Short communication

Using ecological processes to advance artificial reef goals

Margaret W. Miller


The ecological study of natural reef communities has followed a progression from observational/descriptive studies to a more experimental and process-oriented approach. Ironically, most published studies of artificial reefs are observational despite the fact that their manipulative nature lends these reefs to an experimental approach, and despite the potential benefits of an experimental, process-oriented approach to fulfilling their objectives. Most applications of artificial reefs are underpinned by ecological processes ranging from trophic interactions and recruitment to individual physiology and biogeochemical cycling. Examples concerning three goals are discussed; enhancement of fisheries production, ecosystem restoration, and water quality enhancement. These examples illustrate (1) predictions that can be drawn from basic ecological studies of “natural” reef organisms and ecosystems regarding ecological structure, processes, and performance of artificial reefs, and (2) how an experimental ecological approach has been (or could be) utilized to elucidate ecological process and yield specific improvements in the application of artificial reefs to achieve management goals. In fact, answering the “why” and “how” questions addressed by experimental process studies is the only way to improve our success in achieving any sort of ecological engineering objectives.

Introduction

Ecology has followed a progression from observational and descriptive study to a process-oriented, often experimental, approach, and the questions addressed have progressed from “who, what, when, and how much?” to “why and how?” Artificial reef research is an applied field and process-oriented study has often been given low priority. Despite the fact that the construction of an artificial reef, by definition, constitutes a field manipulation (i.e. experiment) that could be used to elucidate ecological process and function, the literature on this topic contains largely observational studies. This irony is further reflected in several reviews that distinguish “study” reefs as a separate goal or genre of artificial reef deployment, as contrasted with “application reefs” (Seaman, 1997; Bohnsack and Sutherland, 1985). In fact, the “why and how” questions are the most important ones to answer in trying to achieve any sort of ecological engineering goals. Because artificial reef goals are underpinned by ecological processes (Table 1), process-oriented research must be undertaken to advance these goals.

Fisheries production is the oldest and most ubiquitous motivation for artificial reef construction. More recently, environmental and conservation concerns have been instrumental in the formulation of novel goals such as water quality improvement and ecosystem restoration. Their attainment, as for fisheries production, is inherently dependent on ecological processes operating at multiple scales (Table 1). The aims of the current paper are (1) to provide examples for these three types of goals that illustrate what “natural” reef ecology has to offer, and (2) discuss how artificial reef research has taken (or should take) advantage of ecological knowledge to make rapid advances.
Fisheries production

The “attraction-production” debate (Lindberg, 1997) has provided the impetus for effective process-oriented research on artificial reefs in relation to fisheries production. As one example, Eklund (1997) utilized standard, hollow units to test the relative importance of two reef characteristics, provision of benthic food resources and refuge availability/heterogeneity, in supporting fish assemblage. One-third of the units was painted with an anti-fouling paint to inhibit the development of benthic forage base, one-third was filled with broken cinder block material to provide additional structural complexity (refuge space), and the remaining third served as the control treatment. The experiment showed that the filled units supported significantly greater fish abundance and richness, while the painted units (providing less reef-based food resources) did not differ significantly from the unpainted units. Thus, in this particular environment (southeast Florida Shelf, USA), the provision of refuge space is much more important than the provision of reef-based trophic resources in supporting fish abundance. This implies that predation is a much more important limitation of fishery production than is competition for food. An additional experiment (Eklund, 1997) confirmed that predation was indeed the mechanism which depressed fish abundance on artificial reefs with less structural refuge.

Thus, Eklund (1997) utilized experimental methods to test the functioning of artificial reefs in providing a productive fish habitat. The results provide a better understanding of the ecological processes limiting fish production, and, hence, can be used to enhance design and management toward the goal of increased fishery production. Specifically, artificial reefs with greater availability and heterogeneity of refuge space will support more fish. Design and management aimed at promoting benthic communities as forage base may or may not be important depending on the particular environment. Applying similar experiments in environments with different benthic food resources could further elucidate this issue and provide additional guidance toward improved fishery production of artificial reefs.

Water quality enhancement

By extracting particles from the water, communities of filter-feeding benthic invertebrates may have a beneficial effect on coastal water quality (Newell, 1988). Some of these animals (e.g. sponges) may even be able to filter and sequester other pollutants, such as heavy metals, as well as organic matter. Thus, artificial reefs supporting filter-feeder communities may be able to mitigate water quality degradation from organic enrichment (Figure 1). While this approach appears to have been adopted, for instance, in the Caspian Sea (Bugrov, 1994) and the Mediterranean Sea (in concert with the goal to produce harvestable sponges; Pronzato et al., 1999), quantitative studies of the ecological processes (individual nutritional physiology and biogeochemical cycling of organic matter and nutrients) and of the effectiveness of filter-feeders on artificial reefs in improving water quality have not been published. Laihonen et al. (1996) describe a similar approach utilizing marine plants for absorbing excess dissolved nutrients.

In contrast, there is a fairly strong literature quantifying the effects of filter-feeders of natural reefs on plankton and benthic-pelagic coupling in temperate, tropical, and even freshwater environments. Depending on the environment, up to 90% (Great Barrier Reef) of the ultraplankton is removed by filter-feeders as water passes over a reef (Ayukai, 1995). Sponges, even if their abundance is low (10% cover), can filter the entire water column of 15 m deep in a single day (Reiswig, 1974). A richer sponge community (44% cover) in Lake Baikal, a freshwater system, extracted 1.97 g C m⁻² d⁻¹ (particulate organic matter) from the water column (Pile et al., 1997).

These findings support the notion that artificial reefs may be able to improve degraded water quality by hosting filter-feeding benthic invertebrates. However, their filtering effectiveness is only part of the story.
The organic matter removed is metabolized and results in a substantial excretion of dissolved inorganic nutrients. For example, the tropical reef sponge Chondrilla nucula, which occupies 12% of substrate on natural reefs in Puerto Rico, releases 4000 μmol DIN m⁻² h⁻¹, representing 50–120% of the nitrogen required to support reef productivity (Corredor et al., 1988). The release of dissolved inorganic nutrients from filter-feeding communities may obviate improvements to water quality accomplished through filtering of organic particles by stimulating phytoplankton blooms (Figure 1).

One possible ecological engineering approach by which to break out of this cycle may be to manage the artificial reef to include both filter-feeding invertebrates and attached seaweeds that can rapidly utilize dissolved inorganic nutrients. Specific management measures may include planting of seaweeds if they do not recruit on their own, controlling herbivory to prevent overgrazing, and harvesting to export excess production from the system and/or for commercial use.

Although ecological studies do suggest that artificial reefs may be able to contribute to water quality enhancement, rigorous quantitative experimental studies at multiple sites with similar environments are necessary. Units with different filter-feeder communities (sponges, tunicates, bivalves) without and with seaweeds must be placed at similar, replicated sites to assess this potential. Simultaneous attention to the underlying processes of feeding ecology and biogeochemical cycling and to the effects in terms of gross water quality changes in such a prototype application should provide insight and allow rapid diagnosis of failures. If successful, fine-tuning of the most effective benthic species composition with respect to extraction of heavy metals or other pollutants, as well as in terms of commercial harvests, might follow. Such experimental assessments are tractable, and could greatly advance this potentially powerful approach to water quality mitigation.

### Restoration

Artificial reefs are often used to replace lost physical structure (e.g. in the case of a ship grounding or coral mining; Clark and Edwards, 1994). Artificial reefs may also be placed in areas where reefs had not previously been present to compensate for destroyed habitat or to restore fish production lost owing to an acute event.

Their use in the restoration of coral reefs flattened by ship groundings seeks to replace topographic structure and secure loose materials and fissures that often result from a large physical impact and may cause additional damage during subsequent storm events. The engineering aspects of these applications have been successful, and the structures have remained stable even through hurricane conditions (pers. obs.). The ecological aspects of what constitutes a successful restoration are less well defined.

A primary consideration in the recovery process of tropical coral reef systems is the successful recruitment
and growth of stony corals. A recent comparative study sought to assess the relative ecological success of two structural restoration projects deployed in the Florida Keys National Marine Sanctuary, USA, in 1995 (Miller and Barimo, 2001) by assessing coral recruitment. These two structures differed in terms of both design and ecological characteristics such as depth. The structure at the site of the MV “Alec Owen Maitland” (3-m depth) consisted of large (2 to 4 m) concrete armour units with small (20–30 cm) quarried limerock embedded in the top surface, which were cemented together to entomb the loose rubble material. The structure at the MV “Elpis” site (10 m depth) consisted of quarried carbonate boulders (~1 m in diameter).

The stony coral assemblages recruiting to these structures differed markedly (Miller and Barimo, 2001). The boulder reef at the Elpis site hosted a greater richness and evenness, as well as approximately double the density of coral recruits compared to the concrete reef at the Maitland site. In addition, within the Maitland structure, significantly more recruits occurred on the embedded limerock than on the concrete matrix of the structure. The basic ecological literature on coral life history (reviewed by Richmond, 1997) suggests several mechanisms that could explain the difference in coral recruitment on the two substrates. These mechanisms include differences in surface rugosity, and facilitation (on limerock) or impediment (on concrete) of coral recruitment by crustose coralline algae or a thick algal turf/sediment layer, respectively.

The study suggests, but does not prove, that carbonate boulders may be more suitable material for coral reef structural restorations than concrete. An experimental study aimed at determining recruitment success on each material at each site, and carefully designed to separate the proposed mechanisms of surface rugosity and mediation by the benthic algal community colonizing each material, would be necessary to overcome the confounding of the results obtained so far owing to differences in the ecological environment at the two sites and to determine the ecological mechanism responsible.

Integrative example

Lenihan and Peterson (1998), Lenihan (1999), and Lenihan et al. (1999) provide a stellar example of how an experimental approach can effectively evaluate ecological performance of artificial reefs with different characteristics, yield insight into ecological processes, and, hence, provide direct guidance on characteristics that would optimize performance.

Oyster populations, landings, and oyster reef habitats in the estuaries of the eastern United States have been in dramatic decline over the past decade or two owing to destructive harvesting techniques, water quality degradation, and disease. An oyster reef restoration programme using dead oyster shells to form mounds about 1 m tall had minimal success, as many mounds experienced significant burial, and most settling oysters died of disease before they reached harvestable size.

Lenihan (1999) performed a controlled experimental study to evaluate various aspects of individual oyster performance (recruitment, growth, and mortality due to predation or physiological tolerance) on artificial reefs with differing characteristics (reef height: short – 1 vs. tall – 2 m; depth of placement: 3 vs. 6 m; position on the reef: crest vs. base) while carefully monitoring the hydrographic and hydrologic conditions experienced by oysters in the different treatments. The major source of mortality for both oysters and other occupants (fishes and crabs) in all treatments deeper than 5 m was exposure to anoxic/hypoxic conditions. All aspects of oyster performance except recruitment were significantly improved in the treatments experiencing enhanced water flow. In fact, 81% of the variation in growth and mortality observed was explained by variation in water flow. Even disease incidence and intensity were reduced under conditions of high flow (Lenihan et al., 1999).

Thus, while it might be anticipated that the implications of ecological process studies for artificial reef design would be unwieldy and complex, the results of Lenihan’s work yield very simple and feasible recommendations. Artificial oyster reefs should be in shallow water or provide elevated habitat to minimize exposure to anoxic/hypoxic conditions and they should be tall (2 m) to enhance flow over the crest, and their functional lifespan should be maximized in the face of destructive mechanical harvesting. Tall reefs, even in deeper water subject to seasonal anoxic events, can provide suitable habitat for oysters and a whole community of secondary producers.

Conclusion

Artificial reef research has, in a few cases, examined ecological processes structuring the developing communities (often with an experimental approach) and thus provided for specific improvements in design, placement, and/or management. The results obtained in natural reef ecology can afford a head-start to the study of ecological processes on artificial reefs by providing predictions regarding organism, population, and reef characteristics as well as techniques for testing these predictions. By understanding the ecological processes— the why and how of the assemblage and performance under observation—artificial reef success may be enhanced at an unprecedented rate, particularly if every artificial reef were treated as a study reef.
Acknowledgements

This contribution was made possible by the consideration and support of Dr. William Seaman, Jr. and greatly facilitated by the cooperation and help of several colleagues, including Drs. Adele Pile (Flinders University, South Australia), Hunter Lenihan, and Anne-Marie Eklund (both NOAA-Fisheries). To all I am extremely grateful.

References


