Sustainable Resources of Corals for the Restoration of Damaged Coral Reefs in the Gulf of Aqaba, Red Sea

Fuad A. Al-Horani

The University of Jordan-Aqaba Branch , Faculty of Marine Sciences, Dept. of Marine Biology
P. O. Box 2595, Aqaba 77110, Jordan, Tel.: +962-3-2090450- ext. 35072, Fax: +962-3-2090460
E-mail: f.horani@ju.edu.jo

Abstract: During the past decade, the coral reefs in the Gulf of Aqaba have suffered from continued deterioration as a result of coastal human activities. For restoration purposes of damaged coral reefs, it is important to have continuous supply of corals without impairment of the natural reef environment. In the present study, suspended and bottom based coral nurseries were established *in situ* for the production of large numbers of selected coral species. After one year, the coral nurseries produced colonies that are suitable for transplantation. The corals grown on the nurseries were produced by asexual reproduction through fragmentation. This method contributes to the improvement of the health status of endangered and/or rare coral species. Parallel to this, settlement devices were constructed and deployed in the sea to allow for settling of swimming larvae in the reef. The settlement devices recruited diverse number of settling reef organisms. This method is suitable for enhancing biological diversity in the damaged reef areas. Based on the results obtained, it was suggested that the coral nurseries and the settlement devices are efficient tools for providing sustainable resources of corals for use in reef restoration. It is highly recommended to have a combination of both techniques when restoration of coral reefs is considered.
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1. Introduction

Despite their very high ecological and economical importance, damage to coral reef ecosystems continues at a global scale (Hoegh-Guldberg 1999; Wilkinson 2004). Both natural and anthropogenic reasons were cited as causative agents of reef damages (Hodgson 1999; Pittock 1999; Kleypas *et al.,* 2001). The increased sea surface temperatures, urbanization of coastal areas, pollution, sedimentation, runoff, tourism and overexploitation are the most significant factors listed (Richmond 1993; Barker & Roberts, 2004; Hasler & Ott 2008). Such factors are threatening the existence of the coral reefs in future (Pockley, 1999). The coral reefs in the Gulf of Aqaba are not an exception to this trend and are deteriorating at relatively fast rate due to similar reasons (Hawkins & Roberts, 1994; Abelson & Shlesinger, 2002; Al-Horani *et al.*, 2006 & 2011). The rates of damage have been intensified during the past decade as a result of industrial and/or touristic activities. For example, several coral reefs were severely damaged as a result of ports construction and expansion processes (personal observation).

When the rate of damage exceeds the reef's ability to self recover, active restoration measures becomes necessary (e.g. Pratt 1994; Risk 1999; Epstein *et al.,* 2001). Traditional conservation methods such as the marine protected areas and the national and international legislations that prohibit the coral reef damage were used for the recovery of ecosystem. In many cases, the conservation methods are not efficient or are too slow to achieve natural reversal of the reef damages (Pratt, 1994; Rinkevich, 1995). Therefore additional restoration methods are needed to enhance the process of reef recovery. Some of the methods used include the development of artificial reefs, transplantation of entire coral colonies or fragments, coral gardening by in situ coral nurseries and the various types of settlement devices (Bohnsack & Sutherland, 1985; Rinkevich, 1995; Edwards & Clark, 1998; Smith & Hughes, 1999; Gleason *et al.,* 2001; Heyward *et al.,* 2002; Epstein *et al.,* 2003; Petersen *et al.,* 2005a; Okamoto *et al.,* 2005 & 2008; Linden & Rinkevich 2011; Al-Horani & Khalaf 2013).

The health status of the coral reef ecosystem is highly determined by the status of its main framework constituent, the scleractinian corals (Sorokin, 1995). It is therefore highly important to maintain sustainable coral resources for the restoration purposes of damaged reefs. There are several natural and artificial methods for supplying coral resources for the reef restoration. Natural sources of corals include the natural settlement of coral larvae, and the naturally occurring coral fragmentation (Hughes, 1999). Many physical and biological factors affect the survival rates of coral larvae and fragments, which might affect the sustainability of the coral reef ecosystems (Smith & Hughes, 1999; Gleason & Hofmann, 2011). Other methods for obtaining corals include the transplantation of corals from other donating sites such as the areas that are destined for destruction (Edwards & Clark, 1998; Muko & Iwasa, 2011a & b). Corals were also generated by harvesting coral larvae using various settlement techniques and by means of underwater nurseries (Harriott & Fisk, 1987; Rinkevich, 1995 & 2005; Petersen & Tollrian, 2001; Epstein *et al.,* 2001 & 2003; Heyward *et al.,* 2002; Petersen *et al.,* 2005 a & b; Okamoto *et al.,* 2005 & 2008; Shafir *et al.,* 2006 a & b; Bongiorni, *et al.,* 2011; Linden & Rinkevich, 2011). In the present study, both the sexual and asexual methods of obtaining coral sources were operated for the purpose of using them for restoration of damaged reef areas in the Gulf of Aqaba. In one hand, suspended and bottom based coral nurseries were constructed in the field, while on the other hand a modified settlement devices (Okamoto *et al.,* 2008) were also deployed in the field. The results of both methods are presented.

2. Materials and Methods

Study area

The study was conducted in the northern part of the Gulf of Aqaba, in front of the Marine Science Station in Aqaba, Jordan (29 27 512 N latitude and 34 58 500 E longitude (settlement devices) and 29 27 517 N and 34 58 541 E (Nurseries)). The study area is characterized by having fringing reefs in some parts of it and seagrass meadows and sandy bottoms in other parts.

Nursery construction

The *in situ* coral nurseries were constructed and distributed at depths that range between 5-10m in front of the marine lab. Four suspended coral nurseries were constructed as described previously (Epstein *et al.,* 2001; Shafir *et al.,*2006a; Shaish *et al.,* 2008). Briefly, the nurseries were made of plastic mesh connected by cables to a 1.5×4.0 m rectangle made of 0.5″ PVC pipes (Fig. 1). The suspended nurseries were kept midway in the water column by using cement sinkers at the bottom and large floating buoys from the top. Smaller mesh trays were also constructed using the PVC pipes and mesh for holding each set of coral nubbins on them. The bottom based coral nurseries were constructed from frames made of Aluminum tubes (100cm x 60cm) and have legs of 80cm high (Fig. 1). The bottom based nurseries were distributed according to the type of cultured coral species and the light requirements of each species, where some of them were fixed in areas with high light intensities, while others were put in semi-shaded areas to provide low light intensities.

Coral collection and transplantation in the nurseries

Mother colonies of thirteen coral species (Table 1) were collected by SCUBA diving. During the collection, the divers used chisel and hammer to cut part of the colony and left the remaining part

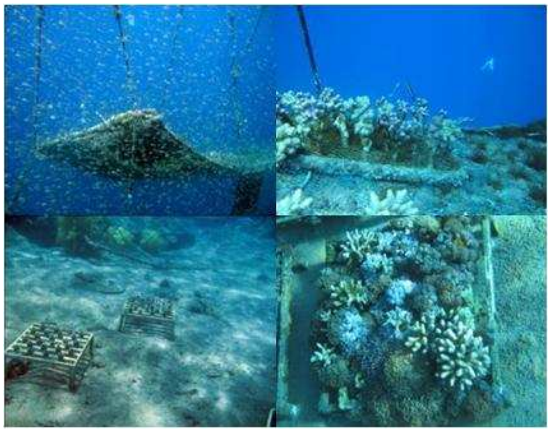

Fig. 1: Suspended (top) and bottom based (bottom) coral nurseries at an early stage (left) and an advanced stage (right) of development.

for self recovery of the mother colony, while the other part was carried in buckets filled with seawater to the lab. Small fragments (ca. 4 cm long and ca. 2.5 g weight) were made using cutter pliers as described by Al-Moghrabi *et al.* (1993). The initial wet weight was recorded for the fragments before being glued to small (8 cm long) pieces of plastic tubes. To reduce the cost of the process, second hand irrigation tubes were cut into small pieces and were used as supporting material for the coral fragments. The tubes were filled in part by sediment to make heavy and small holes were made to allow the water to fill the empty space between the sediment and the coral fragment, which reduces errors when the weight was recorded. After gluing, the fragments were kept for few days in the lab to make sure that they have survived the cutting-gluing process, before being sent to the sea. The prepared fragments were fixed on trays and transferred to the sea under humid conditions, and then were fixed to the nursery net by plastic ties. The same protocol was used for both types of nurseries; the suspended and the bottom based coral nurseries.

Table 1: List of 13 coral species that were cultured in the coral nurseries.

Acropora cf. *valida*	*Hydnophora sp.*
Acropora cf. *maryae*	*Lobophyllia corymbosa*
Acropora cf. *eurystoma*	*Blastomussa sp.*
Turbinaria mesenterina	*Galaxea fascicularis*
Pocillopora danae	*Echinopora fruticulosa*
Stylophora pistillata	*Oxypora* sp.
Erythrastrea flabellata	

Maintenance and monitoring

Every two weeks, the nurseries were visited to check for the deaths and missing fragments. The growth rates of seven coral species were followed with time. From each coral species, 15 fragments were tagged and the change in their buoyant weight was determined, where the fragments were brought back to the lab using the same method described for coral collection. The coral fragments were weighed every month and the survival rates were recorded.

Construction and deployment of settlement devices

The design of settlement devices that was previously developed by Okamoto et al. (2008) was adopted in this study. In order to reduce the costs, the construction material was modified by replacing the ceramic material with modified concrete, which proved to be good for coral recruitment (Al-Horani & Khalaf, 2013).

Columns of five settlement devices were fixed on a custom made aluminum frames before deployment. The frames had dimensions of 50 cm x 50 cm x 80 cm (L x W x H) and had six aluminum plates fixed between two sides of the frame to hold the settlement devices. Each frame had 150 settlement devices. There were 33 frames that were distributed within the coral reef at depths that range between 6-15m (Fig. 2).

Fig. 2: settlement devices deployed in the sea.

3. Results

Successful coral growth was obtained in both types of coral nurseries, where most of the coral fragment could survive the culture conditions and grow to achieve significant growth rates (Figs. 3-4). Thirteen coral species and two sponges were used to start with. It was noticed that the suspended coral nurseries are more suitable for corals that require relatively high light intensities (Fig. 3), while those corals that need low light intensities were cultured on bottom based nurseries, which could be put in relatively shaded areas in the sea (Fig. 4). Examples of the later case are *Blastomussa sp.* and *Galaxea fascicularis*, which need low light intensities. Additional uses of the bottom based coral nurseries were to do field experiments on corals grown in the different in situ environmental conditions (Fig. 4).

Because it is tedious work and needs many workers to monitor all the corals cultured, only seven species were selected to follow their growth and survival rates. From each coral species, fifteen fragments were used to monitor the growth rates over seven months period of culturing. The results obtained have shown that all monitored corals grew continuously during most of the monitoring period (Table 2). There some individual differences among the corals, where the branching corals achieved higher growth rates compared with the more compacted colonies. Some corals started the period very well and then retreated back and showed slightly negative growth rates such as the coral *G. fascicularis*. Despite the differences in growth rates, most of the corals had high survival rates (Table 2).

The settlement devices that were deployed in reef areas have attracted many types of the reef's larvae, such as hard corals, soft corals, sponges, ascidians, calcareous algae, clams and others (Fig. 5). They seem to work as copy machine for the coral reefs, where any available larvae are susceptible to settle on them. Only the hard corals, soft corals and sponges were monitored on the deployed settlement devices. The data obtained have shown variable numbers of each reef category on the settlement devices (Table 3). The number of hard coral recruited on the racks ranged between 1 and 27, with an average of 7.27 ± 5.85. The soft coral were more variable where on some racks only one soft coral was found, while on other racks, they covered 90% of the surface area of the rack. Sponges were also recorded on all racks and ranged between 1- 15 individuals, with an average of 5.94 ± 2.67 (Table 3).

Fig. 3: cultured hard corals and sponges after several months of in situ incubation in the suspended.

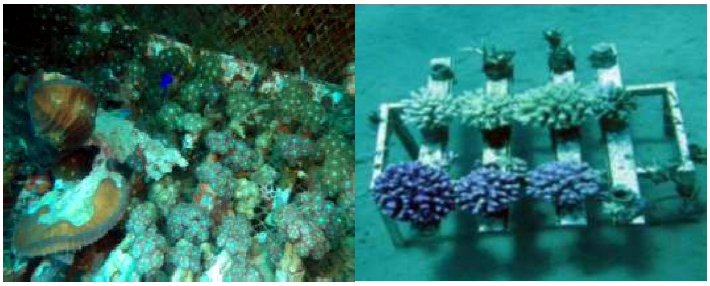

Fig. 4: Bottom based coral nurseries were used for culturing of corals (e.g. *Blastomussa*) that need low light intensities (left) and for *in situ* incubations for experimental purposes (right).

Table 2: Growth and survival rates of seven hard coral species that were monitored on the coral nurseries over 7 months period.

Coral species	Growth Rates (g/day)							Survival Rate (%)
	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	
Stylophora pistillata	0.029 ± 0.008	0.015 ± 0.004	0.013 ± 0.003	0.008 ± 0.011	0.017 ± 0.013	0.012 ± 0.004	0.011 ± 0.007	100
Pocilopora danae	0.030 ± 0.013	0.012 ± 0.006	0.011 ± 0.008	0.009 ± 0.009	0.007 ± 0.019	0.005 ± 0.020	0.006 ± 0.010	93.3
Galaxae fascicularis	0.027 ± 0.012	0.010 ± 0.009	0.004 ± 0.003	0.001 ± 0.004	0.004 ± 0.005	0.001 ± 0.002	-0.005 ± 0.007	100
Acropra cf. *valida*	0.019 ± 0.009	0.010 ± 0.008	0.006 ± 0.003	0.008 ± 0.010	0.004 ± 0.006	0.006 ± 0.003	0.006 ± 0.004	100
Turbinaria mesenterina	0.024 ± 0.017	0.012 ± 0.006	0.004 ± 0.005	0.005 ± 0.010	0.004 ± 0.003	-0.002 ± 0.012	0.009 ± 0.008	93.3
Echinopora fruticolosa	0.029 ± 0.007	0.019 ± 0.008	0.010 ± 0.004	0.002 ± 0.008	0.003 ± 0.006	0.004 ± 0.003	0.001 ± 0.001	80
Oxypora sp	0.017 ± 0.009	0.014 ± 0.013	0.001 ± 0.011	0.004 ± 0.008	0.009 ± 0.018	0.001 ± 0.010	0.002 ± 0.002	73.3

Table 3: Number (or % cover) of settled hard and soft corals and sponges on the settlement devices fixed on racks.
* cover percentage was used when the number of soft corals was not countable.

Settlement Rack	No. of recruited hard corals	No. or % of recruited soft corals*	No. of recruited sponges
1	8	60%	7
2	5	8	12
3	12	10%	5
4	1	5	7
5	7	30%	8
6	13	10%	4
7	20	15%	9
8	1	6	5
9	1	1	4
10	3	5%	15
11	13	30%	5
12	11	70%	6
13	12	15%	8
14	9	95%	1
15	6	90%	3
16	4	50%	6
17	3	85%	4
18	8	60%	5
19	2	10%	8
20	16	20%	6
21	3	30%	6
22	5	85%	4
23	3	75%	6
24	2	40%	4
25	4	63%	7
26	10	30%	4
27	27	15%	6
28	2	70%	8
29	4	1	7
30	5	20%	5
31	5	15%	3
32	6	10%	5
33	9	60%	3

Fig. 5: Successful growth of various reef organisms was observed on the settlement devices after one year of deployment.

4. Discussion

Three main methods were used to supply corals for restoration of damaged coral reefs. The traditional method was through transplanting whole colonies or fragments of colonies to replace the damaged coral habitat (Edwards & Clark, 1998; Smith & Hughes, 1999; Gleason *et al.*, 2001; Muko & Iwasa, 2011a & b). This method might harm the donor site for possible abuse of the habitat at the same time their survival is not guaranteed in the recipient site (Epstein & Rinkevich, 2001; Shafir *et al.,* 2006a; Okamoto *et al.,* 2008). The second method is the *in situ* coral culture for coral fragments depending, which depends on asexual reproduction of the corals (Rinkevich, 1995 & 2000; Epstein & Rinkevich, 2001; Epstein *et al.,* 2001 & 2003; Shafir *et al.,* 2006a; Bongiorni *et al.,* 2011). Although it is effective, the restoration of damaged coral reefs using this method may lead to reduced genetic diversity of the ecosystem (Rinkevich, 2005). The third method depends on harvesting coral larvae by means of restoration devices especially during spawning seasons (Petersen & Tollrian, 2001; Heyward *et al.,* 2002; Petersen *et al.,* 2005a; Okamoto *et al.,* 2005 & 2008). This method is important for maintenance of the genetic diversity in the ecosystem. Though, settlement of coral larvae is affected by many physical and biological factors (Petersen & Tollrian, 2001).

In the marine science station, coral mariculture was started at a small scale during the nineties by using bottom based coral nurseries. The main goal was to produce corals for experimental uses. During the past 10 years, the increased rates of development in the city of Aqaba have lead to increased pressure on the coral reefs in the Jordanian coast of the Gulf of Aqaba. Many reefs in the area have been damaged by coastal activities, while many others became threatened of being destroyed. At the beginning, corals were transplanted from areas destined for reclamation into areas that need enhancement. This source of corals was not enough to provide all needed corals in addition to being unsustainable source of corals as it depends on opportunities available when reclamation of coral reef areas is planned. Therefore, strategic plans to provide sustainable coral resources became crucial to supply the needed corals in the right time. Based on this situation, the goals of coral mariculture were broadened to include mass production of corals for uses in restoration of damaged reef areas. To achieve this goal, two methods were adopted; the first one was through establishing coral nurseries for mass production of selected coral species, while the second one was through the use of settlement devices to provide a tool for the maintenance of genetic diversity in the treated ecosystem.

The use of suspended and bottom based coral nurseries resulted in successful mass production of corals to reach sizes suitable for transplantation in relatively short time. Both types of nurseries proved to be suitable technique for growing corals of various colony shapes and light needs. The suspended coral nurseries were used to grow light-loving coral species, while the bottom based coral ones were used to grow shade-loving coral species. The survival rates were high for all species tested, where sometimes it was 100%. These results are similar to other results obtained previously (Shaish *et al.,* 2008; Levy *et al.,* 2010), which indicates that this method is highly effective way for culturing corals. The corals grown on the nurseries could reach considerable size within one year of culturing. This allows for transplanting newly produced colonies into damaged reef areas, which was described as powerful tool for restoration of the reefs (Epstein *et al.,* 2003; Shaish *et al.,* 2010). In the recipient site, the newly transplanted coral colonies grow very well and have high survival rates even under stressful conditions (Bongiorni *et al.,* 2011). It was also found that they even have better reproductive capacities than the natural colonies (Horoszowski-Fridman *et al.,* 2011).

The coral nurseries were very helpful tool for production of many clones of corals for uses in laboratory experiments. The bottom based nurseries were excellent tools for propagating rare or endangered coral species as they can be used to produce plenty of new colonies starting from very small coral fragments. They can also be used to study the effects of different *in situ* environmental conditions. It was also noted that the nurseries attract plenty of fish communities, which promotes them as recreational diving sites if properly managed. In addition to this, the coral nurseries may serve as sites of larval production for corals and other reef organisms (Amar & Rinkevich, 2007; Shafir & Rinkevich, 2010). In some cases, the nurseries help enhance ecosystem connectivity when they are situated between interrupted reef areas (Shafir & Rinkevich, 2010).

The settlement devices have recruited plenty of settling reef organisms. The number of hard and soft corals as well as sponges that were monitored on the deployed devices were relatively high. Up to 27 new hard coral recruits and 95% soft coral cover were recorded on some of the racks deployed. The number of sponges that were recorded on the racks ranged between 1 and 15. After one year of deployment, the settlement devices were mostly covered by various settling reefs organisms. Other reef organisms such as ascidians, bivalves, encrusting algae were also seen on the devices, which reflect the diversity of larval community in the seawater around them. This has indicated that the devices are suitable for the attraction of larvae of various reef organisms, which qualifies them as excellent tools for the maintenance of biological diversity in any damaged reef area. The technique is harmless to the reef ecosystem as it depends on collecting swimming larvae that would otherwise be lost before finding suitable substrate for settling. It was postulated that wild caught coral larvae during the natural spawning seasons may have applications in reef rehabilitation (Petersen & Tollrian, 2001; Heyward *et al.*, 2002; Petersen *et al.*, 2008). Several types of materials with several designs were used as settlement devices to raise corals in situ and ex situ depending on sexual mode of reproduction of the corals (Harriott & Fisk, 1987; Petersen & Tollrian, 2001; Heyward *et al.*, 2002; Petersen *et al.*, 2005a & b; Okamoto *et al.*, 2005 & 2008; Linden & Rinkevich, 2011). In the present study, the design used by Okamoto *et al.* (2008) was adopted, but modified concrete have replaced ceramic as construction material. This is because the concrete proved to be an excellent material for settlement of reef organisms as well as being cheaper than the ceramic (Al-Horani & Khalaf, 2013). This design help coral larvae to settle, protect them from predation and is easy to handle for deployment, movement and transplantation (Okamoto *et al.* 2008). The successful settlement on these devices is like other settling devices and is governed by a number of environmental and biological factors such as the substrate type, biologically conditioned surfaces, water motion, salinity and light intensity, while eutrophication, sedimentation, biological competition and grazing decrease settlement rates (reviewed by Petersen & Tollrian, 2001; Petersen *et al.*, 2005b)**.**

The cost of reef restoration was addressed before (Spurgeon & Lindahl, 2000; Edwards and Gomez, 2007; Shaish *et al.*, 2008; Levy *et al.*, 2010). In this study, the costs of constructing coral nurseries were minimized through the use of cheap materials such as the use of second hand irrigation tubes for fixing of the corals. Also, the nets used to construct the suspended nurseries were second hand. The racks used to construct the bottom nurseries were made from aluminum and allows for multiple uses of the same rack. The cost for making the settlement devices was reduced through the use of cheap concrete material. The low cost of the techniques used help us and other low income countries to afford the restoration process.

From the results obtained in this study and other similar studies it was concluded that the *in situ* coral nurseries and the settlement devices are efficient means for providing corals at relatively low costs for use in restoration and research purposes.

Implication for Practice

- Coral nurseries are powerful tools for providing sustainable source of corals for possible uses in restoration and scientific research without harming the natural reefs. The suspended coral nurseries are suitable for mass culturing of different types of corals, especially those that need relatively high light intensities. The bottom based coral nurseries are more flexible and can be moved from place to place. The bottom based nurseries are suitable for culturing of shade loving coral species and are also useful for *in situ* incubations of coals in different field environments.
- The settlement devices are helpful tools to enhance biological diversity in damaged reefs since they attract various types of swimming larvae of settling reef organisms.
- The coral nurseries and the settlement devices are relatively cheap and can easily be built with limited funding and technical resources.
- It is highly recommended to use a combination of the two techniques described for best results in restoration planning.

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