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Why Corals Recruit Successfully in Top-Shell Snail Aquaculture Structures?

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Abstract: In 1996 and 1997, concrete box structures were installed in a shallow reef edge at Miyako Island, Okinawa (24°55'45"N 125°15'55"E) for rearing the commercially important top shell snail *Trochus niloticus*. Corals quickly attached on the quartz sand-coated fiberglass reinforced plastic latticed substrata on the bottom of the box. Within few years after severe damage of corals following extensive bleaching in 1998, however, the lattice was covered by *Acropora*-dominated coral colonies. In November 2005, coral coverage in four boxes was 50 to 90%. There were 25 species and the average size of the coral colonies was around 50 cm.

The accidental and rapid recruitment of corals on these aquaculture structures seems to have created an ideal environment for coral recruitment and growth. This finding provides a unique opportunity to gain insight into critical mechanisms of coral recruitment that may be used to improve coral reef restoration. The present paper deals with the aquaculture structures, environment, species diversity of corals, and possible factors that may have contributed to coral recruitment and growth.

Key words: Coral, top-shell snail, aquaculture structure, reef restoration

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INTRODUCTION

Coral reefs have experienced multiple stressors that have been increased in scale and magnitude in the last decades (Hughes *et al.* 2003; Pandolfi *et al.* 2003). These stressors may have overwhelmed the coral reefs' capacity to recover (Connell 1997). Reduction of these stressors is often difficult or may not be sufficient for coral reef restoration. Therefore, efforts must be made to improve restoration through artificial recruitment of coral larvae or fragments. However, recruitment mechanisms remain elusive and many artificial restoration projects have only marginally successful (Edwards and Clark 1998). We fortuitously observed high recruitment and survival of corals on aquaculture structures, installed on a shallow reef edge at Miyako Island, Okinawa Prefecture, Japan (24°55'45"N 125°15' 55"E), which was constructed to rear the commercially important top-shell snail *Trochus niloticus*. These structures seem to have created an ideal environment for coral recruits (Omori et al. 2006). This finding has provided a unique opportunity to gain insight into critical mechanisms that influence coral recruits and that may be used to improve coral reef restoration. The present paper deals with the aquaculture structures, the environmental conditions, coral species diversity, and factors that may have possibly contributed to the recruitment and growth of corals at Miyako Island.

STRUCTURE OF AQUACULTURE BOX

Since 1994, Okinawa Prefecture, Japan, has been promoting aquaculture and stocking of *Trochus niloticus*. Hatchery raised juvenile top-shell snails ~5 mm in diameter are released into concrete boxes placed on shallow coral reefs at three islands in Okinawa and kept for one year until they reach 40 to 50 mm in diameter. The snails are then collected and sold to fishermen who plant them to the exclusively permitted fishing grounds (Kubo 1991, 2000).

The aquaculture structures consist of two concrete boxes (2.1 m W × 2.1 m L × 0.6 m H inside) that are connected to create a single culturing unit with outside dimensions of 2.8 m W × 5.1 m L × 1.1 m H and weighing 26 tons (Fig. 1). In order to avoid sand sedimentation, a Fiberglass Reinforced Plastic (FRP) drainboard (12 cm-thick grating) is placed at the bottom and two sheets of quartz sand (ca. 300 μm grain size)-coated FRP latticed substrate (7.5 cm thick) are placed on the drainboard. The lattice aperture of the substrate is 5 cm × 5 cm. The top-shell snails feed on macroalgae and benthic diatoms that adhere to the lattice (Kubo et al. 1993). There is a drain hole at 30 cm from the upper edge of the box so that the surface of the lattice is daily exposed to the air during low tide. When the holes are plugged, however, the lattices are under water throughout the tidal cycle.

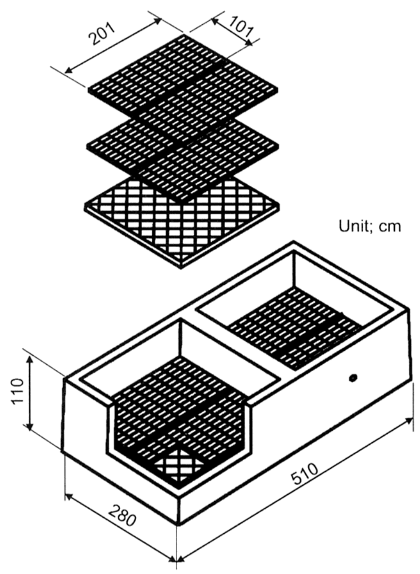


Fig. 1. Top-shell snail aquaculture structure. a. Latticed substrates and drain-board. Patent for the FRP latticed substrate is being applied by Asahi Kasei Construction Materials Co., b. Concrete boxes.

RESULTS AND DISCUSSION

In 1996 and 1997, 56 aquaculture structures were set in three rows along the shallow reef edge at Miyako Island (Fig. 2). Annually about 2000 juvenile top-shell snails were released into each box in early autumn and harvested one year later. In August and September 1998 corals around the structures suffered thermal stress and subsequent bleaching and extensive mortality. Within 1-2 years however, many corals were found on the latticed substrates, which made it difficult to collect the top-shell snails. Because of the considerable manual effort required to remove the corals and other sessile organisms fortuitously four concrete boxes of the east end were left untouched. They were plugged, creating an artificial tidal pool. The juvenile top-shell snails were released into the concrete boxes and corals were allowed to grow.

By November 2003 the lattices in the four boxes were covered by *Acropora*-dominated coral colonies of 40 to 65 cm in diameter. Coral cov-

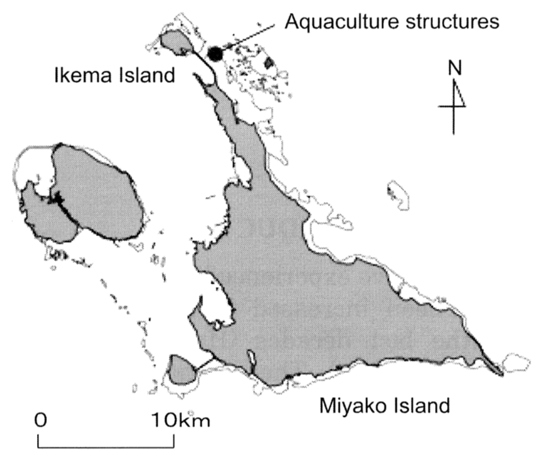
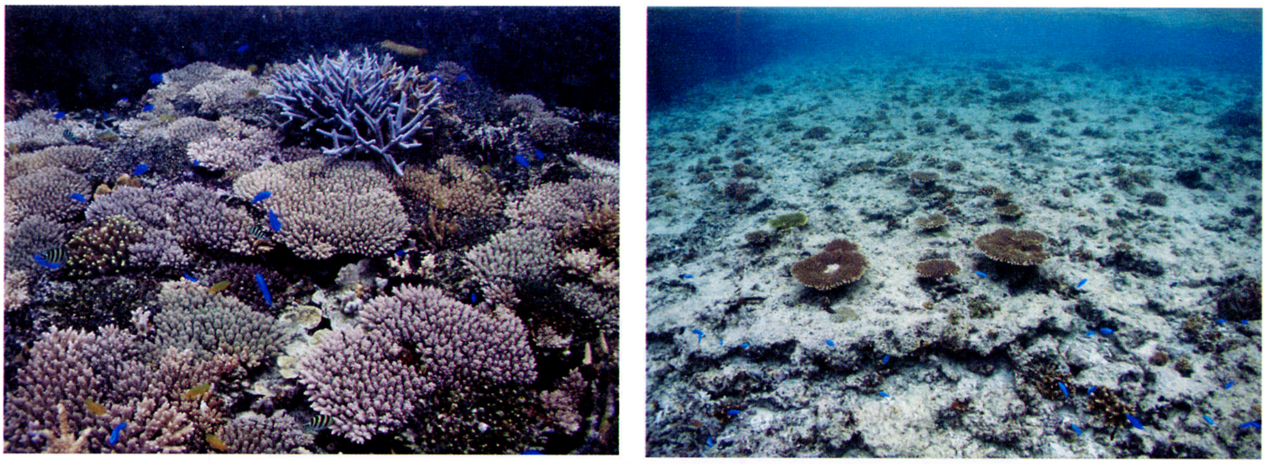
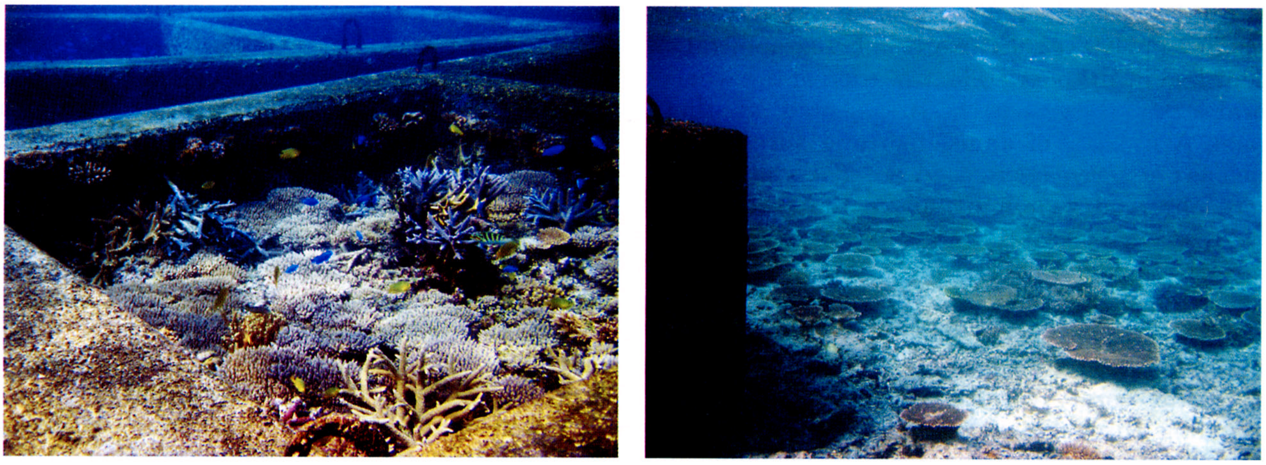


Fig. 2. Location of the aquaculture structures in Miyako Island, Okinawa Prefecture, Japan.



A B Photo by H. Taniguchi (AMSL)

Fig. 3. A. Re-assembly of the coral community in a aquaculture structure (See also Fig. 1 of Omori et al. 2006). B. Condition on the reef edge outside the structures. November 18, 2003.



A B Photo by K. Kajiwara

Fig. 5. A. Re-assembly of the coral community in the aquaculture structure. B. Condition on the reef edge outside the structures. November 27, 2005.

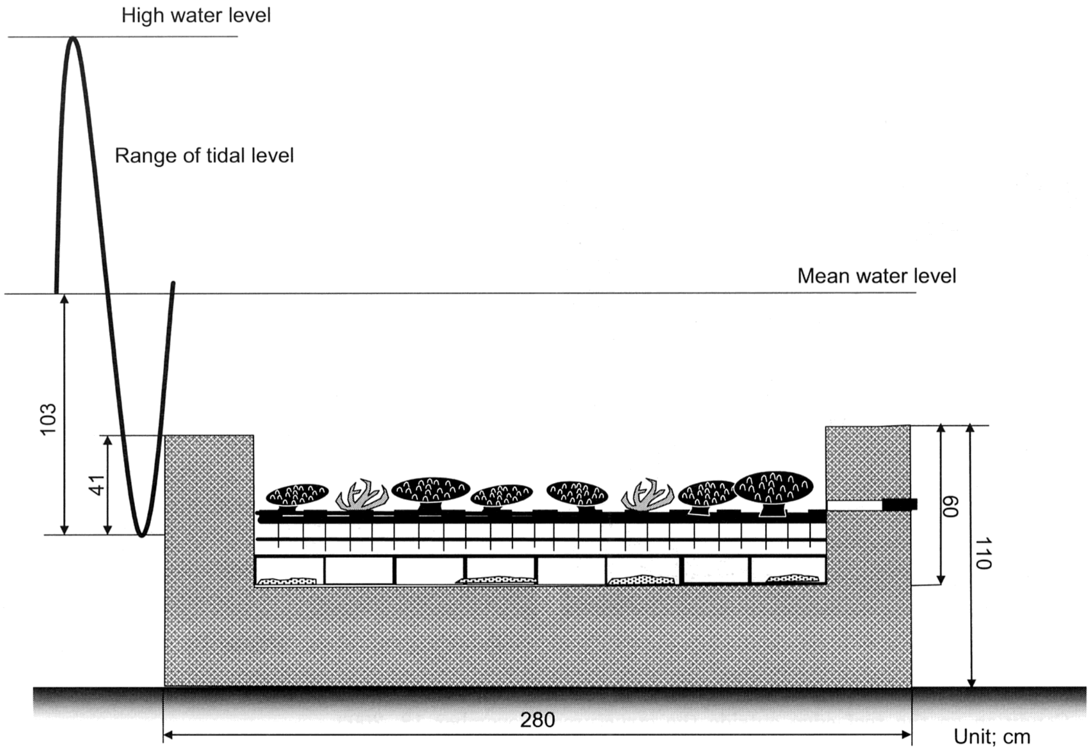


Fig. 4. Sketch of the aquaculture structure set at the depth of 172 cm.

erage in the boxes was ~95% (Fig 3A). In contrast, the coral coverage was 5% or less in the surrounding reef (Fig. 3B). In total more than 20 coral species including *Acropora hyacinthus, A. humilis* and *A. nasuta* were (photographically) identified in the boxes (identification of the whole coral community was not completed at that time). A number of damselfish and surgeonfish such as *Chrysiptera cyanea* and *Acanthurus triostegus* were observed swimming above the corals. On the reef edge near the aquaculture structures, there were few small corals and several large table-type corals that may have survived the 1998 bleaching event. These results suggest that the aquaculture structures have facilitated successful coral recruitment and survival by providing three-dimensional structures and an optimal environment for growth including a high grazing environment because of the high top-shell densities that reduced algal growth, which appeared different than the surrounding reef environment.

To investigate the specific factors that may have led to the high recruitment of corals on the aquaculture structures, we have observed a variety of abiotic and biotic variables. The hydrographic conditions of the boxes were measured using a DIVER water level recorder (Daiki Rika Kogyo Co) and StowAway Tidbit temperature logger during the period from November 18 to December 3, 2003. The tidal level ranged over 206 cm. As the boxes were placed at depths of 70 to 172 cm under the mean water level, the water level at the upper edge of the box that was placed on the depth of 172 cm, for example, varied from 165 cm to –41 cm (Fig. 4). Usually, the water temperature in the box was 3-4℃ lower than the outside in November. However, the temperature was normally higher than the outside in July, occasionally exceeding 31℃ for 2 to 3 hours during daylight (Kubo et al. 1993). In November 2005, two years after implementation of the observation coral coverage in the four boxes was still approximately 50 to 90%. There was some degradation of specific colonies over the two-year period that led to slight reductions in coral cover (Fig. 5A). Average size of the coral colonies on the vertical face of the boxes increased over time. There were 25 coral species, from 10 genera, in the box with the highest coral coverage (Table 1). The largest table-shaped colony measuring ~70 cm diameter, and the average size of coral colonies was around

Table 1. Comparison of coral species composition between inside and outside of the aquaculture structures (open circles mean presence).

Species	In boxes	Reef edge
Pocilloporidae		
Pocillopora		
Pocillopora damicornis	○	○
Pocillopora verrucosa	○	○
Pocillopora eydouxi	○	○
Stylophora		
Stylophora pistillata	○	○
Acroporidae		
Montipora		
Montipora pertiformis		○
Montipora digitata		○
Montipora efforescens		○
Montipora grisea		○
Acropora		
Acropora humilis	○	○
Acropora monticulosa	○	○
Acropora digitifera		○
Acropora verweyi	○	
Acropora nobilis	○	○
Acropora formosa	○	○
Acropora exquista	○	
Acropora microphthalma	○	
Acropora aspera		○
Acropora millepora	○	○
Acropora tenuis	○	○
Acropora yongei	○	
Acropora hyacinthus	○	○
Acropora latistella		○
Acropora nasuta	○	○
Acropora valida		○
Acropora florida	○	
Astreopora		
Astreopora gracilis		○
Poritidae		
Porites		
Porites lutea		○
Porites cylindrica	○	
Siderastreidae		
Psammocora		
Psammocora contigua		○
Psammocora profundacella		○
Galaxea		
Galaxea fascicularis	○	
Mussidae		
Symphyllia		
Symphillia agaricia	○	

Merulinidae		
Hydnophora		
Hydnophora microconos		○
Faviidae		
Favia		
Favia laxa		○
Favia pallida		○
Favia speciosa		○
Favia favus		○
Favia rotundata	○	
Favia maritima		○
Favites		
Favites halicora		○
Goniastrea		
Goniastrea edwardsi		○
Goniastrea aspera		○
Goniastrea pectinata		○
Platygyra		
Platygyra lamellina	○	
Platygyra pini	○	○
Montastrea		
Montastrea magnistellata		○
Leptastrea		
Leptastrea purpurea		○
Cyphastrea		
Cyphastra agassizi		○
Cyphastra serailia	○	○
Cyphastra chalcidicum		○
Cyphastra microphthalma		○
Echinopora		
Echinopora lamellosa	○	
Total number of genera	10	15
Total number of species	25	41

50 cm by rough estimate. Of 25 species occurring in the box 16 species are known to spawn in May or June around Akajima Island, located at northeast from Miyako Island (see Hayashibara et al. 1993, Shimoike 1999). The corals on the surrounding reef, particularly on the neighboring reef edge had recovered significantly by November 2005 (Fig. 5B). In total 41 species were recognized in 20 m × 20 m area on the reef edge nearby the boxes. The largest colony on the reef edge was measured at ~150 cm (many were 80~90 cm) in diameter. The Søren sen's (1948) quotient of similarity between species compositions in the box and reef edge was 42.4.

Throughout the observation period macroalgae and benthic diatoms were hardly seen on the lattices compared with their biomass on the upper edge of the boxes and reef substrate. A few sea urchins (*Echinometra mathaei*) and colonial tuncates (*Didemnum molle*) were found in the boxes however, large grazing fishes, such as parrotfish, were not observed in the boxes. It is known that large grazing fish that have been trapped in artificial structures subsequently avoided the structures (Watanuki, pers. comm.).

Based on these observations, we propose that the following six not mutually exclusive factors may facilitate coral recruitment and survival in the aquaculture structures.

1. Coral larvae may get trapped and entrained in the boxes, particularly after mass spawning of *Acropora*, because the structures act as retention ponds.
2. Latticed substrata provided a highly preferable substrate for larval settlement. Some

Acroporid juveniles such as *A. hyacinthus* prefer high flow that is induced by waves. Furthermore, the aquaculture structures were continuously washed by fresh-ocean water, containing a planktonic food source for the corals. Indeed, the structures may have also acted as a zooplankton trap.

3. Removal of macroalgae and benthic diatoms by high top-shell snail grazing pressure reduced shading and physical abrasion by fleshy algae. Note that top-shell snails did not eat or scrape coral polyps, and they preferred the high light environment, we presume because of the high algal productivity at these localities.
4. The aquaculture structures protected the corals from bioerosion and scraping by large fishes.
5. Corals were continuously under water even at low tides. At this depth, they received preferable sunlight.
6. The corals outside of the structures frequently received sediments. In the boxes, however, while sediment was present, it was rapidly drained through the lattice structures and therefore did not interfere with the corals.

Coral restoration projects in future should be designed to test the relative importance of each of these factors. Controlled testing of these factors may reveal critical mechanisms for successful recruitment, survival and growth of corals that can be used to improve restoration strategies. Moreover, the top-shell snail aquaculture structures provide a model for managing multiple-uses of the coastal zone because they provide not only direct value through the production of top-shell snails but also indirect value through their contribution to local coral restoration.

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どうして宮古島のタカセガイ中間育成礁にサンゴの花園が出現したのだろうか？

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沖縄県宮古島池間大橋東方のさんご礁の浅瀬（24°55'45"N, 125°15'55"）にはタカセガイ（サラサバテイ）*Trochus niloticus* の中間育成礁が56個、礁嶺に向かって並べられている。一個の育成礁は枡形２連（鉄筋コンクリート製，外測5.1m×2.8m×1.1m，重量約26トン、一枡の内測は2.1m×2.1m×深さ0.6m）で、底には砂の堆積を防ぐ目的でFRP製格子板を敷き、その上に厚さ7.5cm、目合5cm×5cmのFRP製格子板２枚が重ねられている。育成礁の側面には天端から30cmの位置に排水口があるが、それを閉じておけば水深60cmのタイドプール状態になる。ところが1996年に設置した後、格子板にサンゴが着生、成長し、その除去（掻き落とし）に多大の労力と経費を要するようになった。そこで東端の２個の育成礁４枡の排水口を閉じたままにしておいたところ、格子板は2-3年後、*Acropora* 属を主とする25種のサンゴに覆われた。内部のサンゴ被覆度は95%にもなり、大きな群体は直径65cm以上にも成長した。写真は2003年11月（Fig. 3A）と2005年11月（Fig. 5A）に写したものである。

予期せぬサンゴ群集の出現は、サンゴ育成技術に多くの示唆を与えると考えた私たちは、育成礁内外の環境測定とサンゴ出現種の同定を行い、サンゴが育った要因として、以下の６つの仮説を挙げた。１）育成礁内にサンゴの幼生、殊に一斉産卵後のそれら、が滞留して、格子板に着生しやすい条件が与えられた。２）育成礁内は波浪の影響を受けにくいので、サンゴは物理的破壊を免れ、しかも常に新鮮な海水に洗われて、十分な餌料プランクトンが供給された。３）格子板上の藻類がタカセガイによって食べられ、サンゴ幼生の着生と育成に好ましい環境が維持された。４）育成礁には大きな魚が入りにくいため、サンゴが生物侵食や食害を受けなかった。５）サンゴは低潮時にも常に水面下にあって、適当な照度を得ていた。６）格子板には浮泥の堆積が少なく、サンゴは懸濁物を被ったり埋没したりすることがなかった。これらの仮定を検証し、工夫を加えることによって、近い将来、理想的なサンゴ育成礁をつくってサンゴを育て、さんご礁の修復だけでなく、観光産業にも役立てる道を開きたいと考えている。