to the uniqueness of each project. This is to a large extent related to the nature of ecological science, which in many ways is a study of case studies (Shrader-Frechette and McCoy, 1993; Simberloff, 2004). The physical and biological conditions are different at each project site both spatially and temporally. We understand these immediate site-specific monitoring requirements, but we also recognize that from a regulatory standpoint it is beneficial in the long term to collect monitoring data that will be applicable to broader questions.

It is necessary that sampling be based on a before-after, control-impact (BACI) basis. Green (1979) described the original BACI design as sampling of an impact site and a control site (we prefer reference site because the term control site has the connotation of a manipulative experiment) before an impact occurs and after an impact occurs (Figure 1). This design was criticized by Hurlbert (1984) for pseudoreplication, as statistical statements can only be made relative to the particular sampling sites and the experiment is not replicated. This is not an easy problem to overcome. This design has been generalized to include the before-after, control-impact paired series (BACIPS)

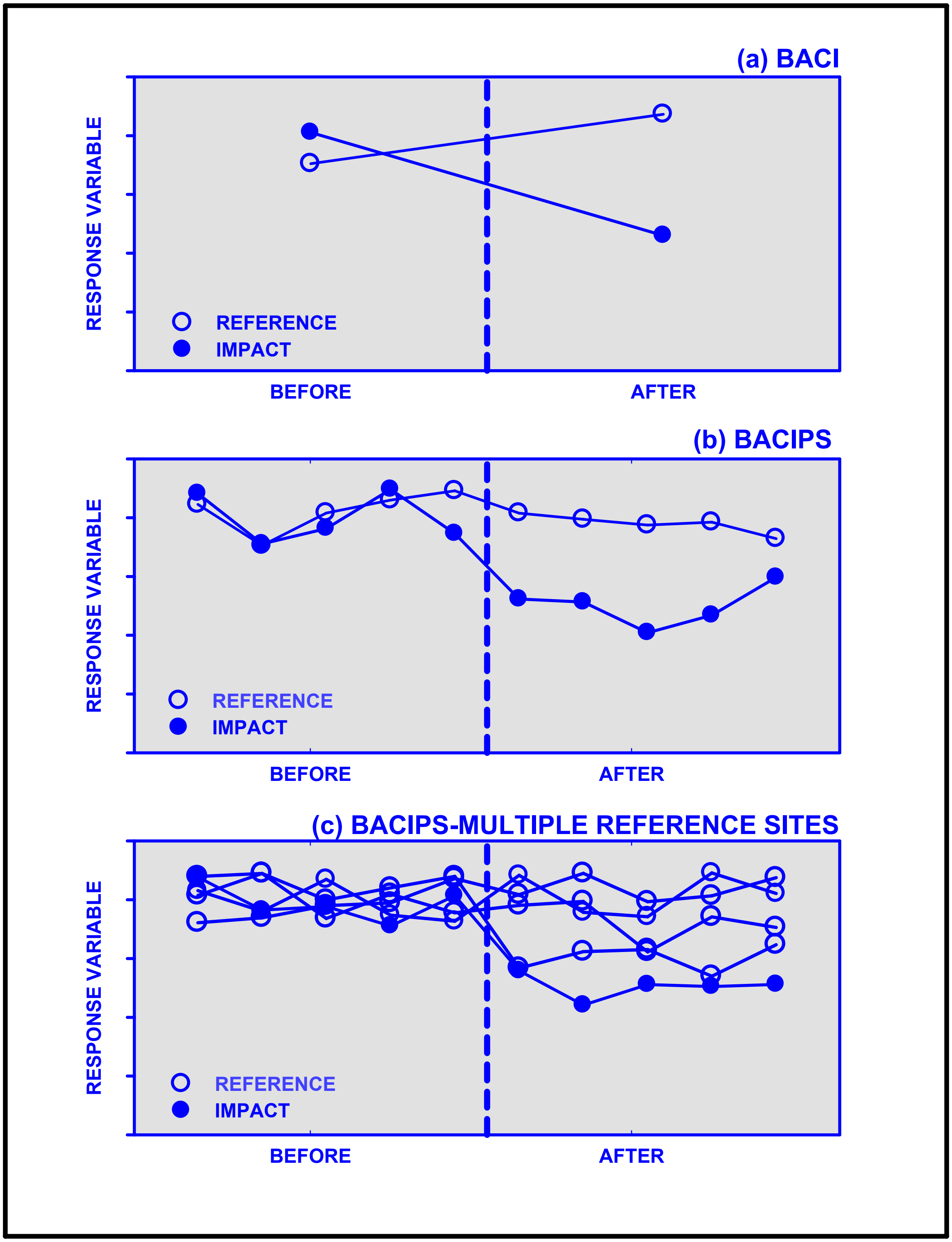

Figure 1. Comparison of three experimental designs: a) before-after, control-impact (BACI), b) before-after, control-impact paired series (BACIPS), and c) BACIPS with multiple reference sites.

design (Figure 1), replicating over time before and after the intervention event such as a beach nourishment project (Stewart-Oaten et al., 1986; Stewart-Oaten, 1996).

Using multiple reference sites helps alleviate some of the problems of pseudoreplication. Underwood (1996) recognized the need for multiple reference sites to capture the variability of ambient conditions and avoid confounding (pseudoreplication). Location treatments (impact/reference) are fixed, and reference monitoring study sites are nested within the reference treatment. There is a single impact treatment because there is a single site of the impact. This design permits better comparison between impact and reference cases because the reference mean better estimates conditions outside of the area that is nourished. This does not solve problems such as the need to intersperse the treatments randomly because there is only one project site for beach nourishment, and in the case of nearshore reefs, often few potential reference sites.

Because the nearshore reef monitoring project associated with each beach nourishment project is unique, statistical statements are limited to each individual study and generalization to beach nourishment overall cannot be made on a statistical basis. Suppose that some time in the future, a number of appropriately designed studies of the effects of beach nourishment on nearshore reefs have been conducted. We believe that each of these situations is unique and that the statistical statements can be made only within each particular study and cannot be statistically generalized. How can general statements be made on a statistical basis that will address the important questions concerning the potential effects of beach nourishment projects as raised in the 70 Scientists' Letter? One plausible approach is a meta-analysis, which is becoming more widespread in ecology.

Meta-analysis is a quantitative method to synthesize, analyze, and summarize the results of a collection of studies (Osenberg et al., 1999). There are several possible goals for a meta-analysis, including (1) construction of an aggregated, more powerful test of hypothesis and estimation, (2) estimation of the magnitude of a response, which could be estimation of a parameter, and (3) examination of relationships between parameter estimates and various environmental and biological variables. Initially at least, the focus of a meta-analysis of some future collection of beach nourishment monitoring projects could focus on a combined test of a "no effect" null hypothesis. An estimate of an effect size and the variance of this estimate for each study are necessary to conduct a formal meta-analysis. For example, a null hypothesis could be that in a beach nourishment project area, there is no decline in the cover of sessile invertebrates in water depths exceeding 4 m. This null hypothesis could be evaluated if the results of sufficient studies were available. An important advantage of this approach is the results will be generalized because we would be looking at a number of beach nourishment projects. We know that additional beach nourishment projects are likely to be conducted in the future. Adopting an overview approach such as meta-analysis and incorporating the principles of sound experimental design into beach nourishment monitoring projects could pay dividends in addressing outstanding questions, such as those raised in the 70 Scientists' Letter.

OTHER EXPERIMENTAL DESIGN CONSIDERATIONS

Clear scientific hypotheses directly related to evaluating potential impacts on nearshore reefs have to be identified. These scientific hypotheses must be incorporated in the experiment. There is currently a debate occurring in the scientific community about the proper way to test hypotheses, e.g., Bayesian versus classical testing of hypotheses. Currently, the classical method is widespread, but researchers should at least follow this debate and continue to consider using alternative approaches. In addition, since the introduction of personal computing, alternative methods are more commonly used to compute the distributions of test statistics for evaluating statistical significance and calculating confidence limits. Among these are rerandomization of data and bootstrapping. There are also newer methods for testing hypotheses for ordination and classification analyses. Examples are CANOCO (Lepš and Smilauer, 2003), analysis of similarities (Clarke, 1993), and multiresponse permutation procedures (Manly, 1997).

There is no silver bullet (e.g., Index of Biological Integrity) that can be routinely measured and computed to estimate the overall impact to nearshore reefs. We opine that population densities should be measured in an observational monitoring project to gain the best understanding of potential impacts to the community. Monitoring projects can be improved by collecting data for potentially confounding factors. Sediment traps can be used to estimate sediment accumulation (albeit biased) at the impact site and reference sites before and after beach nourishment. Similarly, more frequent and widespread turbidity measurements can be made. Other important factors can include volume of discharges and distances from nearby inlets, water depth, distance from shore, and typical wave activity. Differences related to beach nourishment and potentially confounding factors then can be quantified.

Replication of the experimental units is a basic experimental design principle, providing an understanding of the natural variability in the system. Comparisons among means of the experimental treatments can be evaluated to determine if they are more different than would be expected based on the natural variability in the system.

Replication of experimental units is imperative in order to have sufficient power for tests of hypotheses. Power is the probability of rejecting a false null hypothesis (converse of a Type II error). Early in the design phase of a monitoring study, the number of replicates should be determined. Replication is limited often by cost constraints, but if the statistical results of the monitoring project are to be reliable, the number of samples should be evaluated from the statistical perspective (This is not the same as computing a species-area curve, i.e., number of samples versus species richness, to estimate the adequacy of sampling a biological community). The first step in estimating the number of replicates needed is to define what a sufficient power level is; we recommend at least 80%. The next step is to determine the effect size of interest, which is a biological question, not a statistical question. The basic question is what level of change in the response variable (effect size) will be biologically significant to the population and/or community. In many instances, this is very difficult to answer because the dynamics of the biological system are not sufficiently understood to define an appropriate effect size. Peterson and Bishop (2005) recommended at least a 50% decline of a population or a 100% increase of a population to be the minimal level of effect size to be detected. After the power level and effect size have been determined and the statistical model for analyzing the data has been specified, the number of replicates that should be collected can be computed given a particular level of natural variability. If a reliable estimate of the natural variability is not available, then it is necessary to conduct a pilot study to gather the appropriate information. After the statistical analysis for a monitoring project is completed, it is also necessary to compute the actual power levels of the tests of hypothesis. This is particularly important if the null hypothesis is not rejected, as the actual power level is a measure of the reliability of the result, i.e., the lack of rejection was due to insufficient replication.

Randomization of the experimental units within the different treatments and strata of the sampling design is an important aspect of developing a monitoring project that will provide reliable statistical answers. Randomization is the means by which representative samples are obtained. Arbitrary placement of samples along fixed transects may address the immediate need to map the extent of sand movement from a nourished beach, but it is easily criticized as not necessarily being representative of the population inhabiting a nearshore reef. Ideally, randomization should be done not only in space but also within time.

An important aspect of randomization is how quadrats are located for a monitoring project of a nearshore reef. Green and Smith (1997) point out the advantages of permanently marking the locations of random quadrats during the initial monitoring survey, known as a repeated measures design. These quadrats then can be revisited during subsequent surveys, and the response variable of the analysis can be based on differences (changes over time). This approach has the advantage that the inherent spatial variation in abundances of reef taxa does not greatly affect the analysis. An additional advantage is that changes in particular individual specimens can be monitored within quadrats. There are several disadvantages to this approach. The quadrats will need to be marked in some permanent manner, the presence of which may in fact alter processes occurring at the marked location. An example of this is marking quadrats with rods that may attract fish to the vicinity, potentially increasing nutrient input locally as well as possibly increasing the pressure of predation or herbivory on populations in the quadrat. There also is an expense associated with permanently establishing the quadrats and relocating the quadrats during subsequent surveys.

Stratification in the sampling design is a very useful tool to isolate different sources of variability. Examples are distance offshore, water depth, or distance from an inlet. We propose that individual strata be oriented along shelf in beach nourishment monitoring projects to differentiate changes in the nearshore reef at varying distances from shore (cross-shelf gradient), as illustrated simplistically in Figure 2. Random samples would be collected on nearshore reefs in each individual stratum, providing data to statistically test hypotheses. This is in contrast to the cross-shelf orientation of transects (Figure 2).

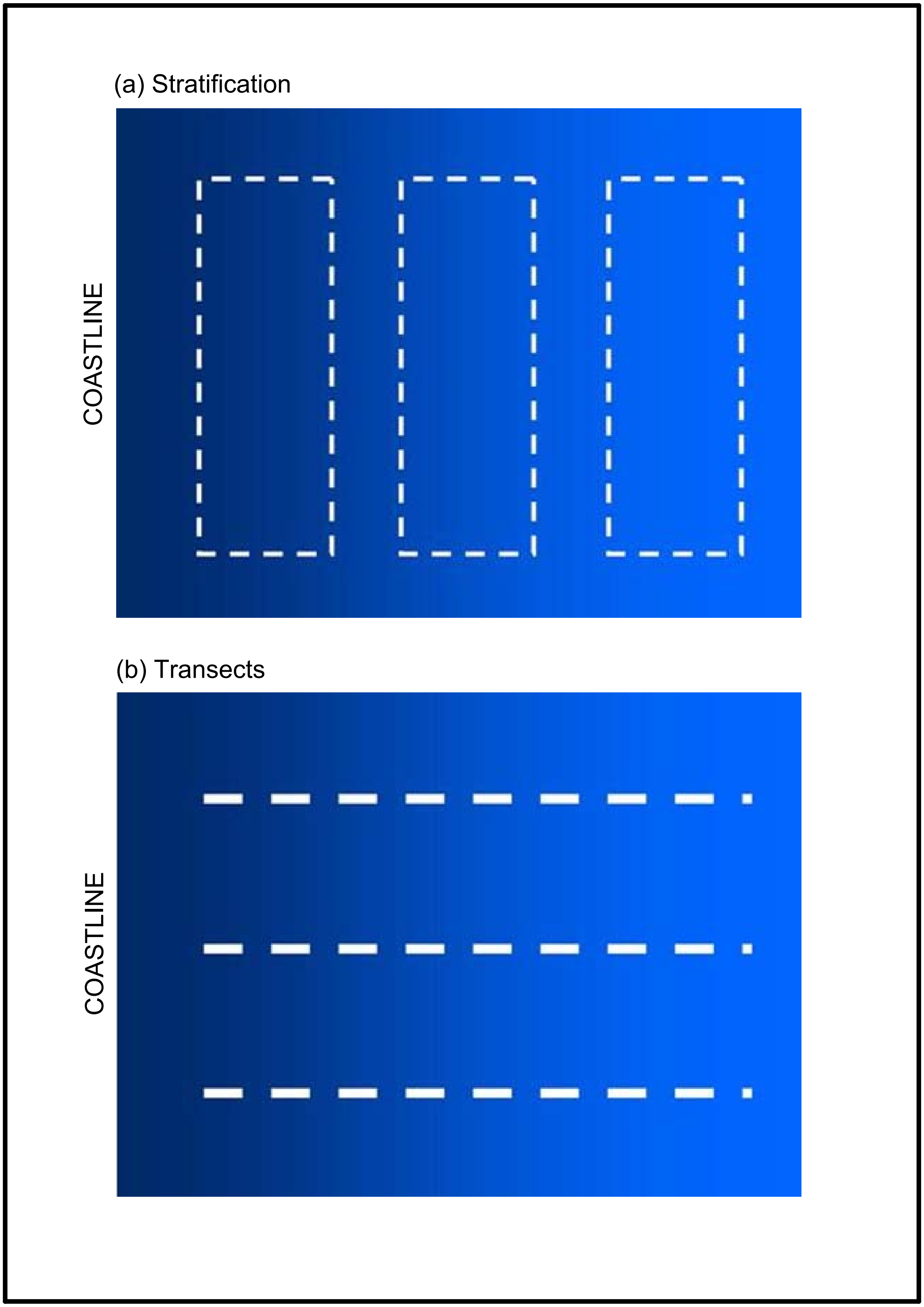

Figure 2. Evaluation of gradients relative to the coastline: (a) stratification and (b) cross-shelf transects.

Given the above considerations, the effects of reality have to be recognized. Project funding is always an issue, and there is never sufficient money to do everything that is needed. Timing is important. If a beach nourishment project is scheduled far enough in the future, then it is possible to collect pre-event data. However, if the beach nourishment is an emergency response to damage from a hurricane, there may not be sufficient time for a series of pre-event samplings. There are practical issues that can affect how monitoring projects are conducted, such as areas where turbidity and/or physical conditions such as water depth or wave action limit data collection. What we hope to accomplish is that experimental design principles be considered and incorporated as much as possible so that eventually there will be sufficient study data to address the more general questions of potential impacts on nearshore reefs.

CASE STUDIES

In this section, we examine two case studies in light of the preceding discussion concerning experimental design principles; Continental Shelf Associates, Inc. (CSA) currently is involved in both monitoring studies. The first is a monitoring project for a beach nourishment for the City of Venice on the Gulf of Mexico coast of Florida, and the second is a monitoring project for beach nourishment in Indian River County on the Atlantic coast of Florida. Both beach nourishment projects are being conducted with emergency funding that was made available in response to damages to the beaches that occurred during the 2004 hurricane season.

Venice Beach

Nearshore hard bottom reefs along the Venice fill site are limestone and range from outcrops with 0.5-m relief to pavement-like areas covered by thin veneers of sand. These outcrops support epibiotal assemblages consisting of macroalgae, sponges, hydroids, stony corals, octocorals, and ascidians. Taxonomic richness and composition of these assemblages vary spatially alongshore and cross-shelf. Macroalgae contribute most to the biotic cover found on the hard bottom. Following macroalgae in terms of cover are sponges and compound ascidians, respectively. Octocorals and stony corals exhibit a patchy distribution through the area, and both taxa occur on high relief as well as sand-covered substrata.

One stated purpose of the monitoring was to assess possible direct and indirect impacts to hard bottom communities. The monitoring is being conducted over 5 years on the premise that the equilibrium toe-of-fill will have reached its final position within that time period.

For the nearshore reef monitoring, 24 permanent, 150-m transects were established prior to the beach nourishment, 21 of which were within the fill area and 3 of which were in reference areas south of the fill area (Figure 3). The transect locations correspond to Florida Department of Environmental Protection (FDEP) monuments.

Figure 3. Placement of transects on nearshore reefs for monitoring the City of Venice beach nourishment project.

Sampling consists of physical and biological attributes along each transect at 7.5-m intervals using a 0.5-m^2 quadrat frame. Physical attributes are

- Sediment type;
- Percent sedimentary cover;
- Sediment depth (thickness) overlying hard bottom; and
- Physical relief of hard bottom.

Biological attributes are

- Counts of all scleractinian coral taxa within four size classes
    - recruits: <2 cm;
    - 2 to 5 cm;
    - 5 to 25 cm; and
    - >25 cm
- Counts of all octocoral taxa within four size classes
    - 0 to 15 cm;
    - 15 to 30 cm;
    - 30 to 45 cm ; and
    - > 45 cm
- Percent cover of fleshy macroalgae and calcareous algae within six cover classes
    - 0% to 1%
    - 1% to 5%
    - 5% to 25%;
    - 25% to 50%;
    - 50% to 75%; and
    - 75% to 100% (with identification of dominant groups of algae)
- Percent cover of coralline algae within four cover classes
    - 0% to 25%;
    - 25% to 50%;
    - 50% to 75%; and
    - 75% to 100%
- Presence/absence of sponges, hydroids, and ascidians.

In addition to quadrat samples, video transects are collected from 0 to 22.5 m, 60 to 82.5 m, 97.5 to 110 m, and 122.5 to 150 m along each transect for general biological and physical descriptions of the transects and analysis of hard bottom community. Sentinel organisms also are selected on an opportunistic basis for monitoring. These organisms are permanently marked and photographed for future comparisons.

During each post-construction survey (conducted at 1-year intervals), the 24 permanent transects will be sampled with *in situ* quadrats and video. Data collection will be the same as for the pre-construction survey. Photoquadrats of the sentinel organisms are photographically sampled at the fill sites.

The question we are posing is what can be added or changed in this program based on the preceding discussion that would make it more statistically based and increase its utility in a future meta-analysis study. Recognizing that our ultimate objective is to determine if beach nourishment affects nearshore reefs in Florida, what would we recommend?

- *Definition of clear, statistically testable null hypotheses.* Viable null hypotheses of the monitoring project include no difference between the beach nourishment project area reef site and the reference (control) nearshore reef site with respect to counts of (1) scleractinian coral taxa (four size classes); (2) octocoral taxa (four size classes); and (3) percent cover of fleshy macroalgae, calcareous algae, and coralline algae (four cover classes).
- *Multiple reference sites.* This monitoring project has three reference transects located south of the beach nourishment project area. The reference sites were located "downstream" of the site of potential impacts out of necessity. This is an example of constraints imposed by site-specific characteristics. We recommend that this one reference area be used as a reference site and additional reference areas be added to the monitoring project to better characterize variability in ambient conditions on nearshore reefs around this project.
- *Stratification with distance from shore for an assessment of potential impacts relative to a cross-shelf gradient.* Transects are somewhat arbitrarily or haphazardly placed on nearshore reef areas. We would recommend stratifying the sampling in a manner similar to that presented in Figure 2a to be able to make statistically defensible statements about the gradient from the fill area.
- *Multiple pre-construction surveys; the time of each survey is randomized within the sampling interval.* Only one pre-construction survey was conducted for this monitoring project. This is likely due to the emergency funding that was made available in response to damages to the beaches that occurred during the 2004 hurricane season. If time permits, additional pre-project surveys would be valuable for characterizing the temporal component of the monitoring.
- *Randomization and replication of quadrat samples within the impact and reference sites and strata.* Randomization and replication of the samples is needed to correctly analyze the data on a statistical basis. The number of replicates to be collected should be determined from an appropriate analysis of power to ensure adequate power for the statistical analysis. A pilot study may be needed if appropriate data are not available.
- *Measurement of potential confounding and covarying variables.* Measurements of turbidity, water depth, and other environmental variables would enhance the ability to interpret the results of the monitoring program.

Indian River County

CSA also is conducting a monitoring project for a beach nourishment project in Indian River County. The hard bottom features consist of shallow water coquina rock outcrops ranging from low to high relief. The hard bottom is primarily colonized by sabellarid worms, macroalgae, sponges, tunicates, and occasional octocorals, and with associated crustaceans, echinoderms, and fishes.

In this project, sessile reef biota are surveyed along 10 permanent transects established within the fill area and along 2 reference transects (Figure 4). These 12 transects are located relative to FDEP monuments and extend seaward from the nearshore edge of hard bottom for 180 m. Fixed quadrats along each transect are sampled to compute percent cover of algae and attached biota, percent sediment cover, sediment thickness/accumulation, and counts of dominant attached epifauna. Quantitative video data also are collected on the hard bottom portion of each transect. These data are analyzed for percent cover of algae, attached biota, and substrate. Biota is identified to the lowest practical taxonomic level. There is a single pre-construction survey and several post-construction surveys.

What would we recommend to improve this project? Our recommendations are similar to those for the Venice project:

- *Definition of clear, statistically testable null hypotheses.* Viable null hypotheses of the monitoring project include no difference between the beach nourishment project area reef site and the reference (control) nearshore reef site with respect to cover of algae and attached fauna.
- *Multiple reference sites.* This monitoring project has only two reference transects, both of which are situated south of the project area. We recommend that this one reference area be used as a reference site. Additional reference areas should be added to the monitoring project to better characterize variability in ambient conditions on nearshore reefs around this project.
- *Stratification with distance from shore for an assessment of potential impacts relative to a cross-shelf gradient.* As was the case for the City of Venice monitoring project, transects are somewhat arbitrarily or haphazardly placed on nearshore reef areas. We recommend stratifying the sampling to be able to make statistically defensible statements about the gradient from the fill area.
- *Multiple pre-construction surveys; the time of each survey is randomized within the sampling interval.* Funding for this project also was an emergency response to damages to the beaches that occurred during the 2004 hurricane season. Only one pre-construction survey will be conducted for this monitoring project, and this may be unavoidable. If time and site conditions permit, additional pre-project surveys would be valuable for characterizing the temporal component of the monitoring.
- *Randomization and replication of quadrat samples within the impact and reference sites and strata.* Again, randomization and replication of the samples is necessary to obtain a statistically valid sample. The number of replicates should be determined from an appropriate analysis of power to ensure adequate power for the statistical analysis, and a pilot study may be needed if appropriate data are not available.

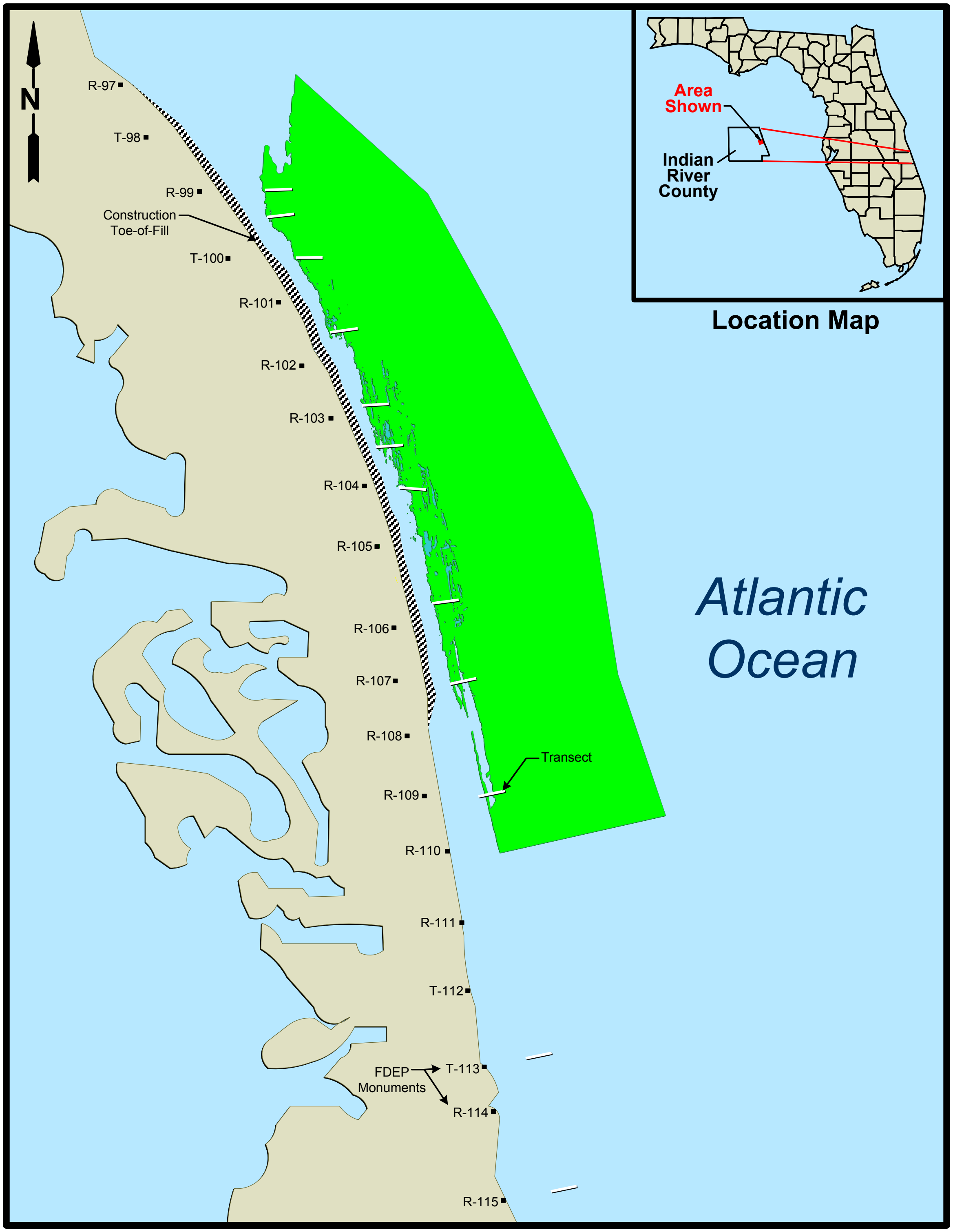

Figure 4. Placement of transects on nearshore reefs for monitoring the Indian River County beach nourishment project.

- *Measurement of potential confounding and covarying variables.* Measurements of turbidity, water depth, and other environmental variables would enhance the ability to interpret the results of the monitoring program.

CONCLUSIONS

1) It would be useful to develop an overall approach to assess potential impacts of beach nourishment projects so that at some time in the future the results from monitoring studies can be generalized to address outstanding questions concerning the impacts of beach nourishment on nearshore reef communities. One such approach would be a meta-analysis based on a number of appropriately designed monitoring studies.

2) A BACI experimental design is recommended. If possible, BACIPS with multiple reference stations would be the preferred approach because it provides a better characterization of the ambient variability.

3) Experimental design considerations that would improve the ability to make statistical statements relative to the effects of beach nourishment on nearshore reef communities for individual projects include

- Clear scientific, testable hypotheses;
- Measurement of potentially confounding and covarying factors;
- Replication;
- Randomization; and
- Stratification.

The reality is that funding, geography, and timing may preclude the incorporation of all of the suggested experimental design principles into a nearshore reef beach nourishment monitoring project. However, considering these principles during the design phase and incorporating as many as possible will certainly improve the scientific basis of a monitoring project.

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