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Strategies for Gardening Denuded Coral Reef Areas: The Applicability of Using Different Types of Coral Material for Reef Restoration

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Abstract

Recreational and other human activities degrade coral reefs worldwide to a point where efficient restoration techniques are needed. Here we tested several strategies for gardening denuded reefs. The gardening concept consists of *in situ* or *ex situ* mariculture of coral recruits, followed by their transplantation into degraded reef sites. *In situ* nurseries were established in Eilat's (Northern Red Sea) shallow waters, sheltering three types of coral materials taken from the branching species *Stylophora pistillata* (small colonies, branch fragments, and spat) that were monitored for up to two years. Pruning more than 10% of donor colonies' branches increased mortality, and surviving colonies displayed reduced reproductive activity. Maricultured isolated branches, however, exceeded donor colony life span and reproductive activity and added 0.5–45% skeletal mass per year. Forty-four percent of the small colonies survived after 1.5-year mariculture, revealing average yearly growth of 75 ± 32%. Three months *ex situ* maintenance of coral spat (sexual recruits) prior to the *in situ* nursery phase increased survivorship. Within the next 1.5 years, they developed into colonies of 3–4 cm diameter. Nursery periods of 2 years, 4–5 years, and more than >5 years have been estimated for small colonies, spat, and isolated branches, respectively. These and other results, including the possible use of nubbins (minute fragments the size of a single or few polyps), are discussed, revealing benefits and drawbacks for each material. *In situ* coral mariculture is an improved practice to the common but potentially harmful protocol of direct coral transplantation. It is suggested that reef gardening may be used as a key management tool in conservation and restoration of denuded reef areas. The gardening concept may be applicable for coral reefs worldwide through site-specific considerations and the use of different local coral species.

Key words: Eilat, *in situ* mariculture, coral nursery, recreational activities, reef restoration, *Stylophora pistillata*.

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Introduction

Coral reefs are among the ecosystems that suffer intense abuse by man (McClanahan 1999). Their worldwide decline (e.g., Wilkinson 1993, 1999; Sebens 1994; Rinkevich 1995; Hodgson 1999) has raised the need for urgent development of adequate restoration methods. In recent years impacts from recreational activities have been classified among the most prominent devastating agents to coral reefs (Rinkevich 1995; Chadwick-Furman 1997; van Treeck & Schuhmacher 1999). Moreover efforts to conserve degrading reefs have failed to produce significant results, and rehabilitation measures have not successfully compensated for the fast degradation (Rinkevich 1995; Risk 1999). Small, tourist-popular reefs are particularly susceptible to fast degradation through intense recreational abuse. In large reef areas, these harmful impacts may still be balanced or compensated by size and increased resilience.

The small Coral Nature Reserve at Eilat, Israel, Northern Red Sea (lat 29°30′ N), may serve as a test case. This easily accessed fringing reef (Loya & Slobodkin 1971) is confined within a 4.0 km long "marine protected belt" (Ortal & Nemtzov 1997), yet hundreds of thousands of registered scuba dives are performed there each year on a limited number of dive sites (Meshi & Ortal 1995). High levels of colony breakage and alterations in population structure of *Stylophora pistillata*, a key coral species, were documented in Eilat (Epstein et al. 1999). This

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contradicts the expectations for reef conservation resulting from the tight legislation and management measures that have been employed in Eilat for years. Reef recovery, therefore, does not sufficiently compensate for the intense destruction by recreational activities.

This has led to the development of concepts and techniques for reef rehabilitation, including the submersion of artificial reef structures (Jensen 1997; Pickering et al. 1998; van Treeck & Schuhmacher 1999), coral transplantation (e.g., Harriott & Fisk 1988; Guzman 1991; Smith & Hughes 1999) and the establishment of low-profile underwater nurseries (Rinkevich 1995, 2000).

Rehabilitation of reef ecosystems may progress through implementation of both preventive as well as active restoration measures. Rinkevich (1995, 2000) has proposed a two-step restoration strategy termed "gardening of denuded coral reefs," whose central concept is the mariculture of coral recruits in nurseries. In the first step a large *in situ* pool of farmed corals is established on low-profile artificial substrates. These nurseries are installed in sheltered zones, and the different types of coral recruits are maricultured for several years. In the second step nursery-grown coral colonies are transplanted to degraded reef sites. This strategy is theoretically linked to terrestrial forest plantation ideas. Tree-silviculture is a core strategy in forest restoration programs (Christensen et al. 1996). Tree cultivation has been practiced successfully for years with forest trees (Anonymous 1988; Vowell 1994; Berg 1995) and with mangroves (Chan et al. 1988; Khoon & Eong 1995).

Corals fulfill a central role in reef communities (Loya 1986, 1998; Bak & Meesters 1997). The replenishment of mechanically degraded reef sites with new coral colonies may support the reef's community structure and its biological functions. Sustainable *in situ* coral mariculture may significantly relieve the pressure from donor reef sites that are currently the sole source for coral transplantation operations. The deployment of *in situ* coral mariculture has already resulted in significant outcomes (Bowden-Kerby 1997; Franklin et al. 1998; Rinkevich 2000), but its applicability on large-scale reef areas needs to be further evaluated (Edwards & Clark 1998).

Branching corals provide four potential types of coral material for nursery purposes. These include small colonies, branch fragments, larvae, and nubbins (minute fragments). Young colonies settled in unstable reef areas can be collected, larvae harvested using plankton nets, and branches detached *in situ* from donor colonies with cutting pliers (Rinkevich 1995). Similarly one can harvest nubbins *ex situ* by pruning a branch into large numbers of single or few polyp-sized units (Rinkevich & Shafir 2000; Shafir et al. 2001). The benefits and costs of mariculture of each one of these types of recruits and their applicability for the *in situ* nurseries should be further considered. Here we studied the usefulness of *Stylophora pistillata*, one of the most abundant coral species in the Northern Gulf of Eilat (Loya 1972). This *r*-strategist species is characterized by rapid growth and a high reproductive rate (Loya 1976*a*; Rinkevich & Loya 1984). Its colonies form highly complex spatial configurations that provide habitat and shelter for many species of crabs, fishes, and cryptic organisms, and its dead skeletons are inhabited by a variety of encrusting and boring organisms (Rinkevich & Loya 1979*a*). It is, therefore, a species of focal importance in Eilat's reef ecosystem that is used as a representative species to test the gardening concept.

Material and Methods

Donor Colonies

This study was carried out in front of the H. Steinitz Marine Biology Laboratory (MBL) at Eilat, Northern Red Sea. Twenty-seven adult *Stylophora pistillata* colonies, averaging 6.5 cm in geometric mean radius ($\bar{r}$; Loya 1976*b*) were chosen from a depth of 5–10 m. Colonies of this size possess about 90 major branches each (Epstein, personal observation). All colonies were labeled *in situ* by alizarin Red S solution (10–15 mg/L) for 24 hours in transparent plastic bags as described by Rinkevich and Loya (1984). The post-labeling acclimation period was 48 hours. Then the colonies were divided into four groups: A (16 colonies), B (3 colonies), C (3 colonies) and 5 control colonies. Using side-cutting pliers, 10 major branches were removed from each colony of group A (about 10% damage), 20 branches from group B colonies (about 20% damage), and 30 from group C colonies (about 30%). The 16 colonies of group A were further divided into two: colonies 1–8 (group A1) were pruned in April 1997 (period of planulae release) and colonies 9–16 (group A2) in October 1997 (period of gonad development; Rinkevich & Loya 1979*a*). Group B and C colonies were pruned in April 1997. We followed the colonies for up to two years. To detect pruning impacts on reproductive activity, female gonads were counted (10 polyps/branch) in histological sections (methodology in Rinkevich & Loya 1979*a*) performed on tissue samples taken from pruned and undamaged colonies each April and November of the years following pruning (1997–1999).

Mariculture of Asexual Recruits

We followed isolated *S. pistillata* branches in two sets of experiments. Experiment 1 examined survivorship of isolated branches at two reef sites, 500 m apart (Epstein et al. 1999): the highly visited reef area of the MBL (60 branches) and the restricted reef area of the Coral Nature Reserve, site NR (40 branches). Experiment 2 com-

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pared growth and survivorship between isolated branches and small colonies maricultured at the MBL site. Three hundred and ten branches (removed from the colonies of groups A, B, and C) were placed at the nursery. In addition 140 young *S. pistillata* colonies ($\bar{r}$ = 2.5 cm ± 0.8) growing on small boulders at the MBL strolling zone (<1.5 m depth) were numbered by means of plastic tags. Seventy colonies were stained *in situ* with alizarin Red S dye, then transported to the nursery at 10 m depth (Fig. 1a). The remaining 70 colonies were left in their original settling site at the strolling zone. Colonies of both groups did not differ significantly in initial weight and size (*t* test, $p > 0.05$).

Handling Procedure and Nursery Type

Branches were pruned *in situ* with side-cutting pliers and then carefully transferred to the nursery substrates where they were promptly held in upright position. In experiment 1, cement tiles that were pre-glued with branch-holding plastic clips (10 branches/tile) were used as nursery substrates. The tiles were securely placed at 10–12 m depths at both sites, about 0.5 m above sandy bottom or directly attached to natural hard substrates. In experiment 2 five crates (1 × 0.5 × 0.4 m in size, each), made of plastic net (mesh size 1 cm^2) were used as nursery substrate and were placed at the MBL site. About 60 branches were placed on each crate. The crates were fastened to the reef bottom within an area of about 30 m^2, two at 5-m and three at 10-m depth. Crates were light in weight and easy to handle and transport underwater, and their design proved durable in storms.

For growth measurements, colonies and branches were brought to the laboratory where coral tissue was removed by hydrogen peroxide solution (Rinkevich & Loya 1984). Skeletons were rinsed under tap water for several minutes and oven dried (60°C, overnight). Growth was measured as new deposited skeleton above the alizarin marked area.

Mariculture of Sexual Recruits

Planula larvae of *S. pistillata* were collected *in situ* during the 1998 reproductive season (January–June, Rinkevich & Loya 1979*b*). Planulae were placed in petri dishes (total 83 plates, Greiner, 35-mm diameter, up to 20 larvae per dish and 85-mm diameter, >20 larvae per dish). Within 3–4 days, most of the larvae settled on either the walls of the dishes or water surface tension. Planulae that settled on the water surface were gently lifted with a thin brush and carefully attached to bottom of dry dishes before being covered with seawater. All dishes were submerged in running seawater in shaded outdoor containers. After 3 months, 30 dishes containing 400 primary polyps were transferred to an underwater nursery (10-m depth) at the MBL. The nursery was constructed of a 2.5-m long iron rod placed 1 m deep into the sandy bottom (Fig. 1b). Fifteen dishes were positioned horizontally and 15 vertically to the substrate, 1.5 m above the sand.

Results

Pruning Effects on Donor Colonies

All 6 colonies of groups B and C (20 to 30% of branches removed) died within the first month following treatment. Extensive pruning of branches was detrimental to donor colonies. Of the group A colonies (10% branches removed), 2 colonies of subgroup A1 and 2 of A2 died within 4 weeks following pruning. Three A1 colonies died within a year; the remaining 3 colonies survived for almost 2 years. Four A2 colonies died within a year, and the remaining two died shortly before the end of the second year (Table 1). During the course of the study, none of the control colonies died.

Colonies of subgroup A1 were pruned in April 1997, at the peak of the reproductive season. Developing oocytes of the next reproductive season were observed in all November 1997 tissue samples taken from the 6 surviving colonies (ranged 0.8 ± 0.6 to 2.2 ± 0.9 gonads/polyp; Table 1). Two of the 3 surviving colonies had gonads in April 1998, the following reproductive period (0.4 ± 0.5 and 1.5 ± 1.2 gonads/polyp), but none was reproductive in November 1998 (Table 1).

Colonies of subgroup A2 were pruned in October 1997 during gametogenesis. After 1 month, female gonads were recorded in tissue histological sections of only 2 colonies (0.5 ± 0.7 and 1.0 ± 0.8 gonads/polyp, Table 1). Mechanical damage during the period of gonad production appeared to immediately reduce reproductive activity. However, 5 months later, at the peak of the reproductive season, 5 out of the 6 were sexually reproductive, with up to 3.2 ± 1.3 gonads/polyp. In November 1998 the 2 surviving colonies of subgroup A2 had no gonads. In April 1999, all colonies of subgroups A1 and A2 were dead. During each of the 4 sampling dates, at least 4 out of the 5 control colonies contained gonads. Reproductive activity of control colonies was significantly higher than in damaged colonies (November 1997, April 1998, ANOVA, $p < 0.05$). In November 1998 none of the remaining 5 group A colonies were reproductive as compared to four-fifths of control colonies.

Mariculture: Asexual Recruits

The survivorship of the branches held on cement tiles at the MBL site sharply decreased to 25% within 6 months and differed significantly from that at the NR site

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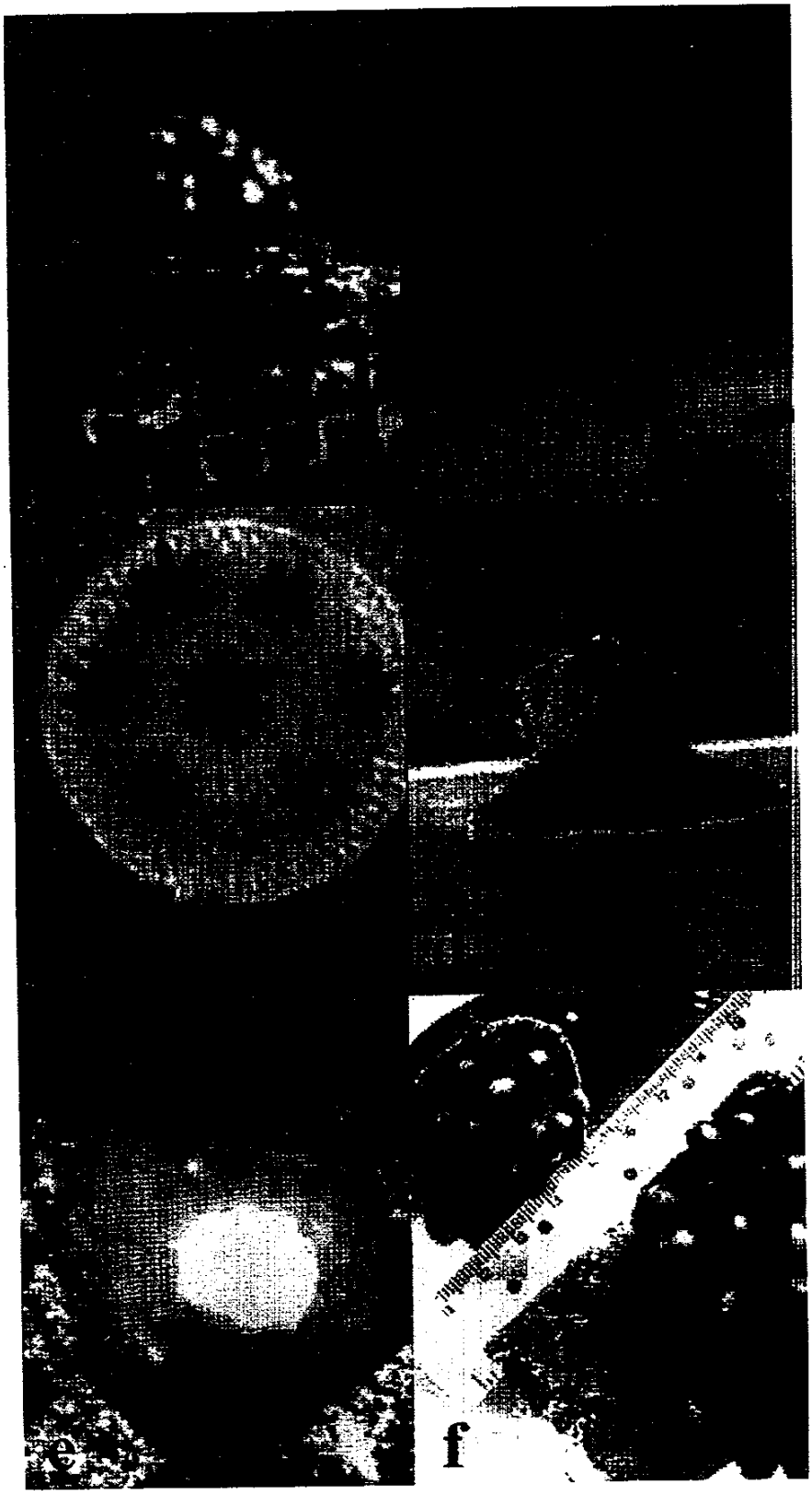

Figure 1. *S. pistillata*: *In situ* mariculture of sexual and asexual recruits: (a) A colony attached *in situ* to a low-profile plastic crate. (b) Spat (sexual recruits) on an *in situ* nursery, 1.5 m above bottom. (c) Two-week old *S. pistillata* spat of 8 polyps size and about 5 mm diameter. (d) Six-month old colony, developed from *ex situ* larval settlement. The basal disc is about 1.0 cm, supporting the up-growing stem. (e) Ten-month old colony, developed from *ex situ* larval settlement. The basal diameter is about 2.0 cm. (f) Eighteen-month old, fully developed, young *S. pistillata* colonies from *ex situ* larval settlement. Colony diameter about 3–4 cm.

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Table 1. Reproductive characteristics of group A (10% damaged donor colonies) and nursery branches up to two years after the pruning events. (D = the donor colony is found dead, 0 = not reproductive).

		Average Number of Female Gonads/Polyp at				
		Nov. 97	*Apr. 98*	*Nov. 98*		*Apr. 99*
Experimental Group	*Colony No.*	*Colonies*	*Colonies*	*Colonies*	*Branches*	*Colonies*
A1	1	1.6 ± 0.8	1.5 ± 1.2	0	1.3 ± 1.1	D
	2	1.1 ± 0.7	D	—	0.8 ± 1.7	—
	3	1.1 ± 0.6	0.4 ± 0.5	0	1.1 ± 1.3	D
	4	0.8 ± 0.6	0	0	1.5 ± 0.9	D
	5	1.6 ± 0.9	D	—	1.3 ± 2.1	—
	6	2.2 ± 0.9	D	—	0.8 ± 1.5	—
A2	9	0.5 ± 0.7	0.1 ± 0.4	D	—	—
	10	0	1.2 ± 1.1	0	1.1 ± 0.7	D
	11	0	0	D	1.8 ± 0.8	—
	12	1.0 ± 0.8	1.5 ± 0.8	D	—	—
	13	0	3.2 ± 1.3	D	1.5 ± 0.5	—
	14	0	0.8 ± 0.9	0	1.2 ± 0.4	D
Controls	1	0	1.5 ± 1.0	1.2 ± 0.9	—	0
	2	2.3 ± 0.9	2.3 ± 1.4	0	—	0.9 ± 0.7
	3	1.7 ± 0.6	1.7 ± 1.0	0.8 ± 1.1	—	1.3 ± 1.2
	4	2.4 ± 1.0	2.1 ± 1.2	1.6 ± 1.3	—	2.2 ± 0.8
	5	3.5 ± 0.8	1.8 ± 1.4	1.2 ± 0.8	—	1.0 ± 0.5

where 82.5% of the branches were still alive (Fig. 2, experiment 1; t test, $p < 0.05$). However, on the plastic crates situated at the MBL site (Fig. 2, experiment 2), branches showed 83% survivorship after 6 months, and 61% after 18 months, significantly higher than the MBL cement tile branches ($p < 0.05$, t test). Survivorship did not differ significantly among the crates, nor did it between the 5- and 10-m depth branches (data not shown; Duncan grouping, $p > 0.05$).

Isolated branches also showed high reproductive activity (Table 1). Between 1–3 branches were sacrificed in November 1998 from branch groups A1 and A2 respectively (1 and 1.5 year subsequent to pruning) for histological examination, and gonads were counted in 10 polyps of each branch. All isolated branches originating from group A1 colonies contained 0.8–1.5 eggs/polyp in November 1998, while none of the respective donor colonies were reproductive. More importantly even

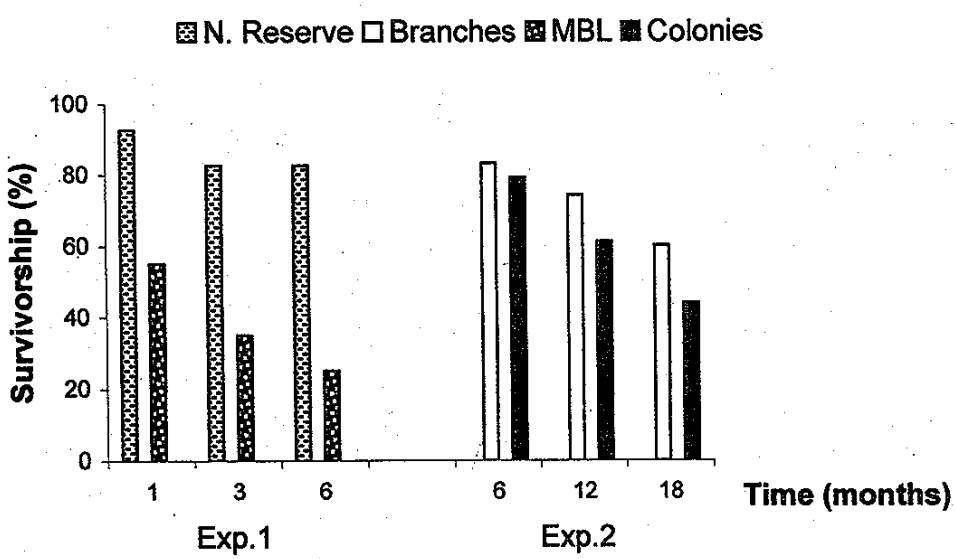

Figure 2. Survivorship of nursery-maintained, isolated *S. pistillata* branches (experiment 1, experiment 2) and small colonies (experiment 2). MBL = Marine Biology Laboratory, NR = Coral Nature Reserve.

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branches derived from donor colonies that later died (numbers 2, 5, and 6, Table 1) were reproductive. Isolated branches of 4 out of the 6 donor colonies of group A2 were reproductive in November 1998, containing 1.1–1.8 gonads/polyp, whereas corresponding colonies (numbers 10 and 14) had no gonads, and numbers 11 and 13 were already dead. Nursery branches can exceed donor colony life span and reproductive activity.

Yearly increase in skeleton mass of isolated branches (average initial weight 4.9 g ± 2.0, $n = 112$) ranged from 0.5–45% and averaged 8.2% ± 9.2.

With regard to the small colonies, 44% survived within 1.5 years of mariculture (Fig. 2; $n = 30$). Of the 70 colonies left at the original settling place that receives the highest trampling and wave energy impacts, only 7 (10%) could be located.

The nursery colonies were clustered into 5 size classes according to initial weight (<9.9, 10.0–19.9, 20.0–29.9, 30.0–39.9, <40 g, Figs. 3a & 3b). Average growth year^{-1} decreased with size increase. The smallest group (<9.9 g) displayed the highest growth rate (119% ± 60) and added 8.8 g/year ± 6.7 on average, as compared to 35% ± 14 growth rate and 24.6 g ± 11 weight addition of the largest group (<40 g, Figs. 3a & 3b). Yearly increase in skeleton mass of the small colonies (average initial weight 32 g ± 28, $n = 30$) ranged 35–119% and averaged 75% ± 32. We found a significant correlation ($y = 3.1939x^{2.2957}$, $r^2 = 0.88$, $p < 0.01$) between $\bar{r}$ (which reflects colony age; Loya 1976c; Muscatine et al. 1985) and weight of small colonies (Fig. 4), which revealed iterative constraints of accretive growth.

Sexual Recruits

Most of the larvae in all dishes settled shortly after release. In total, 85% ($n = 2035$) of the collected larvae settled within 3–4 days. Within two months of *ex situ* maintenance in outdoor containers, about 60% died, and additional mortality of 10% was recorded in the third month, leaving 875 (41%) surviving spat. Four

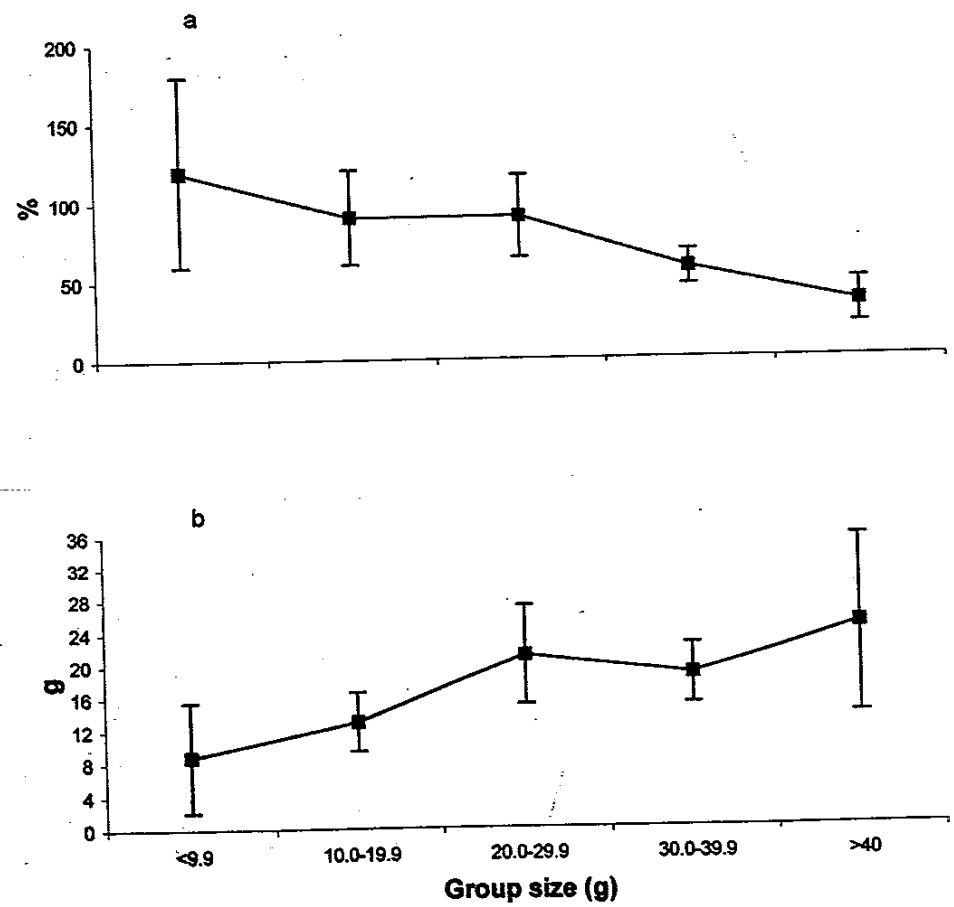

Figure 3. Small *S. pistillata* colonies at *in situ* nurseries: Yearly average growth rates (a = percentages; b = total weight added in skeleton mass) of different group sizes.

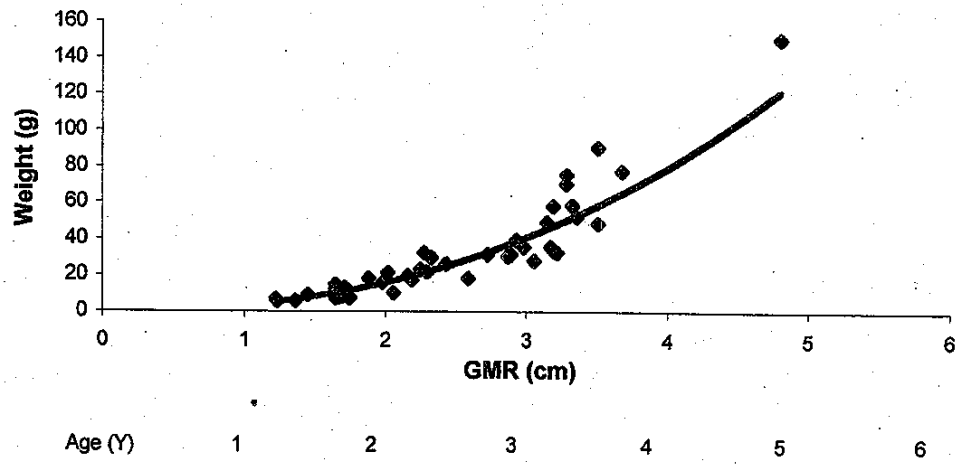

Figure 4. The correlation between geometric mean radius (GMR), weight and age of small *S. pistillata* colonies. The deduced age is calculated sensu Muscatine et al. (1985).

hundred primary polyps were transferred to *in situ* nursery at the MBL site at 10-m depth. After 1 month survivorship of 5% (20 spat) was recorded. In an earlier set of experiments, 599 freshly settled polyps were transferred to *in situ* conditions immediately after settlement and none survived after 1 month. This time, the 20 spat remained alive through the 18 months observational period and grew rapidly. At age of 2 weeks (still in *ex situ* containers), flat spat were about 7–8 polyps and <5 mm in diameter (Fig. 1c). At the age of 6 months (after 3 months *ex situ*) basal disk diameter reached 1.0 cm and the primary up-growing branch appeared (Fig. 1d). After 10 months basal diameter approached 2.0 cm (Fig. 1e) and within 18 months, small colonies of about 3–4 cm in diameter had developed (Fig. 1f).

Discussion

Studies of coral reefs worldwide have documented the harmful physical effects on corals of recreational activities such as scuba diving, snorkeling, and reef trampling (Talge 1992; Rinkevich 1995; Allison 1996; Chadwick-Furman 1997; Muthiga & McClanahan 1997; Rouphael & Inglis 1997). Habitat degradation has been estimated to affect coral populations through alteration of recruitment, growth, and colony (partial) mortality processes (Bak & Meesters 1999). A recent monitoring study at the coral reef of Eilat has further demonstrated that *Stylophora pistillata* population structures differed significantly between a site closed to the public and two adjacent highly visited reef sites. Results reflected differences in living coral coverage, maximal colony sizes, and colony breakage (Epstein et al. 1999). The conclusion of this monitoring program was that the "no-use" zone policy, a management measure implemented successfully in large-reef areas such as the Great Barrier Reef of Australia (Marion 1994; Christensen et al. 1996), is not sufficient in the limited reef area of Eilat. The growing mechanical damage inflicted on corals during recreational activities, however, is not the sole illness of the Eilat reef. As in other coastal areas with rapidly growing human populations, the presence of marine pollution agents of domestic and industrial origins has been documented for decades. The Eilat reef community has undergone numerous species extinctions, and its resilience capacity has been sharply reduced (Loya 1976*d*, 1986; Fishelson 1995). Today, in addition to pollution, the sharp conflicts between conservation and the tourist industry further decimate reef-building coral populations (Riegel & Velimirov 1991).

To alleviate mechanical degradation, Rinkevich (1995, 2000) has proposed a two-step restoration protocol termed "gardening of denuded reefs," which is based on the *in situ* mariculture of coral colonies in protected underwater nurseries. The concept of nursery mariculture on the sea floor has already been applied to other reef invertebrates such as *Tridacna* juveniles grown within plastic cages (Jintana et al. 1996). Our protocol incorporates low-profile artificial substrates as temporary coral nursery sites. First, coral material is relocated into the nurseries and maricultured there to an adequate size. Thereafter, it is transplanted into degrading reef sites.

Branching species like *S. pistillata* offer several types of coral material for gardening. In this basic study, we tested the mariculture of three types, *ex situ* settled sexual recruits (spat) and two asexually derived materials, small colonies and isolated branches. The use of *S. pistillata* nubbins has also been discussed (Rinkevich & Shafir 2000; Shafir et al. 2001). Previous studies that employed either of the above types of coral materials for transplantation (Bowden-Kerby 1997; Franklin et al. 1998;

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Rinkevich 2000 and literature therein) did not evaluate the pros and cons of their use, nor their appropriateness to various circumstances in different reef areas. Our recent studies (this work; Rinkevich 2000; Rinkevich & Shafir 2000; Shafir et al. 2001) provide analytical evaluations of different coral materials for the first time (Table 2).

The following discussion is mainly confined to *S. pistillata* at Eilat's reef. It is obvious that additional evaluation of other coral species at different locations will pro-

Table 2. Evaluation for the use of four different types of *S. pistillata* materials for reef restoration.

			Coral Materials	
Points for Consideration	*Branches*	*Small Colonies*	*Coral Larvae*	**Nubbins*
General ecological impact	Negative; replacement of established genotypes with ramets	Positive; rescuing genotypes settled in areas subjected to frequent disasters	Highly positive; increasing survivorship of sexual recruits by several orders of magnitude	Negative; development of monocultures
Effect on survivorship	Negative; increasing colony mortality with pruning	Positive; survival of genotypes supposed to die in place of origin	No effect	Minimal negative impact resulting from limited pruning protocol used
Effect on reproductive activity	Negative effects on donor colonies; no effect on isolated branches	No documented effects	No documented effects	Unknown
Effect on colony pattern formation	Negative; takes considerable time for proper patterning of lost parts	No effect	No effect	Moderate impacts resulting from the limited pruning protocol used
Amount of material derived from donor colonies	Moderate; each donor colony supplies several units	Minimal; only a single unit by each genotype	Few gravid colonies may produce high numbers of larvae	Few branches from a donor colony may provide hundreds of nubbins
Availability of type material	Year round	Following the reproductive season	Only during reproductive season	Year round
Contribution of material to the species genetic pool	Reduces genetic heterogeneity	No effect	Increases genetic heterogeneity	Highly reduces genetic heterogeneity
Potential biomass added to the reef	Moderate; few added colonies per genotype	Moderate to high, depending on number of rescued colonies	Significantly higher than natural recruitment rate	High; large numbers of added colonies per donor genotype
Transplant survivorship	Variable, according to conditions	High	Low, but several orders of magnitude higher than under natural conditions	High
Transplant growth rate	Moderate	Fastest	Fast	Lowest
Estimated mariculture period	>5 years	2 years	4—5 years	Longer
Working sites	All *in situ*	All *in situ*	*Ex situ* followed by *in situ*	*Ex situ* followed by *in situ*
Manpower	Low at pruning and transplantation and during nursery maintenance	Low at transplantation and during nursery maintenance	High at the stages of larval collection and *ex situ* maintenance; low thereafter	High at all phases
Operational costs	Low	Low	High	High
Priority of use	Recommended for cases where coral fragments are already scattered on reef bottom with low recovery rates	Highly recommended for reefs with areas subjected to frequent disasters	Highly recommended where *ex situ* facilities and manpower are available to support larval collection and maintenance protocols	Recommended where coral materials, especially branches, are limited in quantities

* From Rinkevich and Shafir (2000); Shafir et al. (2001).

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vide more complete strategic protocols for gardening of denuded reef areas.

Small Colonies

Relocation of small colonies from unprotected sites subjected to frequent natural disasters (i.e., storms) and human activity (i.e., trampling) into protected nurseries successfully salvages genotypes from being lost and maintains high genetic heterogeneity (Table 2). This protocol does not involve any documented damage to transplants. Maricultured colonies maintained high survivorship and revealed high biomass addition through rapid growth. On the average, small colonies grew 75% ± 32 in dry skeleton weight per year, the fastest growth rates of the three tested coral materials. Therefore, they require the shortest mariculture phase. A colony of 2.0–3.0 cm $\bar{r}$ in size (20–40 g in weight) that is placed in a nursery may reach, within a period of 2 years, $\bar{r}$ of 4.0–5.0 cm and a weight of up to 90 g, which we consider (Table 2) a suitable size for transplantation. No *ex situ* facilities are needed and operational costs are low. However, this coral material may not be available in all reef locations.

Isolated Branches

The strategy of pruning branches from large colonies is recommended in cases where enough donor colonies are found in or near the impacted area. It is best used in areas where naturally fragmenting species like *Acropora* (Bowden-Kerby 1997) are common. The material retrieved from colonies may be limited, and for some species this approach is not highly recommended. Pruning more than 10% of *S. pistillata* colony branches may result in mortality and reduced reproductive activity. The reduction of a single colony into many ramets may also lead to the formation of reef-monocultures and decrease genetic heterogeneity (Table 2). The average growth rate of isolated branches was about 10 times lower than of small colonies. Isolated branches therefore require a longer *in situ* mariculture period (>5 years) to attain the 90 g weight class (Table 2). Branch survivorship is highly variable, but ramets are available year round, and *in situ* maintenance may reduce operational costs.

Sexually Produced Primary Polyps

Ex situ settled *S. pistillata* spat displayed fast growth rates *in situ*, reaching a colony size of 3–4 cm diameter within 18 months. The mariculture period of these laboratory-settled polyps to a $\bar{r}$ of 4.0–5.0 cm is estimated as 4–5 years from day of settlement (Table 2). The ex situ maintenance phase increases survivorship by several orders of magnitude as compared to settlement in nature. Large numbers of larvae can be obtained *in situ* from a few gravid colonies without inflicting any physical damage. Surviving spat may increase the species' genetic heterogeneity. This approach is only applicable during the reproductive season and is particularly suitable for *S. pistillata*, a species that reproduces 6–7 months each year (Rinkevich & Loya 1979*a*, 1979*b*). In order to obtain high numbers of recruits, the *ex situ* maintenance requires laboratory facilities and higher operational costs. This strategy is highly recommended where funds are available and planulating species are abundant. It has not yet been tested on broadcasting species.

Coral Nubbins

The fourth strategy is the *ex situ* mariculture of huge numbers of nubbins (the size of a single or a few polyps) pruned from any single branch. It involves minimal damage to donor colonies, and evidence is accumulating for fast growth rates and high survivorship under *ex situ* conditions (Rinkevich & Shafir 2000; Shafir et al. 2001). Nubbins may need extended *ex situ* maintenance periods (longer than 5 years, Table 2). Major drawbacks are the reduction in genetic variability (monoclones) and the high investment in manpower and laboratory facilities. This technique is especially applicable when there is an urgent need to preserve a few remaining genotypes in a demolished reef area and where other coral materials are limited.

A Framework for Reef Restoration

Restoration ecology has been emerging in recent years as an independent discipline. However, in contrast to conservation biology, restoration ecology still lacks a solid theoretical background and general guidelines (Hobbs & Norton 1996). Hobbs and Norton (1996) also emphasized the necessity to develop generalities and principles in order to form a conceptual framework for restoration protocols. With regard to coral reef restoration, the goal of the commonly used coral transplantation techniques is to speed up recovery of degrading reefs. These techniques have been criticized for not being sustainable biological tools for restoring degrading reef communities (Edwards & Clark 1998). One of their main drawbacks is the need to obtain coral material from unaffected donor reef areas for transplanting into impacted areas.

The rationale for *in situ* coral mariculture stems from a different point of view. *In situ* coral nurseries can supply transplantation operations with corals adapted to natural reef conditions, causing minimal harm to existing colonies. The consideration of different coral species, depending on location, as well as the various coral materials for mariculture, makes this approach flexible and ap-

plicable worldwide through site-specific adaptations. The basic idea of *in situ* nurseries (Rinkevich 1995) has already been proven applicable by Bowden-Kerby (1997), who demonstrated the potential of a sheltered, lagoon-like reef area to be used as a natural nursery for loosely scattered corals. Franklin et al. (1998) successfully cultured coral fragments *in situ*, cemented into small plastic cups, and Rinkevich (2000) demonstrated the potential of low-profile substrates as nurseries.

The current state of reef biodegradation worldwide results from the synergistic effects of pollution, overexploitation, and tourism, and requires a multifaceted approach towards sustainable ecological restoration. Unfortunately this is impossible in many reef areas where human populations depend on coral reef resources. Therefore, heavily impacted reefs in general, and small popular reef sites in particular, require improved restoration techniques that can specifically compensate for the rapid loss.

We envisage *in situ* nurseries as sustainable sources for coral recruits that will continuously supply coral colonies for transplantation within several years of establishment. This concept of coral mariculture may serve as a key management tool in the conservation and rehabilitation of small-scale denuded reef areas or reefs in danger of extinction.

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