

Caribbean Coral Reef Restoration: A Brief Review and Concept Proposal of a New Method

Restauration des Récifs Coralliens des Caraïbes: Un Examen et le Concept Brève Proposition d'une Nouvelle Méthode

Caribe Restauración de los Arrecifes de Coral: Una Breve Revisión y Concepto de la Propuesta de un Nuevo Método

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ABSTRACT

Coral reefs, particularly those in the Caribbean region, have undergone or are undergoing a phase shift from coral dominance to coral depauperacy. This change has been driven by a multitude of factors including a long history of overfishing and disease. The majority of restoration programs in the region focus on direct enhancement of coral cover aiming to drive coral recovery via increased recruitment. However, with live coral cover at historically low levels and herbivore populations similarly reduced, benthic macroalgae have essentially been released from competition and are, in many areas, becoming the dominant benthic taxa on Caribbean reefs. Thus, restoration of these critical habitats must take into account the provision of appropriate settlement habitat for coral larvae. Here, the most common restoration methods are briefly reviewed, their merits and shortcomings discussed. A new restoration method involving the use of large herbivorous crabs is introduced.

KEY WORDS: Coral reefs, restoration, herbivorous grazers

INTRODUCTION

In 2008, more than one third of all scleractinian coral species met the IUCN red list criteria for threatened or endangered species (Carpenter et al. 2008). The Caribbean region has lost more than 80% of its live coral cover over the last half century (Hughes 1994, Gardner et al. 2003). Global climate change, ocean acidification, and rising sea surface temperatures, combined with anthropogenic stresses such as overfishing and the consequences of coastal development all threaten the resilience and the continued existence of reef-building corals (Hoegh-Guldberg et al. 2007). In the Caribbean, overfishing and disease have left the region with a pronounced paucity of herbivorous species (Jackson 2001). This massive reduction in herbivory and the loss of coral cover throughout the region have led to a major phase shift on most Caribbean reefs (Mumby 2009). Fleshy macroalgae, released from competition for space and herbivory have become the dominant benthic taxa on many Caribbean reefs (Hughes 1994).

As the region's coral reef habitats continue along a trajectory away from a coral-dominant stable state, and both the frequency and magnitude of climatic disturbances increase, the management, conservation, and restoration of coral reefs all become more difficult. The massive losses of live coral cover in the region may very well have already exceeded the threshold necessary to maintain spawning biomass. The rates of algal proliferation on many Caribbean reefs have already exceeded the capacity of the system's herbivores to keep macroalgae in check (Lirman and Biber 2000). As coral spawning biomass is reduced and, consequently, larval supply dwindles, the proliferation of algae and other benthic reef organisms (e.g. sponges, octocorals, ascidians, etc...) is leading to an increasingly narrow *recruitment window* for coral larvae, thus further exacerbating the recruitment limitation of Caribbean coral reef recovery (Arnold and Steneck 2011). Current dogma holds that the establishment of marine protected areas (MPAs) is key for the restoration of coral reef communities (Selig and Bruno 2010). MPAs have indeed led to increases in fish and invertebrate abundances (Halpern 2003, Cox and Hunt 2005). With respect to coral communities, however, increases in the abundance of finfish alone may have unintended negative impacts, such as the indirect facilitation of macroalgae at the expense of scleractinian coral fitness (Burkpile et al. 2013). Thus, the phase status of Caribbean coral reefs may be such that recovery is unlikely or impossible without direct intervention (Bellwood et al. 2004, Mumby et al. 2007).

Many management and conservation programs currently in effect for coral reefs in the Caribbean and around the globe are focused on direct and active restoration of live coral cover (Rinkevich 2008). Increasingly, restoration programs are beginning to focus more broadly, not only on direct enhancement of live coral, but on the provision of appropriate conditions for coral growth, survival, and recruitment as well. The goal of this manuscript is to briefly review these various methods, their merits, and drawbacks as well as present a new alternative method for Caribbean coral reefs.

Direct Enhancement of Live Coral Cover

Over the past several decades, coral reef restoration programs have focused largely on replenishment and restocking of live coral cover. The restoration of live coral cover on degraded or depauperate reefs aims to manage spawning stock so as to drive natural recovery via bolstering coral recruitment (Harriott and Fisk 1988). These methods rely heavily on asexual propagation of coral fragments mimicking natural fragmentation processes (Bowden-Kerby 2001), though the use of larviculture and sexual reproduction of corals *ex situ* are becoming more common as technology and husbandry practices progress (Borneman and Lowrie 2001). In some cases, coral *gardening* on depauperate reefs has been a resounding success. In other cases, restocked reefs have failed to recover. Generally, fragments cultivated *in situ* or in closed systems seem to be more durable than natural coral recruits on stressed coral reefs (Borneman and Lowrie 2001). This suggests that use of transplanted corals may lead to higher survival and growth rates than natural recruits. Additionally, the use of asexual

fragments from multiple donor sites may not only preserve, but may even increase the genetic diversity and thus the resilience of the coral community in restored areas (Borneman and Lowrie 2001, Schopmeyer et al. 2012) especially if the transplants include genotypes most resilient to climate change (Palumbi et al. 2014). Coral nurseries may also serve as important repositories of local genetic diversity during major disturbance events where natural stocks are severely affected (Schopmeyer et al. 2012).

Although coral gardening has seen a great deal of success over the past several decades (Rinkevich 2005), there are a number of drawbacks to this method of coral reef restoration. Many, if not most, of the current active restoration programs in the Caribbean and elsewhere, focus heavily on the production and transplantation of fast-growing, *weedy* species such as Acroporids (Edwards and Clark 1999, Schopmeyer et al. 2012). These species are simple to propagate and transplant, and provide a great deal of structural complexity and habitat, but are less than ideal in restoring the reef-building function of coral communities (Edwards and Clark 1999). A more appropriate restoration model might focus on the slower-growing massive species whose natural recovery is far slower and which account for far more calcium accretion in the reef matrix (Edwards and Clark 1999).

Stock enhancement programs for live coral cover are feasible and show success in some situations (*e.g.* restocking localized areas with rare or uncommon species following bleaching events or ship groundings; Hudson and Diaz 1988). There has been some success in bolstering coral spawning stock on degraded or denuded reefs as well (*e.g.* Rinkevich 2005). However, the restoration of large areas of depauperate reef with coral transplants is logistically difficult, if not impossible (Schopmeyer et al. 2012). Finally, while maintaining a healthy spawning stock of corals is indeed imperative to the restoration of these communities, without the provision of appropriate settlement habitat, recruitment failure will likely continue to present a major bottleneck and hinder recovery. It is advisable, particularly in the Caribbean, that any restoration program aiming to bolster natural coral recruitment involve a macroalgae management component to ensure that proper settlement habitat is available for coral larvae.

Management of Macroalgae

The restoration of coral reefs requires not only a healthy and reproductive coral community, but also appropriate settlement habitat for coral recruitment. In many areas, and particularly in the Caribbean, the provision of appropriate settlement habitat is likely synonymous with a healthy, robust, and diverse community of herbivores. Gross overfishing and disease have both contributed to a general paucity of the major herbivorous species (*e.g.* Echinoid and Scarid grazers) throughout the Caribbean region (Levitan 1988, Jackson 2001).

Parrotfishes are the dominant vertebrate grazers in the Caribbean Sea. Decades or even centuries of overfishing have, in many areas, left Caribbean reef fish communities largely devoid of large parrotfish (Jackson 2001). Due to the substantial effect these fishes have on benthic commu-

nity structure, the protection and conservation of parrotfish has become a major priority in many areas of the Caribbean (Mumby et al. 2007, Kennedy et al. 2013). Kennedy et al. (2013) reported that conservation of parrotfish may well delay reef matrix degradation by close to a decade or, when combined with massive global emissions reform, may maintain a positive carbonate budget on reefs through the 21st century. However, in many parts of the Caribbean, parrotfishes are popular fishery items and without a great increase in the financial assets of many management bodies around the region, enforcement of parrotfish conservation presents a serious challenge. In more temperate areas (*e.g.* Florida), parrotfish grazing may exhibit a seasonal component in intensity as fish migrate in response to seasonal changes in water temperature. The conservation of parrotfish in these areas may not result in the same sustained levels of grazing intensity described for the wider Caribbean populations. Some contend that recovery of the Caribbean's coral reefs is synonymous with a recovery of the long-spined sea urchin, *Diadema antillarum*, commonly referred to as the region's *keystone* herbivore (Lessios et al. 2001). Stock enhancement and transplantation studies suggest that the species plays a disproportionately great role in structuring the benthic algal community on Caribbean coral reefs (Burdick 2008). However, now 30 years after the Caribbean-wide mass mortality of urchins, their populations have seen only limited and sporadic recovery (Chiappone et al. 2002, Carpenter and Edmunds 2006). Thus, while recovery of such a vital ecological function as herbivory on Caribbean coral reefs may appear to hinge on the activity of a single species (*e.g.* *Diadema*), a restoration initiative with such a narrow focus may very well lead to even greater systemic fragility and may even increase the likelihood of future cascading effects or community collapses. Perhaps a more appropriate approach would focus on both the restoration of grazing as an ecosystem function, but also on bolstering redundancy in that function, rather than on a single species.

The role of invertebrate grazers in coral reef ecosystems is poorly studied with the exception of echinoid grazers (*i.e.*, urchins) in the Caribbean region. The role of other invertebrate grazers (*e.g.* crabs) in coral reef communities is currently understudied. In fact, crabs may play a major role in structuring the benthic algal community of coral reefs throughout the Caribbean and elsewhere. Coen (1988) suggested that the grazing activity of the diminutive spider crabs in the genus *Mithraculus* are largely responsible for driving benthic algal community structure in the dense *Porites* thickets in Belizean waters. Stachowicz and Hay (1996) reported a similar mutualistic association between Mithracine crabs and branching coralline algae in the Caribbean. Stachowicz and Hay (1999) also reported that this same species is responsible for the persistence of corals in the genus *Oculina* in the temperate waters off of North Carolina, USA. In each case, herbivorous crabs seemingly benefit from the association via reduced predation risk while the coral host benefits by the antifouling activity of crab grazing. But crabs may play an even larger role in the regulation of macroalgae on reefs.

The Caribbean King Crab, *Mithrax spinosissimus*, is the largest brachyuran crab in the western Atlantic (Baeza

et al. 2012) and, like in its diminutive *Mithraculus* cousins, algae comprises the vast majority of its diet (Baeza et al. 2012), although it also requires some animal protein (Wilber and Wilber 1989). Algal consumption rates of these large spider crabs rival those of Caribbean parrotfish; only the large terminal phase of the stoplight parrotfish, *Sparisoma viride*, eats more algae per gram of body weight than *M. spinosissimus* (Butler and Mojica 2012). The range of *M. spinosissimus* extends throughout the Caribbean and Gulf of Mexico, through Florida and up the East Coast of the U.S.A. reportedly as far north as the Carolinas (Baeza et al. 2012). The species is found at depths from 1m to more than 200m and prefers structurally complex, crevice-rich habitats (Baeza et al. 2012, Butler and Mojica 2012). The nocturnal and cryptic nature of the crabs makes estimating natural abundance difficult, although the animals occur naturally throughout their range in low abundance (Butler and Mojica 2012). The larval duration of the species is exceptionally short (~4-6 days post hatch) (Creswell et al. 1989). This abbreviated larval development, along with the species' large adult size (males up to 3 kg) and rapid growth, all make *M. spinosissimus* an excellent candidate for mariculture production (Brownell et al. 1977, Creswell et al. 1989).

These large herbivorous crabs may well play a substantial role in structuring the benthic algal community on Caribbean coral reefs. Recently, experiments investigating the effect of enhancing the density of *M. spinosissimus* on algal-dominant coral patch reefs in the Florida Keys (USA) suggest that the species is an excellent candidate for stock enhancement-based restoration programs (A.J.S., unpublished data/in prep). The species exhibits remarkably low mortality from predation, as well as a high degree of philopatry or site fidelity in the field (A.J.S., unpublished data/in prep). In fact, during the previously-mentioned stock enhancement study, *M. spinosissimus* tagged with visible implant elastomer fluorescent tags were recaptured up to twelve months post-transplant on the same patch reef (A.J.S., unpublished data/in prep). Additionally, preliminary results suggest that reefs stocked with *M. spinosissimus* exhibit both greater diversity and abundance of reef fishes than nearby control reefs (A.J.S., unpublished data/in prep). As *Diadema* have failed to recover in Florida and many parts of the Caribbean now more than 30 years after their mass mortality, *M. spinosissimus* may well represent a viable alternative to urchins for restoration throughout the region. Additionally, the relative ease and low cost of captive culture of *M. spinosissimus*, compared to that of *D. antillarum*, makes community-based mariculture of crabs for restoration both feasible and attractive throughout the region.

Regardless of the method used to reduce macroalgal cover on coral reefs, effective algae management programs may indirectly benefit coral reefs. When algae cover is reduced, grazing intensity in the system actually increases as the nacent herbivore community acts on a smaller overall area covered by algae. Additionally, preliminary data suggest that fish abundance and diversity both increase with declining algal cover (A.J.S., unpublished data/in prep). Grazing rates of herbivorous fishes increase by 3 - 5 times in areas of higher fish abundance than in

areas of lower fish abundance (Cantano et al. 2014). Additionally, herbivorous fish show a strong preference for grazing in areas where algal cover is sparse over areas of high algae cover (Idjadi, oral presentation, Benthic Ecology Meeting, 2014). Thus, it stands to reason that as algae cover is reduced, either manually or via stock enhancement of herbivores, systemic grazing intensity should increase as transient (e.g. fish) herbivores become more abundant and more effective. This increased grazing intensity, at least on a local scale, might increase the *recruitment window* and improve conditions for coral growth and survival. Thus, benthic invertebrate grazers, or manual removal of macroalgae, may be enough to catalyze a trophic cascade. Rather than apply a single method, combining algae management and coral transplantation methods may be more effective in the restoration of Caribbean coral reefs. Manually denuding the reef of algae, stock enhancement of herbivores, and coral transplantation may be best used synergistically as restoration tools. Doing so may be sufficient, at least on a localized scale, to improve conditions for recovery of coral reef communities.

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