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Incorporating herbivorous sea urchins in ramet culture of staghorn coral *Acropora cervicornis*

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ABSTRACT: Since the 2006 listing of the staghorn coral *Acropora cervicornis* as threatened under the US Endangered Species Act, interest has increased in its culture for laboratory studies, restoration and *ex situ* conservation efforts. A pervasive problem in coral culture is substrate overgrowth by algae and other spatial competitors. We conducted a laboratory study to examine the utility of introducing herbivores, juvenile variegated sea urchins *Lytechinus variegatus*, to tanks containing small (<1 cm^2) *A. cervicornis* ramets. Growth of coral ramets on ceramic tile substrates was monitored in recirculating seawater tanks over 210 d and measured in terms of area change under 3 treatment conditions: (1) presence of laboratory-reared, juvenile, variegated sea urchins; (2) weekly scraping of algal turfs from the tile substrate by means of a razor blade; and (3) absence of both urchins and manual turf removal (i.e. control). Over the course of the study, coral area decreased in the control treatment, but increased in the scraped and urchin-containing treatments. All 3 treatments differed significantly from one another, with the highest growth rate (3.1 mm^2 d^{-1}) associated with the manual removal of algal competitors, followed by the urchin (1.9 mm^2 d^{-1}) and control treatments (–0.8 mm^2 d^{-1}). Given the relative ease of *L. variegatus* culture, the incorporation of variegated sea urchins in the coral ramet production process appears to provide at least a partial substitute for manual algal removal. Although coral growth in the presence of urchins was slower than with manual removal, human labor costs associated with the latter may out-weigh any production rate improvements in large-scale operations.

KEY WORDS: Sea urchin · Coral production · *Lytechinus* · Algae control

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INTRODUCTION

Reef-building corals are the foundation of the most biodiverse ecosystems on the planet, providing myriad valuable and irreplaceable ecosystem services. By virtue of their large spatial extent, high structural complexity and connectivity with seagrass, mangrove and pelagic systems, coral reefs provide, among other services, shoreline protection, tourism, fisheries, and aesthetic and cultural value. However, over the past 3 decades, reef-building corals around the globe have experienced significant declines. This is particularly evident in the Caribbean region where live coral cover fell from ca. 50 to ca. 10% between the late 1970s and the early 2000s (Gardner et al. 2003), and catastrophic events impact coral reefs regularly (e.g. Hughes et al. 2003, Miller et al. 2009). Subsequent and dramatic declines in fish abundances (Paddack et al. 2009) and a reduction in the structural complexity of Caribbean reefs (Alvarez-Filip et al. 2009) have also been reported in region-wide meta-analyses. This region is home to the first corals listed under the US Endangered Species Act (*Acropora cervicornis* Lamarck, 1816 and *A. palmata* Lamarck, 1816). While these losses to populations, habitat quality, ecosystem resilience and services are widely

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recognized, little consensus exists as to the type and sequence of management actions that would protect these resources, as considerable management and conservation effort over the past 2 decades have largely failed to stem declines. The lack of agreement among researchers derives from the lack of understanding of basic coral biology/health, disease etiology and the relative contributions (and synergies) of such stresses as toxins, elevated nutrient levels, overfishing, exotic species, ocean acidification and temperature extremes. This situation hinders the development of effective management actions.

Although *in situ* monitoring of coral reefs is essential for documenting their status and trends, field observations alone are inadequate for discerning the influence of the many possible factors driving coral decline, especially when evidence suggests that the importance of those factors differs among species and locations. Coral researchers have conducted simple laboratory investigations on Caribbean corals to increase understanding of basic coral physiology, especially patterns of settlement and growth, since at least the early 1900s (e.g. Mayer 1914). However, controlled, replicated studies using corals of consistent size, morphology, environmental history and genotype (i.e. a 'white mouse') are increasingly recognized as necessary for understanding, and ultimately mitigating, the myriad threats facing coral reefs (Rinkevich & Shafir 1998, Woodley et al. 2003, Shafir et al. 2006, Riebesell et al. 2010). Interest in laboratory studies, restoration and *ex situ* conservation efforts specifically targeting *Acopora cervicornis* has increased since the 2006 listing of this species as threatened under the US Endangered Species Act.

While the stressors affecting coral populations can differ widely at the local level, competition with macroalgae and algal turfs has been recognized as a global cause of coral mortality (McCook et al. 2001, Diaz-Pulido & McCook 2004, Birrell et al. 2008, Diaz-Pulido et al. 2009, Barott et al. 2012) and as a determinant of coral recovery from climatic disturbances (Wilson et al. 2012). In fact, recent studies on the effectiveness of Marine Protected Areas have identified the preservation of an intact and diverse herbivore guild as one of the keys to enhancing coral resilience (Hughes et al. 2007, Mumby et al. 2007, Mumby & Steneck 2008). The impacts of coral–algal competition can be especially intense for small corals that can be easily overgrown by faster-growing algae in both natural and experimental settings (Lirman 2001, Yap & Alvarez Molina 2003, Calfo 2007). The algal overgrowth problem has prompted examination of the alga-grazing gastropod mollusc *Trochus niloticus* as a potential means of enhancing coral recruitment in the field. For example, Omori et al. (2006) found that coral recruitment was significantly enhanced on *T. niloticus* aquaculture structures off Japan. However, deliberate introduction of *T. niloticus* on artificial reef substrates off the Philippines was unsuccessful in terms of algal removal and coral recruitment due to predation on the gastropods (Villanueva et al. 2010).

In this study, we tested the use of juvenile variegated sea urchins *Lytechinus variegatus* Lamarck, 1816 as a tool for preventing algal turf competition and overgrowth of small coral ramets of the staghorn coral *Acropora cervicornis* within a controlled, ex situ culture setting. The present paper reports on a 210 d laboratory study comparing the growth rates of *A. cervicornis* ramets under 3 treatments: (1) presence of *L. variegatus* juveniles, (2) weekly manual removal of algal turfs by means of a razor blade (scraping) and (3) absence of both urchins and manual alga removal (i.e. control).

MATERIALS AND METHODS

Animal sources and preparation

The *Acropora cervicornis* ramets used in this study were derived from coral samples obtained from a nearshore reef off Broward County, Florida, USA (26°09.138N, 80°05.537W), in April 2006. After a 5 d acclimation period, the broodstock coral was fragmented and mounted on 5 × 5 cm ceramic tiles, which were held in the semi-recirculating culture system described in the following subsection. These corals were kept in culture at the facility for approximately 6 yr before the start of the current experiment. Ramets were produced from these cultured fragments by using a 10 mm biopsy punch (Acu-Punch) to excise circular pieces of coral tissue (approximately 10 polyps) with underlying skeleton from thin areas of lateral encrusting growth over the square tile substrate. Next, each circular coral piece was attached to a 5 × 5 cm ceramic tile using cyanoacrylate gel. Once in place, the mounted ramets were allowed to recover for a period of 14 d before the start of the trial. Only ramets with a solid, uniform attachment to the ceramic substrate were used in the trials; these were subsequently labeled and randomly assigned to the 3 experimental treatments of this study.

The juvenile *Lytechinus variegatus* used in the urchin treatment were cultured at the University of

Miami Experimental Hatchery from broodstock urchins collected from seagrass beds off Key Biscayne, Florida. These adults were induced to spawn by injection of 1 ml of 0.5 M KCl (George et al. 2004, Buitrago et al. 2005). Subsequent larval culture followed the roller-bottle culture procedures set forth in Capo et al. (2009). Briefly, larvae were held in 2.4 l roller bottles and fed a diet of *Isochrysis galbana* Parke, 1949 and *Chaetoceros muelleri subsalsum* Johansen and Rushforth, 1985 for approximately 14 d. Once developmentally competent (presence of rudiment and pedicellaria), metamorphosis was induced using a benthic diatom film. Post-metamorphic animals grew to the juvenile stage with a diet of cultured macroalgae (e.g. *Ulva* sp. and *Gracilaria ferox* J. Agardh, 1852) (Capo et al. 1999) prior to use in the experimental treatment.

Experimental set-up

Coral growth trials were conducted in the semi-recirculating coral culture system contained in a 183 × 51 × 25 cm fiberglass trough. Targeted study duration was 6 mo. Water used in the system was thermally regulated seawater that was sterilized using ultraviolet light (UV), passed through a protein skimmer and mechanically filtered using a 10 µm canister filter. Recirculating water was continuously supplemented at a rate of 1 l h^{-1} with 1 µm filtered, UV-treated seawater pumped directly from the ocean. Artificial light (14 h light:10 h dark cycle) was provided with banks of 175 W, 10 000 K Ushio metal halide bulbs, delivering an approximate illumination of 280 µmol m^{-2} s^{-1} at the water's surface. Water quality (temperature, salinity, pH, dissolved oxygen) was monitored hourly throughout the trial for the recirculating system with a YSI 5200 multi-probe meter.

Groups of 3 coral ramets were randomly assigned among 9 clear, uncovered polycarbonate bins (24 × 24 × 20 cm), and these were randomly assigned among 3 treatments: urchins, scraped and control. Water circulation within each bin was provided with a submersible Hydor Koralia 908 l h^{-1} pump, with incoming seawater entering each bin at a rate of 2 l min^{-1}, resulting in complete water turnover in each bin every 6 min. This rapid turnover ensured all experimental bins were exposed to the same water quality conditions. The urchin-addition treatment included 4 *Lytechinus variegatus*, with initial test diameters (TD) of approximately 1 cm. Using small urchins among the ramets reduced the possibility of mechanical damage from urchin grazing (Forsman et al. 2006). Approximately every 7 d, bins were replaced with clean ones, and the position of the bins within the system and the corals within bins were randomly varied over the course of the study. All coral ramets were fed weekly with a mixture of Zeigler larval fish and shrimp diet (Larval AP100) and Cyclopeze frozen copepods. Every 7 d, the tile surfaces surrounding the ramets in the manual algal removal treatment were scraped using a razor blade until no algal biomass was evident with the naked eye. Care was taken not to damage the coral growing margin with the razor blade, and scraped turf was discarded. Corals in the control treatment were left undisturbed throughout.

Coral growth measurement and analysis

Coral growth in this experiment was primarily lateral; branch formation was not observed. Hence, projected area occupied by each ramet was monitored via digital still photography on Days 0, 15, 29, 42, 71, 84, 98, 140, 182 and 210; a ruler was placed within each image for scale. The digital images were subsequently analyzed to generate area estimates (mm^2) for each ramet at each time interval using the US National Institutes of Health software package Image J. Treatment effects on coral growth (area) were evaluated via repeated-measures analysis using SAS (1990) statistics software. To avoid the problem of pseudo-replication (Hurlbert 1984), analysis was performed such that the dependent variable was the sum of coral area for each replicate bin as opposed to using individual ramet areas within bins. Treatment-specific growth rates were estimated and compared using a general linear model (i.e. PROC GENMOD) within the SAS (1990) software whereby (1) time (day), treatment and the interaction term were the independent variables and (2) each bin was treated as a 'subject' measured over time. Differences among growth rates were evaluated via post hoc *t*-tests. Statistical significance was declared at the $p < 0.05$ level.

RESULTS

A summary of hourly water quality conditions over the 210 d trial is provided in Table 1. The accumulation of turf algae around the control ramets was conspicuous by Day 29, and this pattern persisted until the end of the trial (Fig. 1). In this experiment, observed algal turfs (examined macro- and microscopi-

Table 1. Summary of water quality conditions during the 210 d trial. Data were collected hourly using a YSI multi-probe instrument. DO: dissolved oxygen; % sat.: percent oxygen saturation

Variable	pH	Temp. (°C)	DO (mg l^{-1})	DO (% sat.)	Salinity
Average	8.22	25.86	7.30	104.20	33.77
SD	0.14	0.36	0.51	3.07	2.33
Minimum	7.60	22.00	6.40	74.00	25.00
Maximum	8.53	26.60	10.21	109.00	37.40

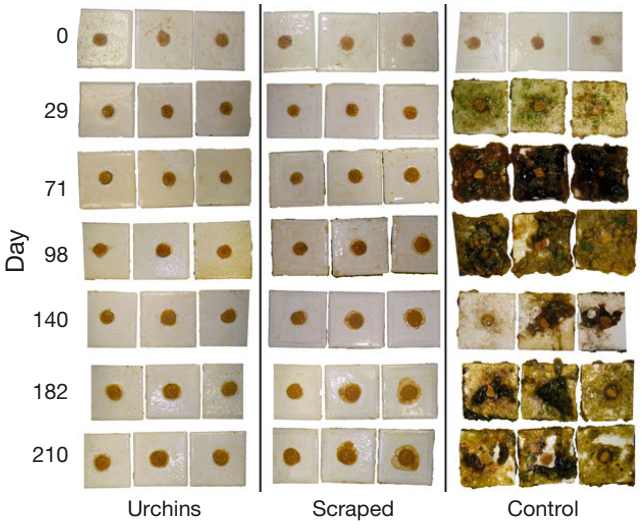

Fig. 1. *Acropora cervicornis*. Examples of images from which ramet area measurements were obtained. Shown are examples of ramets under (A) urchin-removal (grazed), (B) manual-removal (scraped) and (C) control treatments. Images correspond (top to bottom) to Days 0 to 210 as labeled

cally) appeared to be predominantly composed of a diverse group of cyanobacteria, including the genera *Lyngbya*, *Blenothrix*, *Phormidium*, *Schizothrix* and *Nodularia* (L. Collado-Vides, Florida International University, pers. comm.). In contrast, development of algal turf around the urchin-grazed and manually scraped treatments was negligible from the first day of the trial to the last. Day 29 of the trial was also when mean ramet area trajectories of the manually scraped and urchin-grazed treatments diverged from the trajectory of the control (Fig. 2A). By the end of the trial, the mean area of coral ramets held with urchins ranged from 513 to 789 mm^2, and those that had their substrates manually cleared of algal turfs (i.e. scraped) ranged from 761 to 1084 mm^2. Area loss was evident among all control treatment replicates, with declines ranging from 12 to 233 mm^2. By Day 210, complete mortality of ramets within replicates in the control treatment was 0, 66 and 66 %, whereas no mortality occurred within the other 2 treatments. Repeated-measures analysis provided the following coral area change estimates (mean ± SE growth rates) for the control, manually scraped and urchin-grazed treatments: –0.78 ± 0.29, 3.08 ± 0.29 and 1.86 ± 0.20 mm^2 d^{-1}, respectively (Fig. 2B). Post hoc *t*-tests indicated that the growth rates

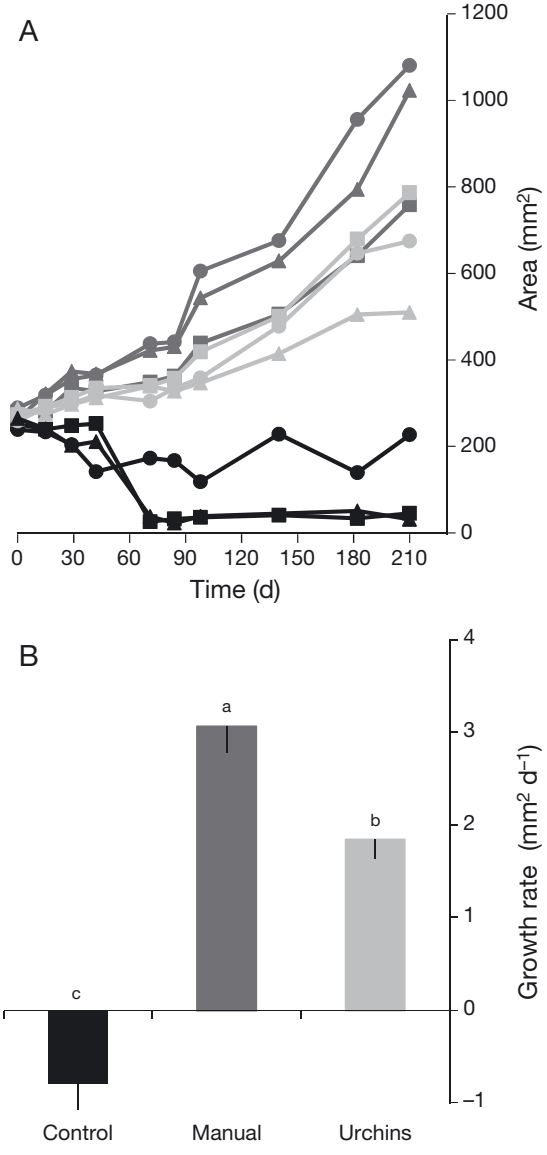

Fig. 2. *Acropora cervicornis*. (A) Ramet growth (for 3 replicates) under 3 laboratory treatments: (1) manual scraping of macrolagae (dark gray symbols and lines), (2) grazing by juvenile urchins (light gray) and (3) absence of both urchins and manual removal of macroalgae (black). (B) Comparison of ramet growth rates (lines indicate 1 standard error) for each treatment. Different lowercase letters indicate all rates are significantly different ($p < 0.001$) from one another

of the manually scaped and urchin-grazed treatments differed significantly from the control ($p = 0.003$ and $p = 0.004$, respectively) and that the manually scraped treatment growth rate was significantly higher ($p = 0.032$) than the urchin-grazed treatment.

DISCUSSION

While the concept of laboratory bioassays using corals is not new, only recently have findings based on such studies appeared in the literature (e.g. Shafir et al. 2003, Bielmyer et al. 2010) and most still utilized field-harvested corals (e.g. Morgan & Snell 2002, Renegar & Riegl 2005, Markey et al. 2007), presenting the disadvantages of unknown ecological history and genotypic identity of the experimental subjects, as well as the depletion of wild populations. Supply of identical coral ramets of sufficient numbers and dimensions for laboratory experimentation requires coral culture systems that maintain high water quality and appropriate light conditions to minimize stress to each colony. Whereas water treatment and illumination systems are readily available from the aquarium industry, unwanted and costly competitors on coral substrates, which, if left unchecked, inhibit coral growth and survival, remain a pervasive problem (Lirman 2001, Yap & Alvarez Molina 2003). Clearly, chemical application and/or light manipulation for reducing algal growth may have deleterious effects on the health of the corals and/or their symbionts (or otherwise compromise the coral assays for which they are intended). While mechanical (manual) removal of algae is a highly effective control option (Calfo 2007), it is a highly labor-intensive activity, especially when culturing 100s to 1000s of individual ramets (Forsman et al. 2006). Therefore, although coral growth in the presence of urchins is slower than with manual removal, human labor costs associated with the latter may out-weigh any production-rate improvements in large-scale (>700 ramet) operations (see cost comparisons in the Supplement at www.int-res.com/articles/suppl/n022p183_supp.pdf). Use of urchins to complement, not substitute for, manual scraping would provide ramet culturists with a degree of operational flexibility, especially if production targets change or labor problems emerge.

The ecological literature makes clear the paramount importance of grazing, especially by the long-spined urchin *Diadema antillarum* in the Caribbean, in enhancing coral persistence and resilience (Sammarco 1980, Lessios 1988, Carpenter & Edmunds 2006). However, there is growing recognition that grazers can also cause incidental mortality of the smallest corals (e.g. Okamoto et al. 2005, Baria et al. 2010); hence, grazing in the context of culturing small corals is a delicate balance to maintain control over competing algae without direct harm. For example, successful co-culture schemes of coral spat with grazing gastropods have proven successful off Okinawa (Omori 2005). Initial trials with laboratory-reared juvenile *D. antillarum* to control competition by macroalgae in coral culture efforts at our facility were unsuccessful, due to the propensity of these urchins to feed on coral tissue, as also reported under field conditions with high *D. antillarum* densities (Sammarco 1980).

Our results suggest that the use of cultured juvenile variegated sea urchins is an effective method of controlling algal turf overgrowth and enhancing coral growth of *Acopora cervicornis* within controlled environments without incurring the loss of coral tissue caused by the feeding action of more aggressive urchins. However, the use of *Lytechinus variegatus* to provide a substitute for labor-intensive manual control does come with some cost in terms of rate of coral production, requiring evaluation of the trade-offs. Juvenile *L. variegatus* culture is a rapid (metamorphosis from the larval to the juvenile stage occurs in about 14 d) and straightforward process as compared to other urchin species (George et al. 2004, Buitrago et al. 2005). Therefore, given the results of the present study and the relative ease of *L. variegatus* culture, we now routinely incorporate *L. variegatus* in the coral ramet production process.

Research is necessary to evaluate the potential role of small herbivores such as *Lytechinus variegatus* for enhancing post-settlement coral survival and growth under field conditions. Moreover, ready access to genetically identical coral ramets of consistent size, morphology, environmental history and condition is essential for laboratory studies designed to examine coral disease, toxicology and physiology, including investigation of the effects of changing ocean temperature and pH on corals and their symbionts. The model culture system involving propagation of small fragments of coral tissue and co-culture of juvenile *L. variegatus* holds promise for meeting the growing needs of the research community for experimental coral material. The present study, therefore, points to an effective, supplementary tool for tackling the algal competition problem — one of the several important, labor-intensive challenges involved in maintaining large numbers of sensitive, slow-growing corals in the laboratory.

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