Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7-11 July 2008
Session number 10

Secondary succession of coral reef communities at Urasoko Bay, Ishigaki Island, the Ryukyus (southern Japan)

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Abstract: Observations of secondary succession of coral reef communities have been carried out at Urasoko Bay, Ishigaki Island, the Ryukyus, southern Japan from 1995 to 2007. Three stations have been permanently established on the outer reef flat, the inner flat, and inshore moat, with four permanent quadrats at each station. At the start of the study in September 1995, all organisms were scraped from the substrate surface. Thereafter, changes in percent cover of hermatypic corals and marine algae have been quantified annually. During the 12-years period, three bleaching events and a typhoon occurred, causing significant disturbance to these sites. Our long-term monitoring results show that recovery to a coral-dominated community (mainly *Acropora* spp.) requires 4-6 years and that transient domination by crustose coralline algae for 2-3 years facilitated coral recovery. It is suggested that crustose coralline algae play a role in construction of firm substrata for settlement and growth of hermatypic corals. The inshore station, which is dominated by rubble, remains nearly in a permanent state of disequilibrium between corals and algae.

Key words: Algae, Coral reef communities, Crustose coralline algae, Ecological succession, Ryukyu Islands.

Introduction

Recently, the health of coral reefs throughout the world has deteriorated due to various natural and human stresses (Hughes 1994; Wilkinson 1998, 2000, 2002; Bellwood et al. 2004). Coral reefs in the Ryukyus have also been gradually destroyed by pollution, excess sedimentation, bleaching and predation by *Acanthaster planci* (L) as well as by other factors (Nishihira 1987; Fujioka 1999; Yamazato 1999; Ohba et al. 2004, 2006). Restoration of coral reefs is a costly and uncertain endeavor, the techniques of which remain largely experimental (Omori and Fujiwara 2004; Precht 2006; Omori et al. 2008). Results are typically evaluated on an empirical basis with only a marginal understanding of the underlying causes facilitating or inhibiting recovery to a coral-dominated state. Long-term monitoring studies of reefs provide a temporal window on changes in community composition, including natural responses to disturbance. However, such long-term, place-based studies are relatively uncommon. At Urasoko Bay, we have followed secondary succession for 12 years (Fujioka 2002; Fujioka et al. 2006), which includes three bleaching events and a typhoon. Here we summarize the most important findings from this ongoing study with respect to natural resilience and the coral-dominated state in the face of these events.

Materials and Methods

Secondary succession of coral reef communities was monitored at three stations established in Urasoko Bay at Ishigaki Island in the Ryukyu Archipelago. These three stations represented the (A) outer reef flat, (B) inner reef flat, and (C) inshore-side moat (Fig. 1-2). The depth of each station was 0.5-1.5 m and the survey was carried out by SCUBA diving and snorkeling. Four permanent quadrats (1 m x 1 m) were put in place at each station. Subsequently, all organisms were scraped from the substrate surface in all quadrats in September 1995 and again in March 1996. The percent cover, number of species and of colonies of hermatypic corals in each quadrat were measured around in September each year from 1994 to 2007. The percent cover of marine algae in each quadrat was also measured in March 2002 and around September from 2002 to 2005. Percent algal cover from 1994 to 2001 and 2006 to 2007 was evaluated from underwater photographs taken at each quadrat. Percent cover is reported as the average of the four quadrats at each station.

Results and Discussion

In 1994, before the reef surfaces were scraped, tabular *Acropora* dominated all permanent quadrats at Station A with a secondary mix of corymbose and branching *Acropora*. Little algae or other invertebrates were observed (Fig. 3). Various growth forms of *Acropora* formed a mixed assemblage in two of the permanent quadrats at Station B. The rubble derived from branching corals filled the other two quadrats at Station B, and also two quadrats at Station C. Small filamentous, creeping and encrusting algae were observed growing on the rubble. Massive *Porites* dominated the two other quadrats at Station C, as well as a mixture of *Acropora, Pocillopora,* Faviidae and other species.

The percent cover of hermatypic corals at Stations A, B and C increased and reached 43%, 28%, and 24%, respectively, in 1998, three years after the substrate surfaces were scrapped. However, a large-scale coral bleaching event took place in coral reefs worldwide in 1998 (Wilkinson 1998, 2000), which also affected the Ryukyus reefs (Fujioka 1999;

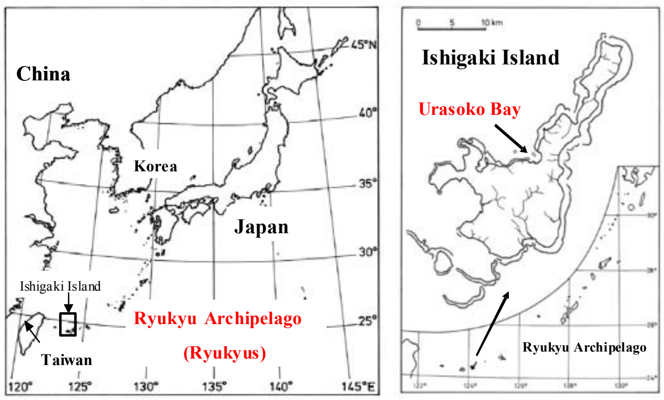


Figure 1: Maps of East Asia and Ishigaki Island in the Ryukyus (southern Japan) showing the study area of Urasoko Bay.

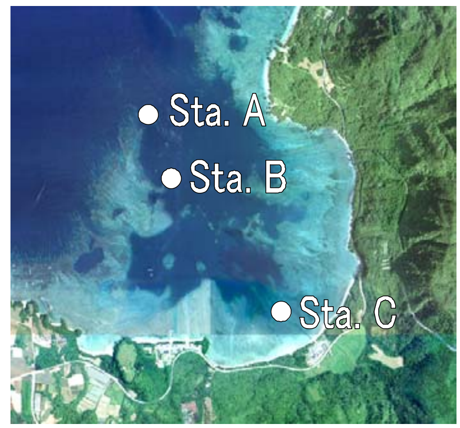


Figure 2: Aerial photograph of the three stations within Urasoko Bay.

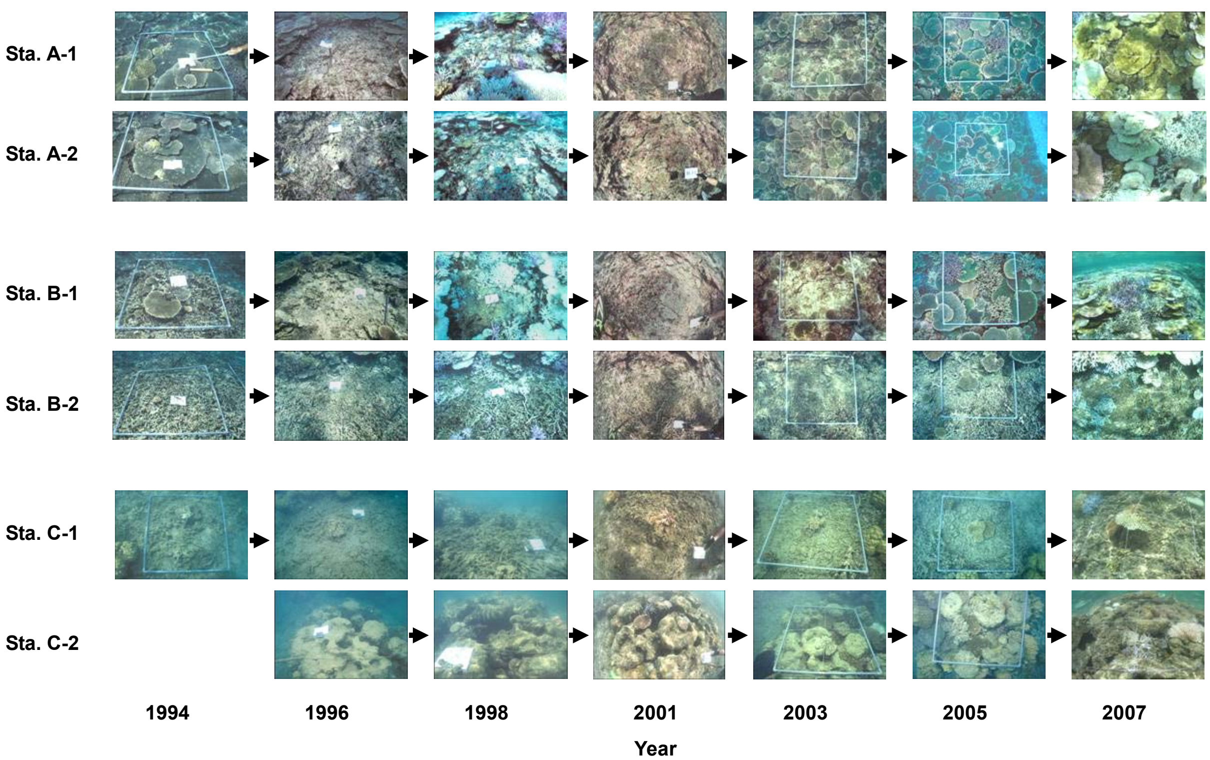


Figure 3: Underwater photographs showing changes in the reef communities in two of the four quadrats at each station in Urasoko Bay. The substrate surfaces in each quadrat were scraped in 1995. A photograph of the Station C-2 in 1994 was not taken.

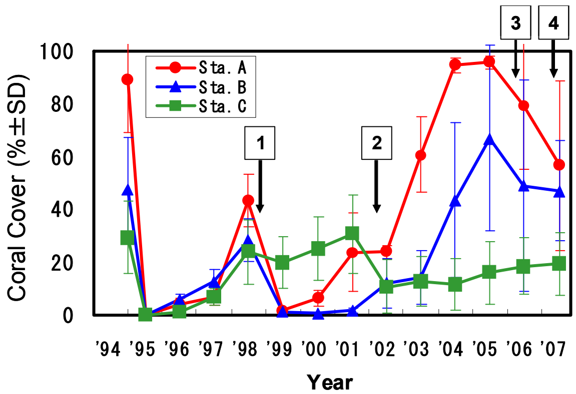


Figure 4: Changes in the percent cover of hermatypic corals at each station in Urasoko Bay from 1994 to 2007. The substrate surfaces in each quadrat were scraped in 1995. Arrows indicate disturbance events: 1. Outbreak of large-scale coral bleaching; 2. Typhoon; 3 and 4. Coral bleaching.

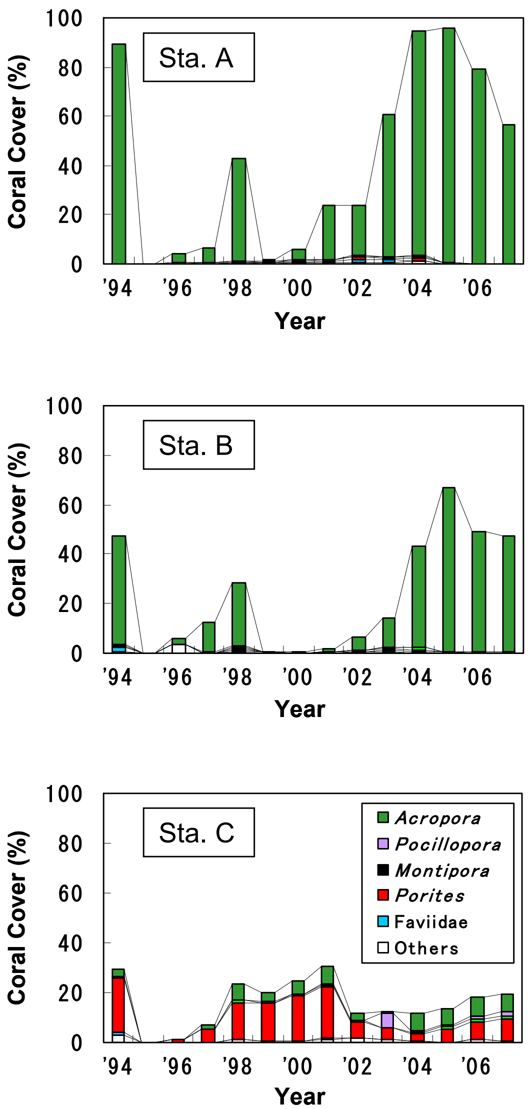


Figure 5: Changes in the percent cover of coral taxa at each station in Urasoko Bay from 1994 to 2007.

Yamazato 1999). During this bleaching event, most of hermatypic corals at Stations A and B died between summer and fall of 1998, although the *Porites* colonies survived at Station C (Fig. 3-4). By 1999, the percent cover of hermatypic corals at Stations A and B was reduced to 1.6% and 0.8%, respectively.

The percent cover of hermatypic corals at Stations A, B, and C increased gradually after the coral bleaching event in 1998 until 2002, when the cover stopped increasing or was again reduced by the damage caused by a large typhoon (No. 16 in 2002). The percent cover of hermatypic corals at Station A rapidly started increasing in 2002 and reached 95% in 2004. The cover at Station B also rapidly increased and reached 67% on average in 2005, with a maximum of 99.5% observed in a quadrat located on the rocks (Fig. 3, Station B-1). The cover at Station C reached a maximum of 31% in 2001, then decreased to only 11% in 2002, followed by a gradual increase to 19% in 2007. Coral bleaching occurred again in the southern Ryukyus in 2006 and in 2007, causing the percent cover of hermatypic ... ns A and

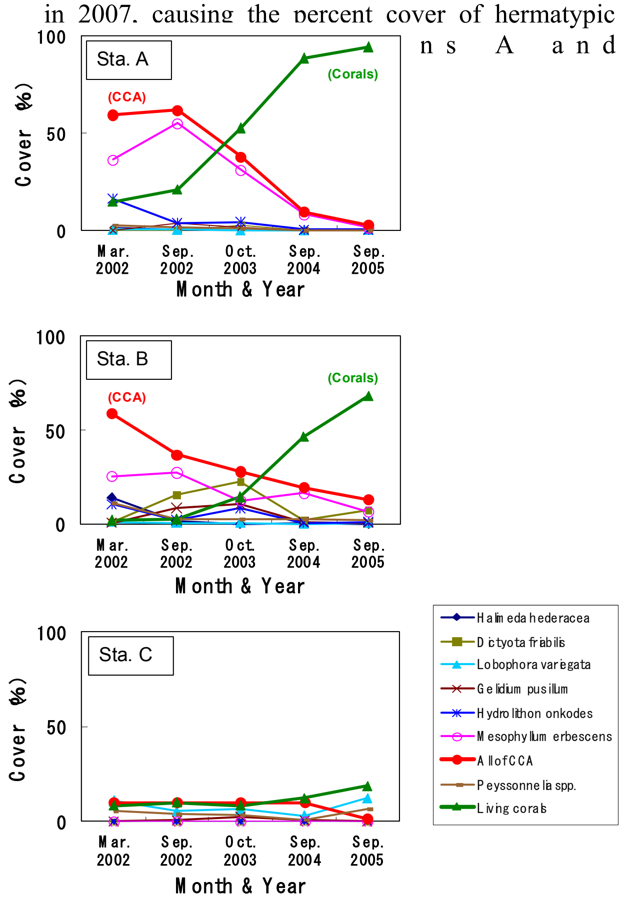


Figure 6: Changes in the percent cover of algae and total corals (- ▲ -) at each station from March 2002 to September 2005. CCA: Crustose coralline algae.

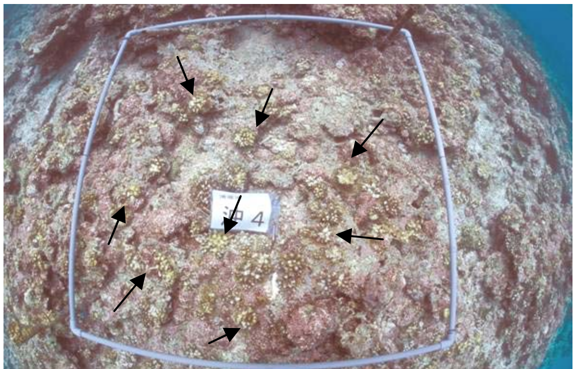


Figure 7: Dead coral reef at Station A in September of 2002. Crustose coralline algae (pink) were luxuriantly growing on dead corals and many small recruits of corals (pale brown: arrows) were beginning to be settled.

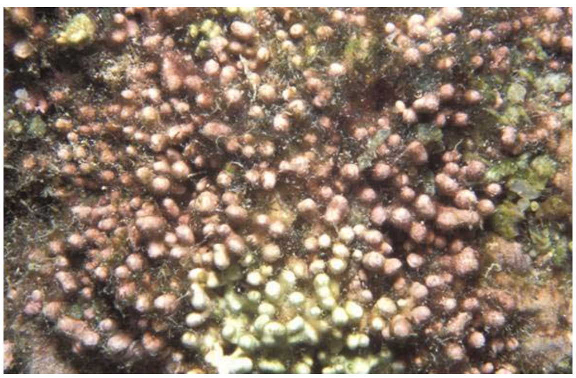
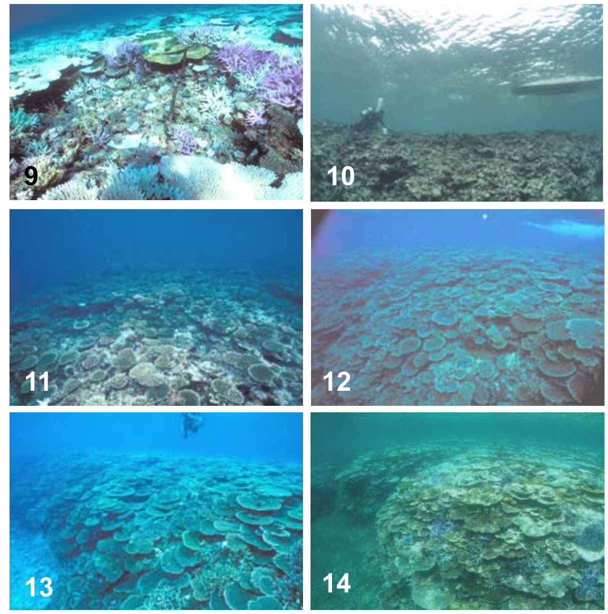


Figure 8: A crustose coralline alga, *Mesophyllum erubescens*, and filamentous algae growing on dead corals at Station A in September of 2002.

B to decrease to 57% and 47%, respectively, in 2007 (Fig. 4).

The changes in species composition at each station are shown in Fig. 5-6. The sequence of secondary succession was quite different at Station C compared to Stations A and B (Fig. 5). Coral recruits, as well as small filamentous, creeping, encrusting algae and crustose coralline algae immigrated and began to grow at Stations A and B in 1996, a year after the substrate surface had been scrapped. This recovery was highlighted by the resettlement of *Acropora* recruits. *Acropora* basal discoid parts were observed from a half to one year after the settlement. These recruits began to grow into an upright morphology from the center of their basal sections in 1997 and 2001. The growth rate of the upright part of *Acropora* was rapid, with an increase in the diameter of the colonies of 30-50 cm by 2005. When the secondary succession on the rocks at Stations A and B reached a climax (i.e., coral domination), the species composition and cover of the hermatypic coral community were similar to those of the original community in 1994. At Station C, *Acropora* recruits were much fewer than those in Stations A and B, whereas the recruits of many kinds of *Porites, Pocillopora, Montipora,* Faviidae and other genera were present on the rocks (Fig. 5). In Particular, massive *Porites* dominated from 1997 to 2002. The species composition and cover of hermatypic corals at Station C in 2001 were similar to those of the original community in 1994.



Figures 9-14: Underwater photographs showing an alternation of damaged and recovered coral reefs at Station A in Urasoko Bay from 1998 to 2007. 9. Large-scale coral bleaching in September of 1998. 10. Dead coral community in September of 2001. 11. Recovered coral community in October of 2003. 12. Almost recovered coral community in September of 2004. 13. Completely recovered coral community in September of 2005. 14. Coral bleaching occurred again in August of 2007.

Green algae such as *Halimeda hederacea*, brown algae such as *Dictyota friabilis* and *Lobophora variegata*, and red algae such as *Gelidium pusillum, Hydrolithon onkodes, Mesophyllum erubescens* and crustose coralline algae (CCA) temporarily appeared and grew luxuriantly during 1995 to 1997 and during 1999 to 2003, before the hermatypic coral community became dominant at Stations A and B (Fig. 6-8). Crustose coralline algae kept growing on the substrate at all stations. In particular, a thick crustose coralline alga, *Mesophyllum erubescens* (Fig. 8), had dominated on the rocks at Stations A and B from 1999 to 2002. The percent cover of crustose coralline algae gradually decreased with the growth of corals (Fig. 6). Previous research highlighted the importance of crustose coralline algae as coral settlement inducers (Morse et al. 1996). In addition, coralline algae may construct the firm substrates for settlement and growth of hermatypic corals by covering the surface like a cement, and therefore may possibly inhibit the perforation of many micro-organisms which damage the framework of substrates. Similarly, it is supposed that, in the Ryukyus, crustose coralline algae may play an important role in facilitating the settlement of coral recruits and acting as an important member of the reef-builder functional group.

On the rocks around the outer reef flat in Urasoko Bay, two sequences of secondary succession are recognized. In the first case, the hermatypic coral community recovered directly between 1995 and 1998. In the second case, the coral community recovered after a phase of algal overgrowth that lasted for 2-3 years between 1998 and 2005. The climax of the secondary succession, where *Acropora* community is formed, seems to be reached 4-6 years after the start of the succession, as long as the coral reefs remain in good health and are not subjected to large disturbance such as coral bleaching, sedimentation, typhoons or other bad factors (Fig. 9-14). In contrast, the coral community found on the rubble and rocks located at the inshore-side of Urasoko Bay seems to take longer to reach the climax of the secondary succession. It is considered that the recruitment of coral planulae may be reduced in the moat, and that the loose rubble is an unstable substrate which limits coral planulae settlement. The sequence and speed of the secondary succession were influenced by substrate stability and the various sources of disturbance that characterized each habitat.

In conclusion, long-term monitoring studies provide insights into the cause of successional differences in response to disturbances that delay or enhance coral domination as an alternate stable state. For fast growing corals such as *Acropora*, recovery from catastrophic events may be ultimately impossible, but as shown here, even with periodic bleaching events and storms, recovery is possible in a timeframe of a few years. Given that coral bleaching and storms are ongoing processes, it remains paramount that anthropogenic impacts such as pollution and dredging be curtailed.

Acknowledgements We wish to thank Jeanine Olsen, a professor of the University of Groningen, Diego Lirman, and anonymous reviewers of the proceedings for improvement of our manuscript and Haruki Ochi for helping with the surveys. This study was partially supported by a grant from the Ministry of the Environment of Japan (Global Environmental Research Fund: F-5).

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