A New Approach to Coral Reef Restoration: The Coral Settlement Device

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オニヒトデ食害やサンゴ白化現象により衰退し、回復の進まない琉球列島石西礁湖サンゴ群集再生のため、有性生殖を利用した連結式サンゴ幼生着床具によるサンゴ礁再生が2002年から環境省により行われてきた。着床具は、毎年、サンゴ産卵1ヶ月程度前の4月下旬、高いサンゴ着床が期待できる礁湖北側海底等に約4.8万個が設置された。約2年間、海底で育成された後、移植種苗としての選別が行われた。2015年3月の採苗率（＝着床のあった着床具数／設置した着床具数×100）は約30%であった。移植種苗は、生息環境が良好であるにもかかわらず、加入が貧弱なため、回復の進まない礁湖南部海域に運搬され、移植された。移植は、主として海底地形が尾根状の頂部岩礁で、エアドリルにより穿孔した穴に接着剤とともに、着床具脚部を挿入し、固着した。2005年度 - 2014年度に、累計約39,000個の種苗が移植された。種苗の多様性は高く、90%以上は多種の *Acropora* 属であるが、20属以上が生産された。最も成長の早いユニット（2008年1月移植開始）では、2016年2月に被度は約60%に達した。2010年5月、2006年2月に移植したハナガサミドリイシ *Acropora nasuta* の産卵を始めて確認し、以後2014年まで、多くの移植ユニットで毎年産卵確認を行っており、石西礁湖への幼生供給を果たした。

In this article we would like to describe our experience of testing and using over about 10 years a design of coral settlement plate that we developed to aid coral community restoration in the Ryukyu Islands of Southern Japan. Coral reefs in the Ryukyu Islands have been deteriorating ever since a serious outbreak of crown-of thorns starfish, *Acanthaster planci,* occurred in the 1970s (Omori 2011). To restore degraded reefs, various reef recovery projects involving transplantation of coral fragments were undertaken beginning in the 1990s. However, strong opposition was expressed by numbers of local scientists to the use of this method without scientific support on several grounds (Japanese Coral Reef Society 2004). Firstly, concern was expressed at the damage being caused to surviving coral colonies and habitat by collection of the coral fragments or branches to be used for planting out. Secondly, concern was raised that repeated collection from corals at a few favored locations would likely result in both a reduction in biodiversity and a decreasing genetic diversity within species (see Rinkevich 2005). Therefore it seemed worth considering whether an alternative restoration technique could be developed that would avoid these undesirable side-effects.

Sexually Reproduced Coral Spat

The alternative to employing artificial asexual reproduction to create new coral colonies must be to take advantage in some way of normal sexual reproduction. Over recent decades much has been learnt about reproduction in corals. Among the most important facts are that while in some genera fertilization takes place internally with the larvae being brooded within the coelenteron prior to release, in most corals both female and male gametes are discharged to the water column with fertilization taking place externally. In some regions spawning involving many species appears to take place synchronously over the same night (or few nights) of the year. Such mass spawning was first recorded on the Great Barrier Reef (Harrison et al. 1984), but also occurs in the Ryukyu Islands, where the dominant genus, *Acropora*, mostly spawn around full moon in either May or June (Hayashibara et al. 1993; Misaki 1994). It was naturally tempting to make use of this fact in searching for a method for restoring reefs there via sexual reproduction.

Broadly speaking two approaches have been used to propagate corals sexually. The tank method uses larvae and embryos collected from spawn slicks or larvae produced from gametes collected from coral colonies, with the resulting larvae then being reared in culture tanks at the laboratory. The seabed method, by contrast, involves deploying on or above the seabed portions of suitable substrate on which larvae will settle naturally post-spawning. While this latter method may seem haphazard and likely to require huge areas of settlement substrate if sufficient larvae are to be acquired, if successful it would have the advantage that no laboratory facilities would be required. Rather, trained workers could deploy the settlement units on suitable areas of seabed, and given sufficient recruitment corals could be economically produced or raised. Researchers at the Akajima Marine Science Laboratory have taken the first approach and trialed the transplantation of juvenile corals produced after fertilization of coral eggs in culture tanks or rearing of the larvae collected *in situ* (Omori 2011). By contrast Okamoto et al. (2005) evaluated artificial substrates for coral settlement using test panels, and subsequently developed the Coral Settlement Device (CSD) (Okamoto et al. 2008), use of which we describe here.

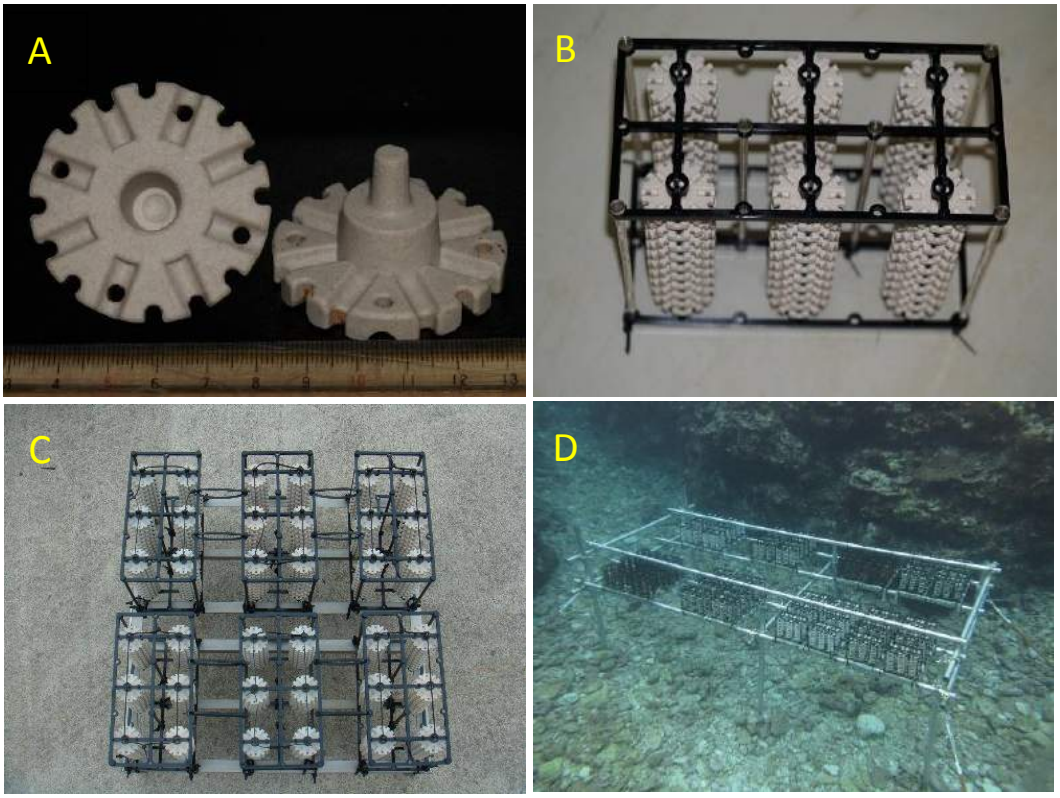

Figure 1. Coral Settlement Device. Ten devices were stacked into one batch. Six batches were arranged in a plastic frame. Six frames were set on a stainless steel platform. Eight platforms were deployed on a steel pipe stand placed on the sea bottom. A: coral settlement device, B: plastic frame, C: stainless platform, D: steel frame.

The Coral Settlement Device

The CSDs described here were designed to provide an optimal surface for coral recruitment on a structure that could then be placed directly on to the reef once the coral larvae had established themselves and metamorphosed into juvenile corals. Each CSD consists of a ceramic vase-shaped component, 5 cm in diameter, and 3 cm in height (Fig. 1). They are designed so that individual CSDs can be stacked together by inserting the peg-like base of the lower side of one into a depression in the upper side of another below it. Several CSDs can be stacked together, and the stacks of CSDs are then installed into a robust plastic frame which is set out on the reef to await recruitment.

We have found that the final design of the CSDs has the following advantages:

(a) The ceramic material used provides a substrate similar to natural reef rock.
(b) Grooves formed on both upper and lower surfaces of each CSD attract and promote the settlement of larvae.
(c) The spaces between the CSDs in each stack are sufficiently small to prevent entry and attack by most predators, or accidental damage by grazing herbivores.
(d) The peg-like design assists transplantation of each CSD out on to the reef, in addition to assisting with stacking.

(e) The stacked units can be set out on the reef in large quantities.
(f) The strong plastic frames used to hold the stacks of CSDs are convenient to carry and resistant to wave action.
(g) Holes formed on the upper side of each CSD also encourage further coral recruitment after the CSDs have been out-planted on to the reef.
(h) Both mass production of the CSDs and their deployment in reef areas has been found to be cost effective and the method economic.

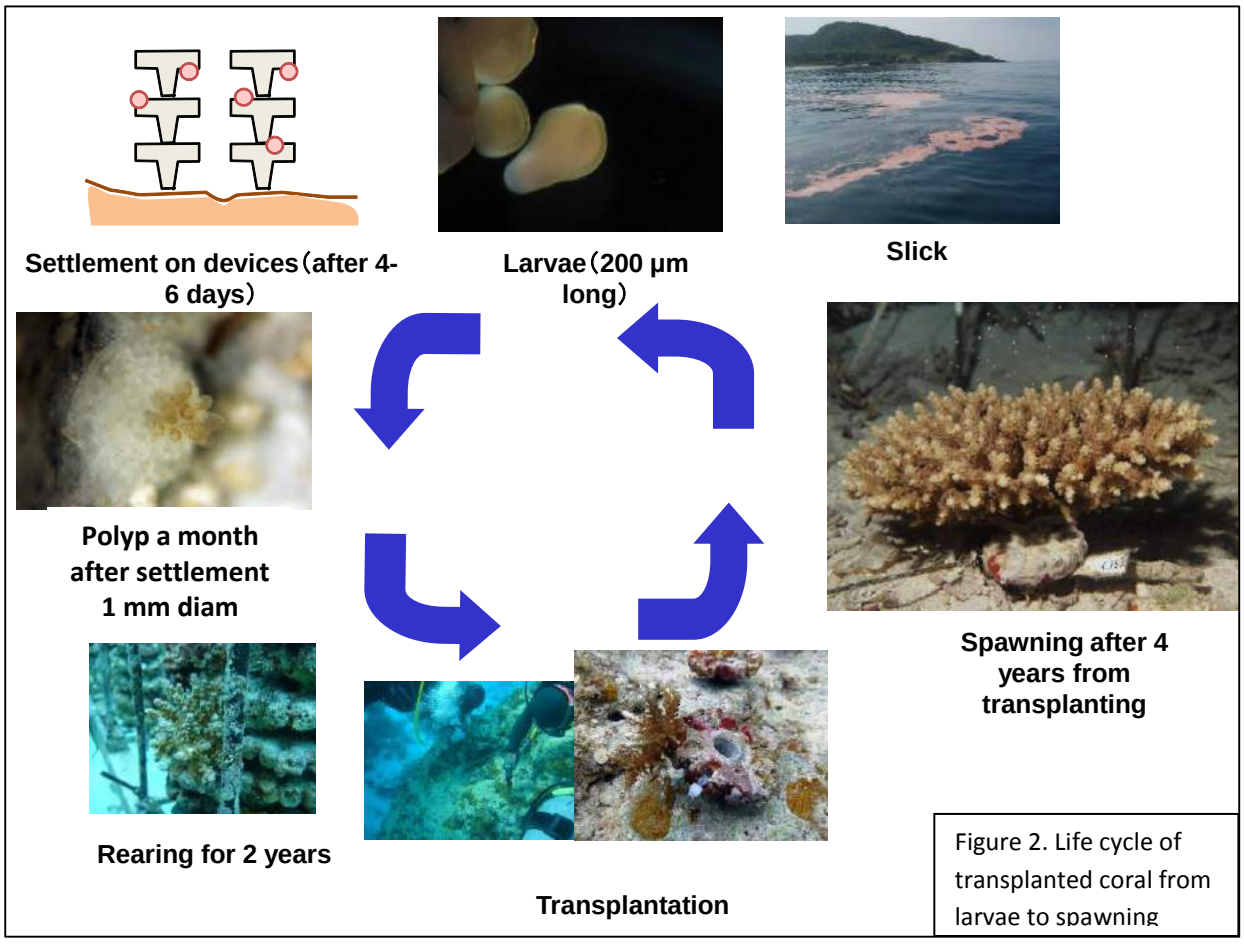

Figure 2. Life cycle of transplanted coral from larvae to spawning

The Sekisei Lagoon

The site where we tested and then employed the CSDs on a coral rehabilitation project was Sekisei Lagoon, which is positioned between Iriomote and Ishigaki Islands in the south Ryukyu archipelago. It is part of the largest coral reef complex in Japan, which extends 20 km from east to west and 15km from south to north and has been designated as the Iriomote - Ishigaki National Park. The broad lagoon is enclosed between the two large islands by various smaller islands and their fringing reefs, in addition to which there are patch reefs scattered around the lagoon. Together these features create a varied environment that supports a diverse coral community. However, the coral communities in the Sekisei Lagoon were devastated by an outbreak of *A. planci* that began in the 1980s and to some extent continues (Fujiwara & Omori 2004). More recently in 1998 and 2001 extensive mortality followed coral bleaching due to thermal stress (Shimoike 2004). Since these events coral community recovery has been slow and very variable depending on location, likely reflecting the fact that coral recruitment can vary both temporally and spatially (Harrison & Wallace, 1990). Because of this patchy recovery a coral reef restoration project using CSDs was launched in 2002 by the Ministry of the Environment. The project aimed in particular to assist rehabilitation of those reef areas which otherwise showed very poor recruitment. It was hoped that once their coral communities had been

rehabilitated, these sites might in turn act as source areas for coral larvae that would assist other sites to recover (Fujiwara, 2010).

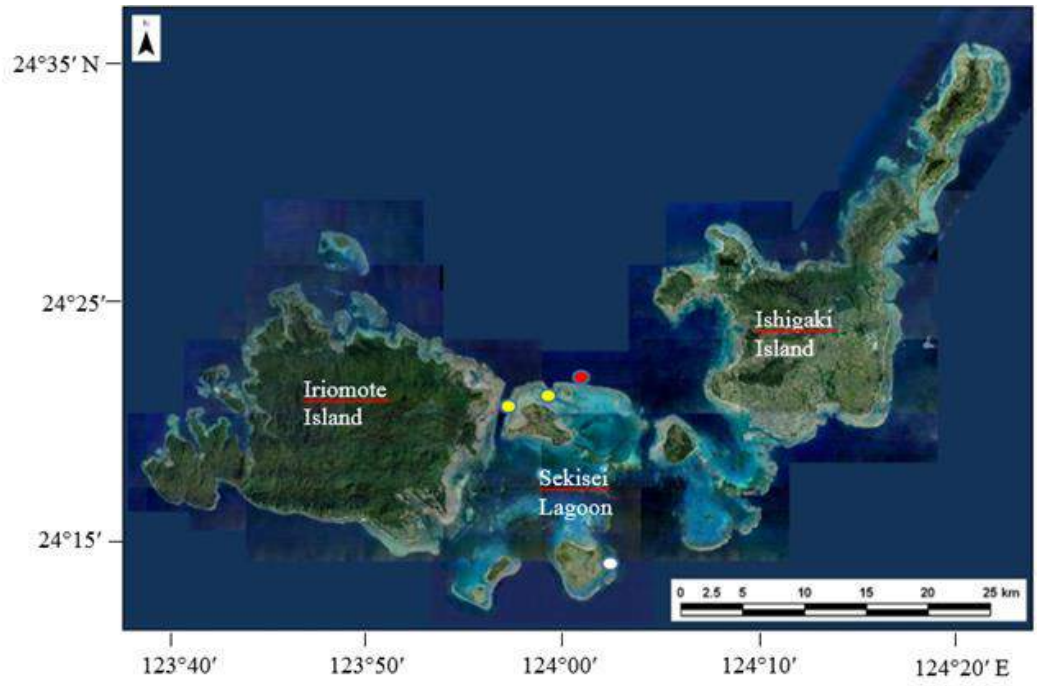

Figure 3. Left, location of the Project Sites in the Ryukyu Islands: White solid circle = transplantation area; Red solid circle = larvae settlement area; Yellow solid circles = rearing areas. Above, location of Ryukyu Islands in the south of Japan.

As on the Great Barrier Reef, in Sekisei Lagoon many corals, especially *Acropora* species, which dominate there, spawn synchronously once a year, usually at midnight around the May full moon when daily mean temperature reach about 26°C (Hayashibara et al., 2004; Fujiwara et al., 2015). Therefore, with this timing in mind, every year, from the start of the project in 2005 until 2015, we deployed approximately 48,000 CSDs in frames on to the reef in late April, up to one month before coral spawning was due (Fig. 2). The main deployment site chosen was in water 5 to 6 m deep towards the northern reef margin in an area where coral recruits were naturally relatively abundant, suggesting a good supply of coral larvae. Here in 2015, for example, settlement rates of 16.2 recruits per 100 cm^2 were recorded on the artificial plates, even though the mean settlement rate across 35 sites in Sekisei Lagoon was only 1.88 colonies per 100 cm^2 (Naha Nature Environment Office, 2016). The dominant coral species *Acropora nasuta* and *A. cytherea* appeared to settle especially at this depth. However, although the reef margin was a good deployment site from the point of view of larval settlement, it is also subject to severe wave action if a typhoon occurs; therefore after a month or two the frames were moved to calmer areas before the beginning of peak typhoon season in July. Besides this move, the frames and CSDs were maintained by regularly removal of fouling algae that might otherwise overgrow any coral spat.

The area selected for transplantation was in the southern part of the lagoon. It was chosen because, while water quality was considered favorable and conditions looked suitable for coral growth, coral community recovery had been impeded there due to poor recruitment (Fig. 3). Most likely this was because with the residual tidal currents moving from south to north, the area received relatively few coral larvae from elsewhere. In addition the area was preferred because generally it did not experience severe waves generated there by typhoons, because it was well away from any sandy bottom areas, which can be stirred up by typhoon waves resulting in sediment being deposited on and smothering the juvenile corals, and because the presence of a ridge topography also protected the area from gravel drift which can be caused by typhoon waves.

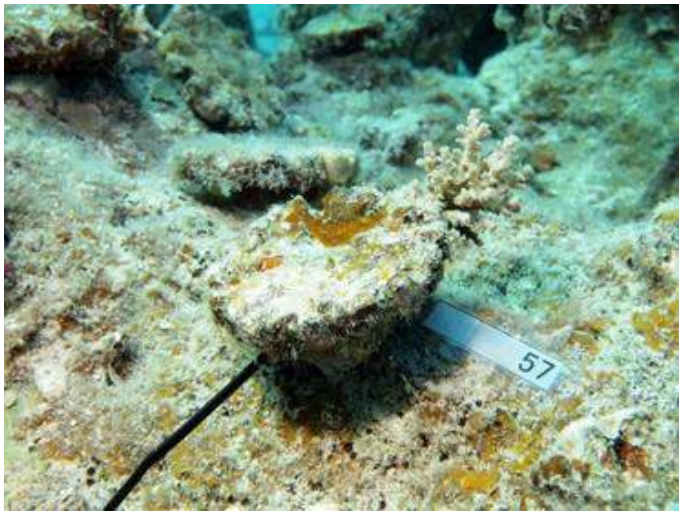

Figure 4 A transplanted juvenile coral (growing from the upper right of an encrusted CSD) which is being monitored.

Figure 5 The camera arrangement used to monitor corals for spawning, taking a picture every 30 minutes.

Transplantation of the CSDs

For transplantation the stacks of CSDs were removed from their frames approximately 2 years after their original deployment, and each stack disassembled so that the CSDs could be planted out individually. The peg of each individual CSD unit was then inserted in to a suitably sized hole drilled in to the rocky reef substrate with an pneumatic (air-powered) drill and the peg fixed in place with a suitable glue. In general about ten juvenile corals were transplanted to every square metre of substrate, with a total of about 39,000 juvenile corals being transplanted between fiscal years 2005 and 2014 over an approximately 1 km^2 area. Unsettled CSDs were removed and reused in subsequent years.

About 10 % of these corals were tagged for monitoring purposes (Fig. 4) and then checked at 1, 6 and 12 months after transplantation and subsequently once a year. The following parameters were recorded: survivorship, coral length, bleaching, destruction, predation, algal smothering, sedimentation, and whether any habitat was being provided for animals. Temperature and turbidity were measured every hour by data loggers. Once they were four-years old a proportion of transplanted corals were observed to see if spawning occurred. Because most *Acropora* corals synchronously release bundles of gametes at around midnight, we set automatic cameras near the transplanted corals and took photos every 30 minutes over four consecutive nights to see whether spawning occurred (Fig. 5).

Recruitment, Growth and Spawning

The production ratio of the CSDs, i.e. the proportion of CSDs with juvenile corals, was monitored. In 2015 for example the ratio was 30 %. The use of the CSDs resulted in a much higher mean density of recruits than elsewhere in the lagoon, much of which suffered from very poor recruitment. Besides producing high densities of juvenile corals, the use of CSDs also resulted in a high diversity of recruits - although over 90 % of recruits were different species of *Acropora*, corals from more than 20 other genera were recorded (Fig. 6). The batch giving rise to the fastest growing corals was planted out in 2008 and by 2016 had generated a mean coral cover of approximately 60% (Fig. 7). At this density the corals were increasingly providing habitat for a range of fish and invertebrates, most noticeably various damselfishes and crustaceans. By creating sufficient coral habitat to provide food and shelter for other reef fauna the rehabilitation project was thus fulfilling one of the important functions of coral community rehabilitation.

The first spawning of a transplanted coral, by an *A. nasuta* that was transplanted in February, 2006, was recorded by our automatic camera in May, 2010. Subsequently we also observed, in 2011, spawning by colonies of *A. nasuta* and *A. selago*. By 2014, when observations ceased, spawning was occurring annually in many of the blocks of

transplanted corals. The extent of spawning suggested that the areas of transplanted corals were also beginning to function as a source of coral larvae for other parts of the lagoon.

Figure 6. A variety of juvenile colonies recruited on to the CSDs 1: *Pocillopora*, 2: *Seriatopora*, 3: *Stylophora*, 4: *Montipora*, 5: *Porites*, 6: Fungiidae, 7: *Galaxea*, 8: *Echinophyllia*, 9: Mussidae, 10: *Symphyllia*, 11: *Hydnophora*, 12: *Merulina*,, 13: *Favites*, 14: *Goniastrea*, 15: *Montastrea*, 16: *Cyphastrea*, 17: Faviidae 1, 18: *Turbinaria*, 19: *Millepora*, 20: Faviidae 2, 21a,b: *Acropora* (the most abundant coral)

Concluding Remarks

Rinkevich (2005) has suggested that the extent of degradation on coral reefs globally is now so high that many reef areas are already beyond the possibility of natural recovery and that transplantation must become an important method for restoration. It seems unlikely that cultured coral fragments or laboratory reared juveniles could be produced on the scale required to restore very large areas. Our experience suggests that, in contrast, CSDs such as those described here can be an invaluable tool in reef restoration. The design of the CSDs appears very effective in encouraging natural settlement of coral spat and in preventing predation by fish and invertebrates. A high proportion of the CSDs are settled by larvae that grow to reproduce. The method avoids damage to existing corals caused by the collection of coral fragments, which may be critical in areas where coral abundance is already very low. The methods also avoids artificial colonisation of an area with only a limited number of coral genotypes, such as might happen if coral fragments are collected from only a few sites. And the method automatically results in the planting out of a wide variety of genera and species in approaching natural relative abundances. We believe that the method deserves further study.

Figure 7. The site showing the fastest recovery of corals following transplantation. Left, the site as it was in January 2008 with few living corals. Right, the site in February 2016, with coral cover increased to approximately 60 %.

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