9-1-2001

Artificial Substrate and Coral Reef Restoration: What Do We Need to Know to Know What We Need

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NSUWorks Citation

Richard E. Spieler, David S. Gilliam, and Robin L. Sherman. 2001. Artificial Substrate and Coral Reef Restoration: What Do We Need to Know to Know What We Need .Bulletin of Marine Science , (2) : 1013 -1030. http://nsuworks.nova.edu/occ_facarticles/142.

BULLETIN OF MARINE SCIENCE, 69(2): 1013–1030, 2001

ARTIFICIAL SUBSTRATE AND CORAL REEF RESTORATION: WHAT DO WE NEED TO KNOW TO KNOW WHAT WE NEED

Richard E. Spieler, David S. Gilliam and Robin L. Sherman

ABSTRACT

To use artificial substrate effectively in coral reef restoration certain basic knowledge is required: (1) what is the artificial substrate expected to accomplish relative to the goals of the restoration effort and (2) what are the expected interactions of the selected substrate's composition, texture, orientation, and design with the damaged environment and the biota of interest. Whereas the first point is usually clear, at least in general terms, the second is not. In this review, we examine: the functions of artificial substrate in restoration and some of the physical (i.e., composition; surface texture; color and chemistry; and design in terms of profile, shelter, shading, size and configuration, settlement attractants, and stability) and environmental factors (i.e., temperature, light, sedimentation, surrounding biota, hydrodynamics, depth, and temporal effects) affecting these functions. We conclude that until substantial additional research is accomplished, the use of artificial substrate in coral reef restoration will remain a 'best guess' endeavor. Areas requiring additional research are identified and some potentially promising lines of inquiry are suggested.

Coral reefs worldwide are in a state of decline (Ginsburg, 1994; Jameson et al., 1995). Although a number of causative factors for the decline are natural in origin (i.e., storms, changing weather patterns, and epizootics), much of the damage is anthropogenic (e.g., coastal development, ship groundings, pollution, etc.). Damage due to natural causes is often so widespread and catastrophic that human intervention or restoration is not feasible. In contrast, there is considerable interest in preventing anthropogenic damage as well as mitigating, rehabilitating and/or restoring coral reef environs subjected to human disturbance. In recent years, there has been increasing interest in using artificial substrate to aid in accomplishing these goals.

To use artificial substrate effectively in coral reef restoration requires certain basic knowledge: (1) What is the artificial substrate expected to accomplish relative to the goals of the restoration effort? (2) What are the expected interactions of the selected substrate's composition, texture, orientation, and design with the damaged environment and the biota of interest?

In contrast to much of the earlier work with artificial reefs, a review of recent papers, gray literature, and request for proposals (RFPs) indicates that resource managers, in general, have a clear idea of what they wish to accomplish with artificial substrate in mitigation and restoration projects. Usually the primary goals deal with easily verifiable physical construction, i.e., reconstructing vertical relief, consolidating substrate, and coral transplantation or reattachment (Hudson and Diaz, 1988; Clark and Edwards, 1994). The construction should, in turn, aid in restoring the biotic community. Restoration is much more difficult to quantify, however, especially in the absence of pre-destruction baseline data.

The second of the two questions is not as readily answered. Relatively little is understood about the interaction of artificial substrate with the ecology of the environment in which it is placed. It is this problem that we address here. This paper concentrates on restoration of coral reefs that have been subjected to physical damage (e.g., ship groundings, coral mining) rather than nutrient or other chemical damage. Restoration is used here in the broadest sense to include mitigation and rehabilitation.

Although there have been a host of other reviews pointing out the state of knowledge, and the substantial deficits in knowledge, of artificial reef function, they have mainly concentrated on fisheries issues (e.g., Bohnsack and Sutherland, 1985; Seaman et al., 1989; Bohnsack, 1991; Bohnsack et al., 1991; Grove et al., 1991; Seaman and Sprague, 1991; Seaman, 1997). There have also been several reviews of workshops on coral reef restoration (Woodley and Clark, 1989; Miller et al., 1993) but apparently this is the first review to specifically examine the state of knowledge of artificial substrate in coral reef restoration efforts with the aim of discerning research needs.

Below we examine the functions of artificial substrate in restoration, the structural and environmental determinants of function, and some considerations of costs and aesthetics. Many of the topics touched on in this paper are backed by an extensive literature, well worth a review unto themselves, for example: structural complexity and community structure or colonization dynamics on artificial substrates. In such cases our citations are intended to be representative, not all inclusive.

Function of Artificial Substrate in Restoration

Artificial structures can be designed and deployed to accomplish multiple functions: (1) provide hard substrate for invertebrate colonization; (2) provide refugia for fish and invertebrates; (3) alter currents; (4) consolidate rubble; (5) impede fishing, for example by obstructing trawling; (6) attract fish; (7) provide a tourist attraction; or any combination of these characteristics.

The first four of these functional characteristics are mainly the ones of interest in restoration efforts. The first two (provide hard substrate and refuge) deal primarily with biological concerns, the latter two (alter currents and consolidate rubble) primarily with engineering concerns. Obviously, there is substantial overlap between biological and engineering concerns. For example, reefs designed as invertebrate substrate will need to consider questions of stability, and consolidated rubble should incorporate biological considerations related to substrate and refuge. We briefly expand on these four functions below.

The main problem in coral reef damage to the corals is the loss of the animals. The loss of corals, and coralline structure, can cause profound changes in the entire reefal community structure (Ebersole, 1999; Swanson et al., 1999). Restoration efforts with corals, using artificial substrate, are therefore aimed at providing fixed substrate, either for coral settlement or for artificial attachment of broken or transplanted corals. For settling corals, at least, the artificial substrate also needs to provide refuge (see below). To date, most of the work on coral reef restoration has concentrated on coral repair, either through reattachment or transplantation to natural or artificial substrate and, to some extent, providing hard substrate for settlement (for references see: Miller et al., 1993; Clark and Edwards, 1995; Oren and Benayahu, 1997; Edwards and Clark, 1998). Edwards and Clark (1998) have critically examined current transplantation approaches and concluded that in most cases, where the degraded area receives sufficient recruits naturally, coral transplantation should be the last resort of a restoration effort. Further, they suggested when coral transplantation is justified that slow-recruiting, slow-growing massive corals be used. These conclusions highlight the need for artificial structure, at least in the short term, to replace the structural function of coral.

In contrast to corals, with fishes and some macroinvertebrates the problems associated with coral reef damage, such as a ship grounding, are usually not the direct loss of the animals per se but rather the loss of refuge supplied by coral and epifaunal structure (Dennis and Bright, 1988). There is some debate as to what generalizations on fish-habitat interactions can reliably be formed from research to date (Jones and Syms, 1998). Nonetheless, there have been a number of studies reporting a positive correlation between reef complexity, or refuge, and diversity of fishes as well as total numbers of fish (Shulman, 1984; Roberts and Ormond, 1987; Hixon and Beets, 1989; 1993; Beukers and Jones, 1998; Rilov and Benayahu, 1998; Friedlander and Parrish, 1998; Eklund, 1996; Gilliam, 1999; Sherman, 2000) or lobster (Herrnkind et al., 1997). Most of these studies have concentrated on refuge from predation. However, refuge from current can also be an important consideration in some areas (Bohnsack et al., 1991; Hobson, 1991). Damage to coral reefs also destroys some food resources; although it is not clear if food resources on the reef are limiting for many species (Shulman, 1984; Jones, 1991). By increasing diversity and the numbers of some fishes and invertebrates, replacing refuge also increases the amount of food available to higher trophic levels; thereby replacing food resources lost due to physical destruction. Thus the major goal of artificial structure in coral reef restoration efforts, as relates to fishes and some macroinvertebrates, is to replace necessary refuge.

As fixed structures, corals are hydrodynamic elements affecting current flow. The loss of corals can, therefore, dramatically affect downstream currents and wave action, producing scouring and destruction of biota that are adapted to lower energy environments. There have been several attempts to mitigate the loss of current-protective corals or natural reef structure with artificial structure (Clark and Edwards, 1994; Harris, 1999).

Ship groundings, and the associated attempts to dislodge the ship, as well as coral mining can produce extensive rubble. Left unaltered, rubble can be moved about on the sea floor by current action and can damage attached or nearby invertebrates (Gittings et al., 1993; Clark and Edwards, 1994). There have been several recent efforts, with limited success, to consolidate rubble using artificial substrate such as lime-rock boulders and concrete mat or modules (Clark and Edwards, 1994; Waxman et al., 1999).

From a biological perspective, to take full advantage of the functions artificial substrate can provide to restoration efforts, we must understand both the restoration objectives and which attributes of artificial structure provide its functionality. How associated organisms will interact with an artificial reef will depend, in large measure, on the specific structural attributes of that reef and the environment in which it is deployed.

Structural Determinants of Function

The physical attributes of artificial substrate that contribute to its function are discussed in this section, e.g., composition; surface texture, color and chemistry; and design in terms of profile, shelter, shading, size and configuration, settlement attractants, and stability.

Composition.—A variety of materials have been used in the construction of artificial reefs: e.g., wood, steel, fiberglass, PVC, materials-of-opportunity, tires, boulders, concrete, electro-deposition of $CaCO_3/Mg(OH)_2$ (Grove et al., 1991). Although there may be exceptions, such as the use of tires or plastic (Chua and Chou, 1994; Oren and Benayahu, 1997), in most coral reef restoration or mitigation efforts some form of concrete (usually steel reinforced) or natural rock (lime rock boulder) or a combination of the two has been the material of choice (Hudson et al., 1989; Clark and Edwards, 1994). These materials have the advantages of: providing a substrate of similar composition as that replaced, durability, high weight for stability, economy, and in most cases, availability. In addition, concrete is readily engineered into a specific design. However, from an ecosystem restoration perspective, additional research is required to examine the organismal assemblages associated with these materials. Scott and coworkers (1988) found differences in endolithic fauna between limestone and a concrete aggregate and Miller and Barimo (this volume) found differences in coral recruitment to concrete and lime rock.

The deposition of $CaCO_3/Mg(OH)_2$ on to steel frames, or other conductive material, by the application of low voltage direct current (1–24 v), also appears to have a number of advantages. The substrate is created at the restoration site from natural materials and allows for a rapid attachment of coral transplants to a wire frame that can be shaped as desired (Hilbertz, 1981; van Treeck and Schuhmacher, 1997; Hilbertz and Goreau, 1998). This technique appears to be a promising area for further research; however, we are unaware of any long-term, in situ studies using this construction approach.

Because, in general, scleractinian corals are slow growing, most restoration efforts intend the artificial substrate to become a permanent part of the environment. A $CaCO_3$ substrate, in some form, is admittedly the most natural and probably least obtrusive material for such use and, although both lime rock and concrete structures are subject to bioerosion (Scott et al., 1988), both are relatively long lived in the marine environment. However, if a specific reefal attribute needs to be immediately restored as a temporary fix, e.g., juvenile habitat or predator exclusion structure, then the use of other materials would be appropriate, such as those that would deteriorate naturally (e.g., metal caging) or which could be removed periodically for maintenance.

SURFACE.—Essentially all colonizing biota, from bacteria to corals and fishes, exhibit substrate-dependent settling preferences. In general, these preferences are due to some physical or chemical aspect of the substrate surface, i.e., texture, color, and toxic or attractant chemicals.

Texture.—There has been extensive work on the texture of the preferred substrate for settling coral, and this information has been a consideration in reports of reef restoration efforts. However, it is not clear if these considerations have been a pre-design intent or fortuitous byproduct of other construction priorities. For the most part, scleractinian corals appear to prefer a rough textured, vertical surface, often shaded and/or protected (for references see: Benayahu and Loya, 1987; also Carleton and Sammarco, 1987; Harriott and Fisk, 1987; Tomascik, 1991). However, there may be important species-specific exceptions to this generality (Wallace, 1985; Schuhmacher, 1988). It has been hypothesized that more common corals are less sensitive to texture (Carleton and Sammarco, 1987). Some soft corals also prefer rough textured substrates with an organic coating (Benayahu and Loya, 1984) and settle mainly on edges and lower surfaces (Benayahu and Loya, 1987). Fishes also exhibit substrate preference, although it is not clear what aspect of the substrate is the responsible attribute (Jones and Syms, 1998). Eckert (1985) found significant differences in substrate settling preferences among 15 species of fishes settling to live or dead coral or coral rubble. Benthic assemblages (algae and invertebrates) are more abundant and diverse on textured surfaces. Further, small-scale relief appears to increase diversity of this community in the presence of grazing fish (Hixon and Brostoff, 1985). Thus, although exceptions can be expected, in general it appears a rough, irregularly contoured surface is appropriate for artificial substrate in restoration projects.

Color.—Aggregating fishes have been reported to prefer darker colored (dark red and black) to lighter colored artificial reefs (Grove and Sonu, 1985). Fouling organisms, in general, apparently prefer dark-colored to light-colored surfaces (Long, 1974). Corals exhibit preferential settlement to shaded versus unshaded substrate in shallow waters, conversely in deep (Wallace, 1985); perhaps this indicates a color preference as well. The interaction between surface color and the initial settlement of epibiota warrants additional research because the initial colonizers could, as adults, potentially influence succeeding assemblages (Peckol and Searles, 1983; Ambrose, 1984; Bailey-Brock, 1989; Fearon and Cameron, 1997; Holm et al., 1997; Dunstan and Johnson, 1998).

Toxic Leachate.—There has been some work on the potential of artificial substrate to leach toxic substances, acids/bases and the like (Duedall et al., 1985; Day et al., 1993; Livingston, 1994). One artificial reef manufacturer recommends the addition of microsilica to concrete to provide a neutral pH surface (Reef Ball™). Leachate does not appear to be a consideration in current restoration efforts, most of which use experience-validated materials, e.g., concrete. Presumably, even if these materials do release a leachate it must be a temporary situation as witnessed by the epibiota they rapidly accumulate. Nonetheless this approach may require reevaluation. A clean substrate immersed in seawater quickly acquires an organic/microbial biofilm. This biofilm, in turn, is used by many invertebrate species, but not all, as a positive settling cue (for references see Wieczorek and Todd, 1997). Differences in leachate on initial immersion may, at least in part, be responsible for differences in the accumulation of colonizing epibiota to differing materials (Fitzhardinge and Bailey-Brock, 1989). As mentioned above, these initial colonizing microbial, algal, and invertebrate assemblages, as established residents, may affect succeeding biota.

Surface Chemistry.—The surface chemistry of artificial substrate is receiving increasing attention. For example the wettability of a surface can differentially affect initial colonization by some invertebrates (Rittschof and Costlow, 1989; Holm et al., 1997). The addition of growth promoting substances or attractants to artificial substrate has also received some attention. Eklund (1996) found adding fertilizer to artificial reefs was not successful in increasing epibenthic production. However, there are reports of increased coral recruitment on steel surfaces (Fitzhardinge and Bailey-Brock, 1989) and in some marine environments iron appears to be the limiting nutrient for primary production (Millero, 1997). The fertilizer used by Eklund (1996), Osmocote®, does not contain iron. Perhaps enriching the surface of artificial substrate with iron would, either directly or indirectly, enhance growth of the associated biological assemblage. It is well established that some corals will preferentially settle on substrate encrusted with red coralline algae (for references see Morse and Morse, 1996). The chemical inducer for settlement and metamorphosis of Agariciid corals has recently been extracted, and the authors hypothesized a larval ‘fly paper’ that could be applied to a surface to attract corals (Morse and Morse, 1996). Preliminary work apparently supports this contention (Morse and Morse, 1996; J. D. Thomas, unpubl. data). There does not yet appear to be extensive work on species-specific responses of invertebrate larvae to differential organic or microbial makeup of biofilms. Nonetheless, the fact that biofilms differentially influence invertebrate settling indicates a potential role for manufactured biofilms to promote selective recruitment to artificial substrate. Further, work with settling fishes indicates the importance of a chemical cue for some species (Sweatman, 1983, 1988). This work was done with planktivorous damselfish (Pomacentridae); presumably there are chemical attractants for other fishes as well. Perhaps chemical fish attractants may be used to indirectly structure reef communities. For example, some herbivorous damselfish can affect coral settlement and growth (for references see Jones et al., 1991; Gleason, 1996). On the whole, the use of attractants in restoration biology appears to be a fertile area for future research.

DESIGN.—*Vertical Profile*.—Corals settle preferentially on vertically oriented substrate (Carleton and Sammarco, 1987; Harriott and Fisk, 1987; Tomascik, 1991). We are not aware of similar work on fish settlement. Some post-settled fishes do appear to be attracted by vertical aspects of artificial reefs. However, substrate associated fishes, the fishes of primary interest in restoration, usually aggregate within 3 m from the bottom of an artificial reef (Bohnsack et al., 1991; Grove et al., 1991). Therefore, from a biological perspective, although the vertical profile of artificial substrate can be an important factor in an effective restoration design, great height, apparently, is not.

Shelter.—Although still a debated topic, there is a growing body of literature indicating that in at least some, if not all, coral reef environs, the major post-settlement determinant of community structure, for fishes, corals, and lobsters, is predation (for references see Hixon, 1991; Tomascik, 1991; also Caley, 1993; Carr and Hixon, 1995; Beets, 1997; Eggleston et al., 1997; Hixon, 1998). Thus, in terms of biology, shelter is a critical attribute of artificial substrate function. Under the broad heading of shelter we include here a variety of interrelated attributes: complexity, hole size, void space, architecture, shade, and caging.

Many corals, as well as other invertebrate larvae, prefer to settle in complex interstices of substrate rather than on a flat surface (for references see Carleton and Sammarco, 1987). In addition, when given a choice, corals often have higher settlement rates to the undersides of horizontal substrate. Presumably such preference is adaptive for sessile species to avoid predation and grazing. Settling on the underside of horizontal substrate also avoids smothering by sedimentation (Maida et al., 1994). Recent research, however, indicates coral settlement on preferred sites may not confer advantages throughout subsequent development. Babcock and Mundy (1996) found that that during the first few months after settlement coral mortality was highest on highly sedimented upper surfaces; but after a few months, growth and survivorship were highest on these same surfaces. Thus, to reduce mortality and maintain optimum growth, artificial refuge may require structural modification through time.

There have been a number of reports examining the relationship between reefal complexity, natural and artificial, and the associated assemblages of fishes. Most of these studies have used differing hole sizes or total holes as measures of complexity. Those studies, with few exceptions, where structural complexity is associated with diverse refugia, find a positive correlation between structural complexity and species diversity and total numbers of fishes. Likewise most studies, but not all, examining reefs with varying hole sizes find a correlation between hole size and the size of the associated fishes; a shelter-scaling effect (reviews: Bohnsack and Sutherland, 1985; Bohnsack et al., 1991; Hixon, 1991; Jones, 1991; also Potts and Hulbert, 1994; Friedlander and Parrish, 1998; Nemeth, 1998; Sherman, 2000). Void space, the amount of open space within an artificial reef, has also been examined by several groups relative to associated fish assemblages, and specific recommendations for the size of void space have been suggested for fisheries reefs (review: Bohnsack and Sutherland, 1985). Recent work on model reefs, however, suggest that void space does not provide some unique biological function to an artificial reef. The refuge function of a void space does not differ from any other hole, and for restoration at least, the size of the void should be governed by the desired assemblage (Sherman et al., 1999).

For spiny lobster, shelter is clearly a major determinant of survival and appropriately sized artificial structure can maintain lobster populations when natural shelter is destroyed (Herrnkind et al., 1997). Eggleston and co-workers (1990, 1997; Mintz et al., 1994) have shown that refuge scaling reduces predation on appropriately sized lobsters.

For fishes and lobster the architecture of the shelter also appears important. For example some blennioid fishes are found in blind-ended tunnels, while other fish appear to prefer ledges or complex coral structure with multiple escape routes. Spiny lobster prefer refuge with multiple entrances (Spanier and Zimmer-Faust, 1988; Herrnkind et al., 1997).

As already mentioned many corals prefer shaded areas for settlement, at least in shallow water (Wallace, 1985; Maida et al., 1994). For spiny lobster shading appears to be even more important than physical contact with the refuge (Spanier and Zimmer-Faust, 1988). Fishes will often congregate in shaded areas to avoid predators, or at least to gain visual range on a potential predator (Helfman et al., 1997) and incorporation of structural elements that produce shadow has been recommended for fisheries reefs (Grove et al., 1983).

Substantial work on the importance of post-settlement processes in determining community structure has been acquired with predator-exclusion studies using caging. In comparison to reefs without caging, these studies show an increase in juvenile fishes on artificial reefs from which large piscivores have been excluded (Doherty and Sale, 1986; Eklund, 1996; Gilliam, 1999). Because of fouling problems, caging material is not appropriate for long-term, unattended use in restoration projects. However, for short-term enhancement of settlement and survival of juveniles, caging could be a valuable tool in restoration projects.

To briefly summarize these diverse studies on shelter, it is clear that: (1) predation is a major determinant of reef community structure and thus (2) in terms of biological function, a major attribute of artificial substrate lies in its ability to provide refuge. Much more research is required to understand how to use this attribute effectively. Not only are the species-specific shelter requirements of the varying sizes and life stages of individual species needed, but, ideally, the shelter requirements of the intended replacement community as well; a daunting task at best.

Size and Deployment Configuration.—There has been considerable work with artificial reefs for fisheries which have examined the fish assemblages associated with different sized reef modules or different spatial configurations among reef modules (reviews: Bohnsack et al., 1991; Grove et al., 1991; also Borntrager and Farrell, 1992; Bohnsack et al., 1994; Frazer and Lindberg, 1994; Seaman et al., 1994). In restoration work involving rubble consolidation or wave attenuation these are probably not major concerns since the amount of artificial substrate will primarily be determined by the amount of damage. However, these are critical concerns in habitat restoration.

With fisheries the research on optimal size and deployment configuration has focused on maximizing the resources, both artificial (i.e., the amount of material deployed) as well as natural (i.e., prey availability) to gain the greatest economic benefit in terms of harvest. With restoration efforts, the goal in configuring the artificial structure(s) should be to provide a natural spatial distribution of predators and prey. At this point, the ideal size or dispersion of artificial substrate for restoration is not known. It is unlikely that a single optimal configuration exists, as this will depend on the range and refuge sizes of the pre-damage community. Concentrating replacement habitat, as is done in some mitigation projects, should probably be avoided. Close placement of artificial modules can result in lower species abundance and diversity of fishes than the same number of modules more widely dispersed (Bohnsack et al., 1994; Frazer and Lindberg, 1994). In addition, concentrations of fishes or invertebrates can attract predators and possibly produce density-dependent increases in mortality thereby potentially reducing the refugal effectiveness of the artificial substrate (Forrester, 1995; Hixon and Carr, 1997; Beukers and Jones, 1998; Steele, 1998).

Attractants.—In addition to the chemical attractants already mentioned (subsection: Surface) there have been several attempts to increase larval fish settlement on artificial reefs using added structure. The use of midwater FADs (fish aggregating device) attached to artificial reefs increased recruitment of juvenile fishes to the benthic structure (Beets, 1989; Brock and Kam, 1994). Presumably this increase is due to focusing settlement of larval fishes from the water column when they encounter the FAD (Brock and Kam, 1994). However, surface buoys moored to natural reef (Munday et al., 1998) or 12-m lengths of polypropylene line attached to small floats and artificial reefs in 21 m of water did not enhance settlement (Sherman et al., 1999). It is not clear if these discrepancies are due to equipment or environmental differences among the studies. A light aggregating device has also been used to focus larval fish onto natural reef (Munday et al., 1998). However, larval focusing using floating line, and presumably lights as well, may also focus recruitment of predators, as well as planktonic invertebrates which can compete with the normal benthic fauna (Thomas, 1998).

The use of attractants, both chemical and physical, to enhance settlement on artificial substrate is potentially an extremely productive research direction. Clearly, if the substrate does not supply the species-dependent habitat requirements in terms of food and shelter, increased settlement is of little pragmatic value.

STABILITY.—Questions of stability are critical. There have been several studies on the movement and/or destruction of artificial structures due to severe storm events. In some cases portions of artificial reefs have been thrown ashore, in others they have damaged nearby natural reefs (Sheehy and Vik, 1983; Blair et al., 1994; Seaman, 1997; Turpin, 1999). In restoration efforts, which take place on the natural reef, such movement could cause more damage than the original problem. Artificial structures will be exposed to varying wave action depending on their location, for example reef crest or lagoon, and their stability or attachment to the natural substrate must take into account this exposure as well as predicted forces from severe storm events. Calculations for determining the stability of artificial reefs are available (Grove et al., 1991; Lin, 1999) as are wave tank determinations. As previously mentioned the rubble formed by ship groundings or coral mining can produce extensive damage if left on site. There has been some attempt to consolidate such rubble with artificial substrate (Clark and Edwards, 1994; Waxman et al., 1999). However, these efforts have apparently not produced a substrate sufficiently stable to withstand severe storm events. A full understanding of the appropriate methods to stabilize rubble (including biological consolidation, Wulff, 1984) remains to be elucidated.

As a general comment on artificial substrate design, it is noteworthy that coral reefs show a distinct fractal organization (Bradbury and Reichelt, 1983; Basillais, 1997). It is not clear how critical this organization is to biological or hydrological functions. However, complexity, or rugosity, is an important factor influencing species richness and abundance at differing scales, from surface texture to fish refuge. Thus, fractal geometry would appear to be a potentially important area for future research aimed at ecosystem restoration and may aid in designing artificial structure to provide a natural spatial distribution of predators and prey.

Environmental Determinants of Function

The functions of any artificial substrate will be determined in large measure on where it is deployed (for references see Sherman et al., this volume). Major site dependent determinants can be specific or general and include temperature, light, sediment, surrounding biota, hydrodynamics, depth, and temporal effects. Obviously, these characteristics are often highly interrelated; they are separated here for ease of discussion.

Temperature.—Marine organisms are well known to have a preferred temperature range. Taking this fact into account in restoration efforts is normally not a problem as the goal in such efforts is to return indigenous species. However, temperature may also affect settlement of corals and fish (Doherty et al., 1996; Zaslow and Benayahu, 1996) and therefore the temperature regimen when artificial substrate is deployed may, in part, determine the makeup of the initial colonizers and succeeding assemblages.

Light.—The preference of fouling organisms in general, as well as corals, macrobenthos, and fishes to prefer shaded substrate has been discussed above. In addition to light intensity, for coral settlement there are also species specific differences in response to light in terms of intensity or spectral quality (Baker, 1995; Mundy and Babcock, 1998).

Sediment.—The amount of sediment that accumulates on an artificial substrate can affect invertebrate settlement, including corals (for references see Tomascik, 1991). Likewise, the amount of suspended sediment can affect light penetration which will in turn affect light levels and coral settlement (Hodgson, 1990; Tomascik, 1991).

Surrounding Biota.—There has been extensive work documenting the effect of nearby natural reef populations on artificial reefs in terms of recruitment and predation (for references see Bohnsack et al., 1991; Sherman et al., this volume). In several restoration studies coral recruitment appeared to come predominately from nearby species with short-lived pelagic stages and the establishing community at a grounding site was affected by predators and grazers from nearby reefs (Benayahu and Loya, 1987; Smith, 1988; Gittings et al., 1993).

Hydrodynamics.—Water movement affects a reef in multiple ways. The amount of current or wave action can determine the distribution of algae, corals, and other benthic invertebrates (Baynes and Szmant, 1989), and fishes (Grove et al., 1991) on a structure. With sessile benthos, increased abundance and diversity on an artificial or natural reef is associated with those areas of the structure receiving higher current flow (Baynes and Szmant, 1989) but not necessarily higher wave energy (Tomascik, 1991). It is not clear if this is due to decreased sedimentation, increased rates of recruitment, increased food for planktivores, or some combination of these factors. It is clear, however, that the orientation of artificial substrate to prevailing current needs to be taken into account in design and deployment. Water flow around artificial substrates is also the primary environmental determinant of the structure's stability (Grove et al., 1991; Lin, 1999) and is, therefore, a critical consideration in artificial substrate design.

DEPTH.—There have been several studies reporting differences in the populations associated with artificial reefs (references: Sherman et al., 1999) or substrates (van Moorsel, 1988) deployed at different depths. There has been, however, no attempt to examine experimentally the specific biotic or abiotic variables associated with the differing depths in any of these studies. It is likely one or more of the variables described above (temperature, light, sedimentation, etc.) are responsible for the depth-associated differences rather than hydrostatic pressure or other unique depth-dependent variable. For example, it has been suggested that optimum depth for adult coral survival is selected by coral planula using photo cues, e.g., light intensity or spectral quality (Mundy and Babcock, 1998).

TEMPORAL EFFECTS.—There are seasonal differences in larval availability of invertebrates and fishes as well as seasonal differences in the presence of motile adults, i.e., fishes. Thus the colonizing assemblage can differ depending on time-of-year artificial substrate is deployed (for references see Bohnsack et al., 1991; Dunstan and Johnson, 1998; Rilov and Benayahu, 1998). Because resident individuals of both invertebrates and fishes can affect succeeding recruitment, the season of deployment could, in large measure, determine the final, steady state assemblage composition.

To summarize this section, effective use of artificial substrate not only requires an understanding of the physical attributes of the substrate that determine function, but of the interacting ecology of the specific deployment site as well. Neither of these is a trivial task. Ideally, the site will have been researched prior to damage to allow for an ecological baseline on which to base restoration goals and methodology.

OTHER CONSIDERATIONS

CONSTRUCTION AND DEPLOYMENT COSTS.—The costs of restoration need to be offset by the benefits gained. This simple economic reality requires a monetary value be attached to the damaged area. There have been a number of papers discussing cost:benefit ratios for artificial reefs. Most of these papers are concerned with either commercial or recreational fishing reefs, or artificial reefs to attract divers (Milon, 1983; 1991; Brock, 1994; Whitmarsh, 1997). With such structures economic benefit is readily defined and economic gain vis-à-vis construction and deployment costs can be calculated. In coral reef restoration efforts the economic benefits of a restored ecosystem may be equally clear (Clark and Edwards, 1994) but in most cases is more difficult to fully quantify (Spurgeon, 1992; 1998).

In general, coral reefs are held in public trust by governing bodies. Placing value on the anthropogenic loss of such property is a contentious affair at best; especially since losses also occur naturally and coral is a renewable, albeit slow growing, resource. In some cases a habitat equivalency analysis (HEA) has been used to assign value to damaged reef. In other cases, previous fines have been used as precedent. Ship groundings in the United States have resulted in payments by ship owners of from about \$1200 to \$11,000 m^{-2} of totally destroyed coral reef. Recently, coral reef in the Florida Keys National Marine Sanctuary has been valued at \$2,833 m^{-2}. Whether or not this amount, or any other, is a fair figure for the restoration effort and lengthy period of habitat loss, or if it provides sufficient motivation for deterrence, is likely to remain an unresolved question between ship owners, their insurers, and coral reef managers and scientists.

It is noteworthy, that in most cases fines for coral reef damage are based on the assumption that the damaged area will eventually return to a pre-damage state. Current research data are interpreted by some researchers to indicate that in some cases a damaged coral reef that is not restored will not return to a pre-damaged condition (Ebersole, 1999; Swanson et al., 1999) and is therefore, on a human time scale, permanently lost. Others apparently disagree with this assessment (Gittings et al., 1990; 1993); however, should it prove correct, that non-restored reefs do not return to a pre-damaged state, the findings may tip the cost:benefit ratios heavily towards restoration.

AESTHETICS.—Unlike fisheries reefs, with restoration efforts aesthetics can be a major concern and it has been taken into account in the design of artificial reef modules used in reef restoration (Hudson et al., 1989). Admittedly, a wide diversity of artificial reef designs from ships to Christ statues and abstract sculpture have been deployed near or on coral reefs for tourism; and these structures are undeniably popular with recreational divers (Milon, 1983). Nonetheless, in areas where coral reefs are a major tourist draw, e.g., Florida Keys, presumably most individuals would equate aesthetic value with natural looking. Ideally, the required functional attributes necessary can be incorporated into natural-looking structure. This is a fertile area for interaction between engineering, biology, and art. However, as stated elsewhere: aesthetic concerns need to be balanced against the value of accelerated recovery (Miller et al., 1993).

CONCLUSIONS AND RECOMMENDATIONS

Ideally, a resource manager should be able to survey a damaged area of coral reef and list, with a relatively high degree of certainty, the required methods and structures needed to restore that specific site; currently this is not the case. Although it is clear that artificial substrates can be important tools in coral reef restoration, the understanding of the interaction between their various attributes and the ecology of the environment in which they are deployed is sketchy at best. Until this functionality is better understood, the use of artificial substrate in coral reef restoration will remain a ‘best guess’ approach.

The need for research has been highlighted throughout this review. Yet we are unaware of any state or federal body devoted to funding coral reef restoration research. At present, all monies acquired by the U.S. Federal government as the result of a grounding incident are used in habitat restoration efforts. This situation harkens back to artificial reef policies of the 1970s and 80s when there were large sums available for artificial reef deployment but none for research on their function. This is a highly questionable policy which forces resource managers to proceed with a ‘best guess’ approach to restoration rather than one based on research derived knowledge. A better approach would surely be to sequester some of the funds derived from grounding incidents for research on artificial substrate function. If this is not feasible then a different source of funds needs to be directed to such research efforts.

To return to the question of this paper’s title: what do we need to know to know what we need? It is difficult to distill the contents of this paper and make specific recommendations for future research priorities as ‘what we need to know’ will differ depending on the needs of a particular restoration. Nonetheless, some generalities are possible. In terms of research at the local level, we suggest a proactive, rather than an after-the-fact crisis management, approach to research. Certainly one of the corner stones of any restoration project is knowing what to restore. It is difficult to restore an environment without knowledge of the pre-damage condition. In a 'war games' approach, resource managers should identify likely areas of disturbance (e.g., areas around passages and anchorage), and possible destruction scenarios. This will afford the time to research the basic ecology of potential damage sites and acquire the baseline information critical to designing site-specific restoration plans. For example, a site that is an important back-reef nursery area would obviously require a different restoration plan than a fore-reef feeding area. Grounding incidents, or other destructive influences, will certainly occur at other, unanticipated, sites, and in such cases restoration efforts will need to rely on faunal distributions from general reef ecology. However, a little planning should reduce the need for such reliance.

Monitoring a completed restoration project for an extended period of time (minimum 5–10 yrs, ideally longer) is critical. Without monitoring there is no assurance that a particular restoration plan is effective and should or should not be repeated. Monitoring, however, as used here, is evaluation not research. It allows resource managers to evaluate how one restoration plan functioned at one specific site. It does not address if it was a particularly good restoration plan, relative to another, or if its effects could be extrapolated to other sites. To answer these questions multitreatment, hypothesis-based experimentation is required. Until a better understanding of restoration methodology is acquired, we recommend every restoration project include such a research component. This research should be relevant to the area and goals of the restoration project. For example, in a back-reef area where the destruction of nursery habitat is a main concern an examination of differing designs of artificial juvenile-habitat would be appropriate; in a fore-reef area important for wave attenuation examining the stability and hydrodynamics of differing modules might be a good idea; on a reef crest where extensive rubble has been created, varying methods of rubble consolidation could be tested.

In terms of research at the state or federal level, we suggest research initiatives to examine overarching questions of artificial substrate functionality. For example, from an engineering perspective: studies on artificial substrate stability and durability as well as innovative studies on capping or consolidating rubble would be applicable to most restoration efforts. From a biological perspective, studies on community refuge and the structures to supply such refuge clearly are needed. Despite an abundant literature correlating complexity, rugosity, hole-size and the like with species richness and abundance it would be difficult, with current knowledge, to design optimal refuge for most species much less a community. The potential for chemical attractants to promote settlement of corals and fish also appears to be a topic of wide interest and a promising area of research.

Acknowledgments

We thank K. Maxson for exceptional library services and S. Teel for graciously allowing us access to her unpublished manuscript and a wealth of gray literature on reef restoration in South Florida. We also thank the three anonymous reviewers who provided constructive, critical comments of the initial version of this paper.

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