

Do Artificial Reefs Increase Regional Fish Production? A Review of Existing Data

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ABSTRACT

We reviewed the scientific literature to determine whether the construction of artificial reefs increases the regional production of marine fishes. An evaluation of this technique is warranted by its high cost and logistical difficulty. Our review indicated that reef construction may have potentially deleterious effects on reef fish populations, including (1) increasing fishing effort and catch rates, (2) boosting the potential for overexploitation of stocks by increasing access to previously unexploited stock segments, and (3) increasing the probability of overexploitation by concentrating previously exploited segments of the stock. In contrast, the literature contained few studies that unambiguously demonstrated that artificial reefs increased regional fish production rather than merely concentrated available biomass. In addition, the literature on population regulation in reef fishes did not provide convincing evidence that reef fishes were limited by insufficient quantities of hard-bottom habitat. Consequently, potential positive and negative aspects of reef construction should be carefully evaluated prior to the addition of new reefs to marine environments.

During the last 30 years, the construction of artificial reefs has become a popular management tool employed by both government and private groups (Seaman and Sprague 1991). During this period more than 500 reefs have been constructed in U.S. coastal waters. Almost half the national total (at least 350 reefs) are located in Florida, where state funding related to reef construction and management have averaged close to \$1 million annually (Pybas 1997). Despite these figures, our understanding of the biological effects of reef deployment on marine ecosystems is still quite limited. In particular, scientists are concerned that artificial reefs may harm fish stocks if they merely concentrate available biomass rather than increase its production on a regional basis (Polovina 1991).

Our purpose for this paper is three-fold. First, we describe the utility and consequences of reef construction for marine fisheries management. Second, we review aspects of reef fish population dynamics that are relevant to the production-v-attraction question. Finally, we evaluate the conjecture that artificial reefs increase the regional production of economically important marine fishes and propose an experimental test to resolve the production-attraction dichotomy.

Why is the Construction of Artificial Reefs so Widespread?

This question has a simple answer: There is tremendous popular support for the construction of reefs because anglers visiting these habitats frequently experience high catch rates. High catch

rates are supported by the relatively rapid colonization of artificial reefs by economically important species (Bohnsack et al. 1991). In addition, political reasons may favor the continued construction of artificial reefs. For example, fabrication of artificial reefs involves highly visible management activities (i.e., gathering and deploying cubic tons of concrete or scrap materials for the reef body). Given that anglers are typically required to purchase an annual fishing license, we suspect that user groups are more likely to feel that their money is being spent wisely when they can see the tangible efforts of management activities. Consequently, user groups likely exert tremendous pressure to continue the production and deployment of artificial reefs, despite the lack of rigorous scientific data regarding

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Scientists place culverts in the Gulf of Mexico for the Pinellas County Reef Program.

foraging habitat of adult, juvenile, or newly recruited fishes; (2) an increase in the nesting habitat of adult fishes; and (3) an increase in the amount of resting habitat or refuges from predators. As a result, stock sizes of economically important species increase, and both recreational and commercial fishers benefit.

It also is possible that hard-bottom habitat does not limit regional fish production, especially if exploitation has already reduced stocks to levels substantially below carrying capacity. If true, construction of additional artificial

overexploitation may increase substantially.

Given that the relationship between reef construction and the probability of stock overexploitation is influenced by changes in fishing effort, it is appropriate to assess the likely effects of new reefs on fishing effort in a given area. We believe that reefs almost certainly increase access, and perhaps fishing effort, on hard-bottom habitat (McGlennon and Branden 1994). This assertion can be made with confidence because artificial reefs generally are placed in areas thought to have "insufficient" hard-bottom habitat. However, if new reefs are attracting fishers who previously did not fish hard-bottom areas due to a lack of availability, the probability of stock overexploitation may increase. In addition, several investigators have suggested that artificial reefs and pelagically located fish-attracting devices also may increase catch rates (Buckley et al 1989; Polovina and Sakai 1989; Friedlander et al. 1994). Consequently, the combined results of artificial reefs on angler effort (i.e., increases in angler access, fishing effort, and catch rates) may deleteriously affect the resource, especially if artificial reefs redistribute regional biomass rather than increase it.

Is Habitat Limiting for Reef Fishes?

The question of habitat limitation lies at the heart of the artificial reef controversy. We address it by briefly summarizing aspects of the relevant literature on population regulation of coral reef fishes (see Sale 1991). First, we examine the methodological strengths and weaknesses of the data; second, we evaluate the evidence in support of, and in opposition to, the habitat limitation hypothesis. In general, three types of studies have sought to identify the role of

whether reefs have a positive or detrimental effect on marine ecosystems.

The Real and Potential Effects of Artificial Reefs on Marine Fisheries

The basic philosophical assumption underlying the continued deployment of artificial reefs is that regional fish production is limited by a paucity of hard-bottom habitat (Bohnsack 1989; Bohnsack et al. 1991; Polovina 1991). However, this assumption is supported mostly by short-term descriptive studies of individual reefs (Bohnsack 1989; Bohnsack et al. 1991). Nonetheless, if habitat is limiting, new reefs can potentially increase fish production through three mechanisms: (1) an increase in the

reefs will have no effect on fish production; it will merely cause a redistribution of existing biomass (Bohnsack 1989; Polovina 1991). This may have differing effects on stock size depending on the stock segment affected. For example, if reefs disperse exploitable biomass and have no effect on unexploited biomass, then construction of new reefs should reduce the chance of stock overexploitation, assuming that fishing effort or power does not increase (Polovina 1991). However, if reefs concentrate both exploited and unexploited segments of a stock, then the probability of stock overexploitation increases, even if effort does not change (Polovina 1991). If effort increases concomitantly, then the probability of

habitat limitation in structuring reef fish assemblages: (1) descriptive studies of artificial reefs, (2) descriptive studies of natural reefs, and (3) experimental studies of reef isolates. Most studies that examine the effects of reef construction are (1) relatively short-term (one to five years), (2) lack adequate control sites, and (3) have no replication (i.e., one reef is examined). Thus, conclusions drawn from such investigations may be of limited scientific value. [It is noteworthy that much of the research reported in this volume does not suffer from the aforementioned experimental flaws (e.g., short time span, no controls or replication).] Similar problems typically are found in data gathered from descriptive studies of natural reefs. Conversely, experimental studies on reef isolates (isolated coral heads or artificially constructed units that mimic coral heads) generally have adequate controls and are well replicated. Some of these studies also are relatively long-term (Sale et al. 1984). Nonetheless, it is entirely possible that the dynamics of fishes on these habitats do not mimic those of the reef fish populations on larger reefs (i.e., the spatial scale may not be appropriate for identifying processes regulating population size; Tolimieri 1995). In addition, most studies on reef isolates examine species that typically are not exploited by fishers (e.g., labrids, chaetodontids, holocentrids, pomacentrids, blenniids); hence, we also are assuming, perhaps inappropriately, that the population processes regulating these taxa are similar to those governing exploited species such as serranids and lutjanids. Consequently, methodological shortcomings may mar the results of many studies relevant to the habitat limitation question.

Recognizing the potential limitations of existing data, we will now examine five lines of evidence

in our assessment of whether habitat is limiting for reef fishes: (1) habitat abundance relationships, (2) effects of reductions in available habitat on reef fish assemblages, (3) tests of whether refuges from predation limit reef fish populations, (4) tests of whether recruitment affects the size of adult populations, and (5) tests of whether removal of reef residents (typically adults) produce a change in subsequent recruitment to the population.

Habitat-Abundance Relationships

These studies test the null hypothesis that the abundance and/or distribution of species on one or more reefs is not correlated

with an environmental factor(s). If a positive correlation is obtained, some investigators have concluded that space is limiting for these fishes (e.g., Luckhurst and Luckhurst 1978), although such a finding does not necessitate habitat limitation (i.e., it could also be produced by food limitation or recruitment limitation). The evidence for habitat limitation in reef fishes based on habitat-abundance relationships is equivocal. Several descriptive studies demonstrate such a relationship (de Boer 1978; Luckhurst and Luckhurst 1978; Roberts and Ormond 1987). However, two other studies (Robertson and Sheldon 1979; Robertson et al. 1981) that experimentally reduced the amount of available space did not observe concomitant negative responses in a variety of population and demographic parameters (e.g., abundance, survival, body

weight, and fat reserves) of two common reef species: three-spot damselfish [*Stegastes* (= *Eupomacentrus*) *planifrons*] and bluehead wrasse (*Thalassoma bifasciatum*). As a result, the less-powerful descriptive studies provide evidence that positive relationships exist between reef fish abundance and distribution, and habitat availability, although such findings do not require habitat to be limiting (den Boer 1978; Luckhurst and Luckhurst 1978; Roberts and Ormond 1987). Conversely, more rigorous but smaller-scale experimental studies do not support the contention that overall reef size or the availability of sleeping sites limits two common reef species (Robertson and Sheldon 1979; Robertson

Although there is fairly strong evidence that increases in refuge availability may positively affect some reef fishes, including predators, this does not mean that constructing artificial reefs always will increase fish production.

et al. 1981). Resolution of habitat availability v fish abundance relationships only will be accomplished with further experimentation at spatial scales ranging from reef isolates to entire reefs.

Reductions in Available Habitat

These studies generally examine fish assemblage structure before and after declines in available habitat. The declines are caused by a variety of factors including (1) hurricanes (Kaufman 1983), (2) unusual sea temperatures (Wellington and Victor 1985), and (3) biological agents such as crown-of-thorns starfish (*Acanthaster planci*) (Sano et al. 1987). The general pattern observed is that corallivorous fishes decline in abundance when living coral biomass is reduced by a disturbance (Pfeffer and Tribble 1985; Sano et al. 1987; Jones and Kaly 1996).

Nonetheless, scientists have observed a variety of results for noncorallivorous fishes. In some locations these species decrease in abundance in response to declines in coral abundance (Sano et al. 1987); however, in other areas they either increase (Jones and Kaly 1996) or display no change in abundance (Wellington and Victor 1985; Williams 1985). Consequently, it seems likely that the abundance and distribution of coral-livorous fishes may be limited by the amount of living coral habitat on a reef, but this relationship does not always hold for noncorallivorous fishes. Finally, it should be noted that most of the species that anglers seek as sport or commercial targets are noncorallivorous (e.g., serranids, lutjanids, scombrids).

Refuge Limitation

Several researchers have suggested that predators are capable of limiting reef fish populations and, thus, increasing the availability of refuge sites will increase fish production (see Hixon 1991). Artificial reefs provide a potential mechanism for attaining this goal. The evidence regarding refuge limitation comes from several sources: descriptive studies correlating fish abundance or survivorship and refuge availability, predator removals on natural reefs, and experimental manipulations of refuge availability on reef isolates. A number of investigators have demonstrated positive correlations between fish abundance and the topographical complexity of reefs or numerical abundance of refuge sites (de Boer 1978; Shulman 1984, 1985; Roberts and Ormond 1987). Evidence from predator removal studies is equivocal. Bohnsack (1982) showed that several small species (including *T. bifasciatum*) increased in abundance when human exploitation reduced the number of large predators on a

Florida reef in comparison with a similar unfished reef. However, this effect was not observed in most species occupying the reef. The predator exclusion experiments of Doherty and Sale (1985) produced similar results (i.e., some species affected, others unaffected), although their results also may suffer from several potential limitations typical of caging studies (Hixon 1991; Jones 1991). Finally, several investigators have demonstrated that refuge availability may limit both assemblage structure and survivorship of several reef species on reef isolates (Molles 1978; Hixon and Beets 1989, 1993; Buchheim and Hixon 1992). Although there is fairly strong evidence that increases in refuge availability may positively affect some reef fishes, including predators, this does not mean that constructing artificial reefs always will increase fish production. For example, even when a positive effect can be demonstrated (e.g., a one- to two-year increase in fish abundance in increased-shelter treatments), the population-level consequences of these increases are unknown. Hence, it is unclear whether local increases in refuge availability will then be translated into sustained regional increases in fish abundance and production because we do not know whether regional abundance is more strongly affected by recruitment limitation or refuge limitation (Tolimieri 1995). Nonetheless, based on the positive results obtained in small-scale studies, it is possible that artificial reefs could be used to increase local population sizes for reef species that are clearly limited by refuge availability.

Effects of Recruitment on Population Size

The null hypothesis examined in recruitment studies is that recruitment (i.e., number of larvae

settling and surviving to either juvenile or adult status) has no effect on population size (Jones 1991). If hard-bottom habitat is a limiting resource, then variation in recruitment should have no effect on subsequent population size because all available habitat would be occupied. This presumes that recruitment always is sufficient to balance mortality from predation, disease, starvation, etc. Doherty and Williams (1988) have reviewed the data on recruitment variation in reef fishes; hence, we will merely summarize their results and discuss several more recent studies. The results of many recruitment studies demonstrate a positive correlation between recruitment and subsequent adult population size. Consequently, when recruitment is high, adult populations increase, and when recruitment is low, populations decrease (Doherty 1991; Jones 1991; Tolimieri 1995). This suggests that habitat may not be limiting to many reef fish populations. Nonetheless, this relationship is not universal (Jones 1991), and several investigators have shown that recruitment does not strongly affect subsequent adult population size, nor is it significantly reduced by post-settlement mortality, presumably through intraspecific competitions (Robertson 1988a,b; Jones 1991; Forester 1995). In these systems, adult population size is regulated by a variety of post-recruitment processes, including food availability and complex social interactions. In conclusion, it appears that both recruitment and post-recruitment processes may limit adult population size of coral reef fishes. The relative importance of the two types of processes depends on the species being examined.

Resident Removal Studies

These studies involve the removal of resident adults to test the

hypothesis that adult presence influences future settlement rates and, eventually, adult population size (Jones 1991). If habitat is limiting, rather than recruitment or some other post-recruitment factor, one would expect successful recruitment to increase as new individuals replace the adults removed, and population size eventually returns to preremoval levels. If habitat is not limiting, then we would expect recruitment to either remain unchanged or decrease after resident removals. Resident removal studies have produced all three of the aforementioned results: (1) increased recruitment (Shulman 1984, 1985; Jones 1987), (2) no change (Doherty 1983; Sweatman 1985; Jones 1987), and (3) decreased recruitment (Sweatman 1985; Jones 1987; Tupper and Boutilier 1995). As with all other lines of evidence, resident removal experiments provide results that are consistent with the predictions of a variety of mechanisms capable of limiting reef fish populations.

Do Artificial Reefs Increase Regional Fish Production? An Experimental Test

Because all artificial reefs are colonized by fishes at the level of the individual reef, increasing habitat usually produces a local increase in fish abundance or biomass. Nonetheless, this result can occur either when habitat is limiting (as carrying capacity increases with reef size) or recruitment is limiting (larger reefs attract more recruits). However, the issue of interest is whether or not regional fish abundance (or biomass) increases as more reefs are progressively added to a region? Does stock size continue to increase as some function of total reef area (Figure 1, habitat-limitation line), or will the population plateau since all available recruits have found suitable habitat (Figure 1,

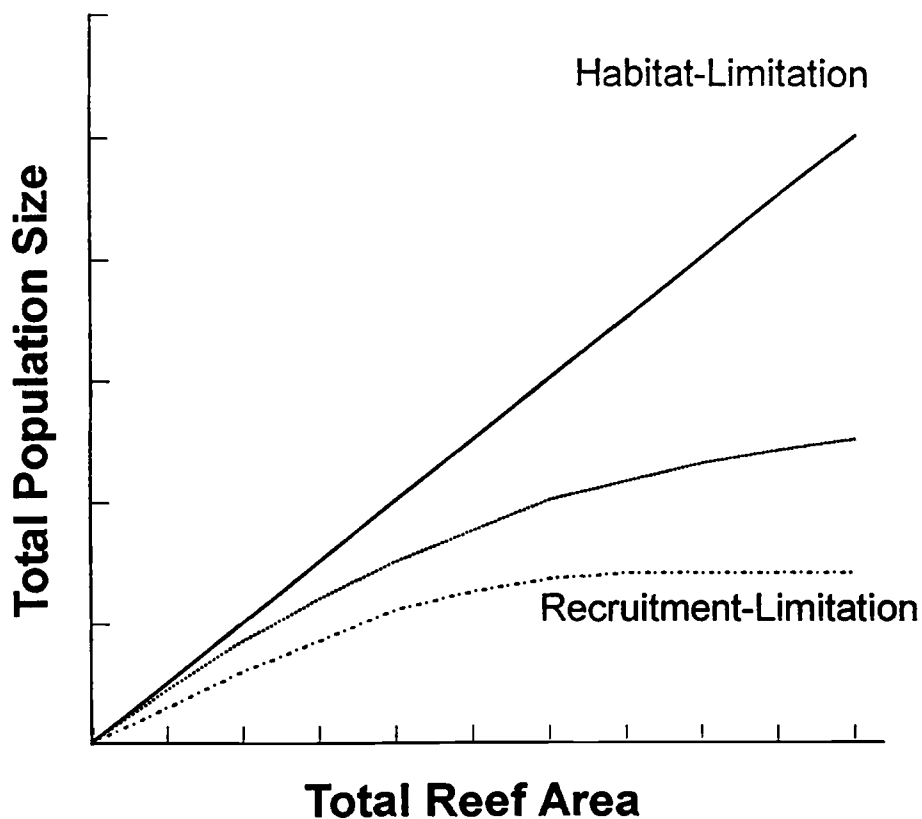


Figure 1 represents a graph of the expected results on reef isolates where populations are limited by either habitat or recruitment. See text for further information.

recruitment-limitation line)? In the latter situation, increased populations on individual reefs must reflect colonization via movement and must be compensated for by a decline on the source reefs. Total population size should remain the same. The contrasting relationships in Figure 1 represent two extremes, and the real situation may lie somewhere between the two curves (e.g., Schroeder 1987). The relative importance of habitat and recruitment-limitation might be tested by progressively increasing the number of artificial reefs within an area largely free of natural reefs, and measuring the form of this relationship. Any positive relationship will indicate some value in constructing artificial reefs, but there may be some density after which adding new reefs becomes superfluous.

An alternative approach to resolving this issue may be to

survey a small cluster of natural reefs and use stratified sampling procedures to estimate the total population size of the cluster (c.f. McCormick and Choat 1987). Artificial reefs then could be constructed within the general area. Continued monitoring of both natural and artificial reefs would provide estimates of the population size on individual reefs and the total regional population size (natural plus artificial reefs). If colonization of natural reefs simply represents a redistribution of individuals, the total population estimate would not significantly increase. An intensive tagging program could provide additional information on the degree of colonization by movement.

Conclusion

Constructing artificial reefs is costly and logistically difficult (Seaman and Sprague 1991). Hence, an evaluation of the scientific

basis for reef construction and deployment is critical. Nonetheless, existing data yielded mixed results when used to test the primary assumption underlying reef deployment (i.e., that hard-bottom habitat is a limiting resource for reef fish populations). This makes the continued construction and deployment of artificial reefs problematic, especially when there are competing management options. Without being overly pessimistic, however, there are cases where artificial reefs may increase the production of organisms favored by sport or commercial fishers. For example, Polovina and Sakai (1989) showed that refuges were probably limiting to octopi (*Octopus dofleini*) in Japan and that adding structure to soft-bottom habitat increased refuge availability, which then resulted in increased octopi yields. Thus, if a species is limited by refuge availability, deployment of a reef with the appropriate refuges may result in increased regional production with subsequent increases in yield. Another example of reef deployment that is unlikely to cause widespread ecological damage is the creation of a geographically restricted, hard-bottom fishery in an area of extensive soft-bottom habitat. Nonetheless, if individuals are merely being attracted from other locations rather than being produced by the new reef, this may increase the probability of stock overexploitation. The likelihood of this possibility could be minimized by ensuring that new reefs are located well outside the home ranges or migration paths of species inhabiting nearby reefs. However, if managers choose to create such a fishery, they also should ensure that the reef does not cause extensive harm to the biota of the soft-bottom habitat.

We also want to comment on several aspects of current and future research on the production-v-attraction question. First, it is clear from the results described in this volume


that scientists have made great strides in the design and execution of artificial reef studies. More studies now include control sites and adequate replication, and more emphasis is being placed on experimental or mechanistically oriented aspects of reef research (see Bohnsack et al., Herrnkind et al., and Carr and Hixon, all this issue). In addition, artificial reef researchers now realize that reef fish populations are embedded within a larger spatial matrix that may profoundly affect the local distribution and abundance of fishes through its effect on recruitment (Doherty 1981; Hixon and Beets 1993; Tolimieri 1995). It remains to be seen whether

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these broad-scale spatial factors (e.g., current patterns, distances from source populations, etc.) have a stronger regulatory effect on the reef-wide abundance of resident fishes than on local physical factors such as reef size and refuge number. Nonetheless, recognition of all of these factors will greatly increase our ability to answer the attraction-production question in a more timely manner.

In summary, the current evidence is insufficient to support the contention that hard-bottom habitat is limiting to most reef fish populations. Thus, the construction of future reefs must balance uncertain increases in

organismal production against the potential problems of high cost and possible increased probability of stock overexploitation. 

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