RESEARCH ARTICLE

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Steps in the construction of underwater coral nursery, an essential component in reef restoration acts

Abstract Many coral reefs worldwide are rapidly declining, but efficient restoration techniques are not yet available. Here, we evaluate methodologies for reef restoration based on the "gardening concept". A floating mid-water prototype nursery was placed at 6 m depth (14 m above sea-bottom) within the nutrient-enriched environment of a fish farm (Eilat, Red Sea). Ten colonies from five branching coral species provided 6,813 fragments (0.5–3 cm height). The fragments, each attached to a plastic pin, were inserted into plastic nets that were tied to a rope-net floating nursery. After 144 nursery days, only 13.1% of the fragments died and 21.2% were detached by mechanical forces. Small colonies ready for transplantation developed within 144–200 days. Ramets' ecological volumes increased 13–46 folds and their heights by a factor of 3.5. After 306 days, the ecological volumes of the colonies increased 147–163 fold as compared to original volumes (revealing a daily growth rate constant of 1.67% during the first 5–10 months) and height values by a factor of six. Building and maintenance costs of the nursery were low. This nursery prototype demonstrates the feasibility of the coral "gardening concept" by fulfilling several important needs, namely, mass production of coral colonies at low costs, high survivorship, fast growth, short nursery phase and improved methodologies for handling farmed colonies.

Communicated by O. Kinne, Oldendorf/Luhe

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Introduction

Coral reefs, the rain forests of the sea, are undergoing a worldwide decline (Epstein et al. 2001, 2003; Wilkinson 2002; Bellwood et al. 2004). Global changes (Chadwick-Furman 1996) and continuous intense abuse of reefs by humans (Hodgson 1999; McClanahan 1999) are the main factors for this decline. Adverse anthropogenic activities such as over-fishing, recreational activities, waste discharge, deforestation, reef mining and dredging have all been listed as primary causes for this degradation (Yap 2000; Lirman and Miller 2003). The decline of coral reefs has raised the need for adequate restoration methodologies as efforts to conserve degrading reefs have failed to produce significant results and rehabilitation measures have not compensated for the rapid reef degradation (Rinkevich 1995; Risk 1999; Epstein et al. 2001). A World Bank report on coral reefs (Hatziolos et al. 1998) identified this ecosystem as the highest priority area for conservation, especially in countries with an economic dependence on coral reefs. This concern is further supported by reports discussing the ecological and socio-economic issues of worldwide reef degradation (Abram et al. 2003; Gardner et al. 2003; Hughes et al. 2003; Pandolfi et al. 2003).

The fast degradation of coral reefs has prompted greater attention to remediation and restoration activities. In many reef areas, the status of the reef has reached a critical point of reduced resilience (sensu Young 2000), forcing active restoration measures. However, established theories and approved management and restoration techniques for marine ecosystems, including coral reefs, still lag behind and rely largely on those developed for terrestrial habitats (Allison et al. 1998; Keough and Quinn 2000; Rose 2000). As a result, the principles underlining reef restoration measures have become part of the many ill-defined issues of this discipline (Edwards and Clark 1998; Rinkevich 2000).

The fast worldwide reef degradation has invoked discussions on suitable restoration measures to be applied

as management tools supplementary to the traditional conservation measures (Rinkevich 1995, 2000; Edwards and Clark 1998; Yap 2000; Epstein et al. 2001, 2003; Spieler et al. 2001). Various approaches have been proposed (Rinkevich 2005) including construction of artificial reef structures (van Treeck and Schuhmacher 1999; Sherman et al. 2001; Abelson and Shlesinger 2002; Schumacher 2002), the transplantation of entire coral colonies or fragments (Smith and Hughes 1999; Gleason et al. 2001; Ortiz-Prosper et al. 2001) and the concept of "coral gardening" by means of underwater nurseries (Rinkevich 1995, 2000, 2005; Shafir et al. 2001; Sabater and Yap 2002; Fox et al. 2003; Soong and Chen 2003).

Until recently, attempts to restore degraded reef areas were based on whole colony transplantation (Edwards and Clark 1998) in which dead coral colonies are replaced with new ones in order to accelerate natural recovery. However, harvesting corals for transplantation usually abuse and inflict trauma to the donor reefs while survival and growth of the transplants are left to the mercy of conditions within the damaged reef site (Edwards and Clark 1998; Epstein and Rinkevich 2001). To alleviate coral reef degradation, a two-step restoration protocol termed "gardening of denuded reef areas" has been proposed (Rinkevich 1995, 2000; Epstein et al. 2001). During the first step, a large in situ pool of farmed corals is established in nurseries that are installed in sheltered zones. In the second step, nursery-grown coral colonies are transplanted to degraded reef sites. This gardening strategy is theoretically linked to terrestrial forest plantation ideas (Epstein and Rinkevich 2001; Rinkevich 2005) that have been practiced successfully for years with forest trees (Berg 1995; Vowell 1994) and mangroves (Khoon and Eong 1995; Chan et al. 1988).

Here, we present results on the operation of a large in situ coral nursery, a major component in the first step of "gardening of the coral reefs" concept (Rinkevich 1995, 2000, 2005). Growth and survival of an initial 6,813 coral fragments of five different coral species were recorded during the first 5–10 months of nursing in a prototype, mid-water floating nursery, situated in a nutrient-enriched area close to a fish cage farm in the northern Gulf of Eilat.
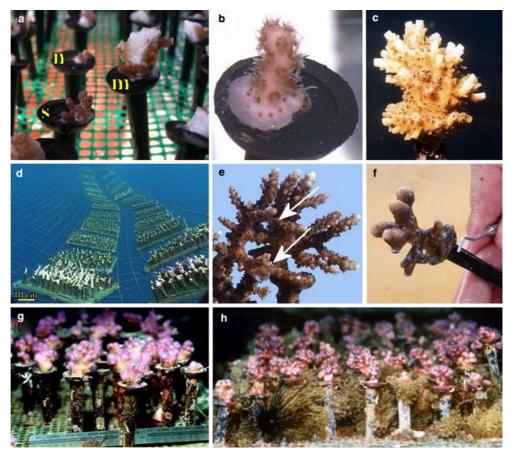
Materials and methods

The mid-water floating nursery was suspended at a depth of 6 m (14 m above sea bottom) in a nutrient-rich water body (during 2001, the monthly average nutrient levels were 0.095 μM nitrite, 0.385 μM nitrate, 0.123 μM orthophosphate and 1.016 μM ammonia; cited in Bongiorni et al. 2003). The nursery was situated at a distance of about 10 m from a large fish cage (containing gilthead seabream, *Sparus aurata*) of the Ardag fish farm facility at the northern shore of the Gulf of Eilat, Red Sea (29°32.45′N, 34°58.40′E). This site was protected from the impacts of skin and scuba divers.

Ten branching coral colonies from five species were used, namely three *Stylophora pistillata* (10–20 cm diameter), four *Pocillopora damicornis* (15 cm diameter), and one colony from each of the following *Acropora* species: *A. pharaonis* (15 cm diameter), *A. eurystoma* (20 cm diameter) and *A. valida* (15 cm diameter). The colonies were collected from artificial substrates in Eilat's navy port and transported, submerged in seawater, to the nursery site. All colonies were pruned during a period of six days (mid-July and mid-August 2003) by electrician's wire cutters providing fragments of different sizes according to the species used and branch sizes. The fragments that were clustered into three ramet sizes generated nubbins and small branches < 1 cm, medium branches 1–2 cm and long branches > 2 cm. Nubbins refer to the smallest fragments (about 0.5 cm size) lacking any branch-like structure. Old and new parts of each colony, and tip and mid- branch areas (Fig. 1a) were used equally as source material for fragment preparation.

In an attempt to minimize stress conditions (Shafir et al. 2001), the isolated ramets were instantaneously immersed upon separation in a tank of fresh seawater. Then, the exposed skeletal surface area of each individual fragment was dried with a paper towel and the ramet was attached with a drop of cyanoacrylate glue (Super Glue 3, Loctite, Ireland) to the flat surface of a plastic pin (9-cm long, 0.3–0.6-cm wide leg with a 2 cm diameter "head", Red-Sea Corals LTD., Israel; Fig. 1a–c). The plastic pins carrying the glued coral ramets were positioned within plastic nets (0.25 cm^2 mesh size) that were stretched over PVC frames (each 50×30 cm). Frames with the pins were tied at a depth of 6 m to an underwater floating rope net (10×10 m) that served as the nursery basis (Fig. 1d). Each plastic frame carried 80–110 pins with coral ramets belonging to a specific coral species/genet. Different size ramets of the same coral genet were interspersed randomly on the PVC frame (Fig. 1d, g). Detailed monthly observations were conducted on the status of each ramet (missing, dead, and alive). Ramets were digitally photographed (Nikon coolpix 995) at day 0, just before immersion and at day 144. A smaller number of the ramets were photographed at days 200 and 306. Side and top views of the plastic nets were analyzed with image-analysis software TINA 2.07 to obtain height (h), width (w) and length (l) of each branch/colony. The diameter of each fragment/colony (d) was calculated by the following formula: $d = (l + w)/2$. Results are presented as means with standard deviation.

An ecological volume index was established for each branch, or a colony, by approximating the initial and developing structures to the shape of a cylinder with volume $V = \pi r^2 h$, in which $r = (l + w)/4$ (Rinkevich and Loya 1983). The morphology of well-developed colonies resembled the shape of half a sphere or a cylinder. In this study, three-dimensional volumes of the colonies were calculated according to the volume of a cylinder since this most accurately expressed the total volume taken by

Fig. 1 The prototype nursery in Eilat. **a** Newly prepared fragment of *P. damicornis*: nubbin (*n*), small (*s*), medium (*m*) size fragment with a large bare exposed skeleton area. **b** *Acropora eurystoma* ramet. Lateral growth of tissue and skeleton, one month from attachment. **c** 3-month old farmed *A. eurystoma* ramet, showing the typical structure of a colony developed from a single small branch. The whole pinhead surface area is covered. **d** A general view of Eilat's mid-water coral nursery: horizontally situated rope net, on which plastic frames are installed, each packed with 80–100 ramets. **e** Isogeneic fusion between two *A. eurystoma* colonies. *Arrows* point to fusion areas. **f** Hand cleaning of a farmed colony; scraping the plastic pin with a dental tool. **g** One-month old *Pocillopora damicornis* ramets on a plastic frame. **h** Three-month old PVC frame packed with *Pocillopora damicornis* ramets. Spaces between plastic pins are filled by dense populations of the sea anemone *Boloceroides memurrichi*. (Photos c, d by D. Gada. a, b ,e–h by S. Shafir)

the colony and the water volume between and below the branches (the "ecological volume"). Following the exponential growth rates of the colonies, their growth rate constants (k) per day for ecological volumes (E) were calculated by the formula $E_t = E_0 e^{kt}$, providing $k = (\ln E_t/E_0)/t$ (t = time in days, 0-values at the beginning of the experiment).

Results

A total of 6,813 composite coral fragments from the ten colonies (five coral species; 212–1,054 ramets per coral colony; Table 1), were produced by a team of seven untrained volunteers. A single untrained worker was capable of making 25 fragments/hour from the large ramets (>2 cm on average, Table 2) of *A. pharaonis* and *A. eurystoma* or 100 fragments/hour from the small and medium (<2 cm average) ramets of *A. valida*, *A. eurystoma*, *S. pistillata*, and *P. damicornis*.

The five species responded differently to the stress conditions inflicted during composite preparations (branch pruning, fragment dissection, attachment procedures to the plastic pins). One criterion for measuring stress was the amount of mucus produced during the operation. *A. pharaonis* and *A. eurystoma* secreted considerable amounts of mucus. *A. valida* fragments secreted small amounts of mucus, whereas *S. pistillata* and *P. damicornis* preparative did not secrete any excess mucus.

The largest fragments were prepared from *A. pharaonis* and *A. eurystoma* ($n = 527$, height = 23.6 ± 6.6 mm, diameter = 10.0 ± 5.6 mm; and $n = 311$, $h = 22.1 \pm 7.7$ mm, $d = 12.3 \pm 6.8$ mm, respectively; Table 1 and 2). Characterized by thin branch structures with narrower exposed skeletal surface areas, these fragments revealed the highest height/diameter values (H/D = 2.9 ± 1.4 and 2.2 ± 1.2, respectively; Table 2). Smaller and thinner ramets from the same *A. eurystoma* colony ($n = 376$, $h = 6.2 \pm 1.9$ mm, $d = 6.3 \pm 2.4$ mm) had almost half the H/D values (H/D = 1.2 ± 0.7; Table. 1 and 2). *A. valida* had wider branches and the colony provided many small fragments with the lowest H/D values ($n = 1054$, $h = 7.3 \pm 2.6$ mm, $d = 8.6 \pm 2.6$ mm, H/D = 0.9 ± 0.4). The three studied *S. pistillata* colonies provided small (minimum height 4.6 mm) to large (maximum height 25.2 mm, Table 2) fragments ($n = 1502$, $h = 11.7 \pm 4.3$ mm, $d = 8.0 \pm 1.9$ mm, Table 1) as did the four selected *P. damicornis* colonies ($n = 3043$, minimum height 3.2 mm, maximum height 35.8 mm, average height 15.8 ± 7.8 mm, average diameter: 11.8 ± 4.0 mm). The latter two species were characterized by colonies with wider branches (H/D 1.5 ± 0.7 and 1.4 ± 0.6,

Table 1 The status of farmed coral ramets (144 days) in the prototype underwater nursery

Donor colony	Ramet status	Number and percentage of ramets at day							
		0	32	%	66		100	%	144	%
Stylophora-1	Lived	1047	956	91.3	921	88.0	859	82.0	805	76.9
	Detached		69	6.6	77	7.4	116	11.1	147	14.0
	Died		22	2.2	50	5.1	73	7.8	96	10.7
Stylophora-2	Lived	212	185	87.3	176	83.0	156	73.6	136	64.2
	Detached		15	7.1	18	8.5	31	14.6	43	20.3
	Died		12	6.1	18	9.3	25	13.8	33	19.5
Stylophora-3	Lived	243	193	79.4	176	72.4	160	65.8	153	63.0
	Detached		45	18.5	61	25.1	74	30.5	79	32.5
	Died		5	2.5	6	3.3	9	5.3	11	6.7
Pocillopora-1	Lived	577	450	78.0	383	66.4	375	65.0	368	63.8
	Detached		109	18.9	163	28.2	167	28.9	172	29.8
	Died		18	3.8	32	7.7	36	8.8	38	9.4
Pocillopora-2	Lived	927	760	82.0	728	78.5	709	76.5	662	71.4
	Detached		129	13.9	154	16.6	167	18.0	184	19.8
	Died		38	4.8	46	5.9	52	6.8	82	11.0
Pocillopora-3	Lived	825	643	77.9	621	75.3	611	74.1	583	70.7
	Detached		105	12.7	119	14.4	128	15.5	149	18.1
	Died		77	10.7	78	11.2	79	11.4	86	12.9
Pocillopora-4	Lived	714	636	89.1	604	84.6	580	81.2	522	73.1
	Detached		29	4.1	34	4.8	39	5.5	56	7.8
	Died		49	7.2	76	11.2	95	14.1	136	20.7
A. pharaonis	Lived	527	335	63.6	299	56.7	273	51.8	256	48.6
	Detached		176	33.4	202	38.3	218	41.4	227	43.1
	Died		16	4.6	27	8.3	37	11.9	45	15.0
A. eurystoma-L	Lived	311	208	66.9	178	57.2	171	55.0	162	52.1
	Detached		92	29.6	117	37.6	121	38.9	126	40.5
	Died		11	5.0	17	8.7	20	10.5	24	12.9
A. eurystoma-S	Lived	376	266	70.7	253	67.3	246	65.4	238	63.3
	Detached		79	21.0	81	21.5	86	22.9	90	23.9
	Died		31	10.4	43	14.5	45	15.5	49	17.1
A. valida	Lived	1054	893	84.7	839	79.6	821	77.9	785	74.5
	Detached		105	10.0	133	12.6	143	13.6	168	15.9
	Died		56	5.9	83	9.0	91	10.0	102	11.5
Total	Lived	6813	5525	81.1	5178	76.0	4961	72.8	4670	68.5
	Detached		953	14.0	1159	17.0	1290	18.9	1441	21.2
	Died		335	5.7	476	8.4	562	10.2	702	13.1

A. eurystoma fragments were divided into two groups (*L* large, > 2 cm length, *S* small, < 1 cm length). Mortality rates (%) were assessed relatively to number of attached fragments

respectively; Table 2). Colonies of these species markedly varied in ramet height and usually exhibited wider exposed skeletal surface area available for attachment to the plastic pins.
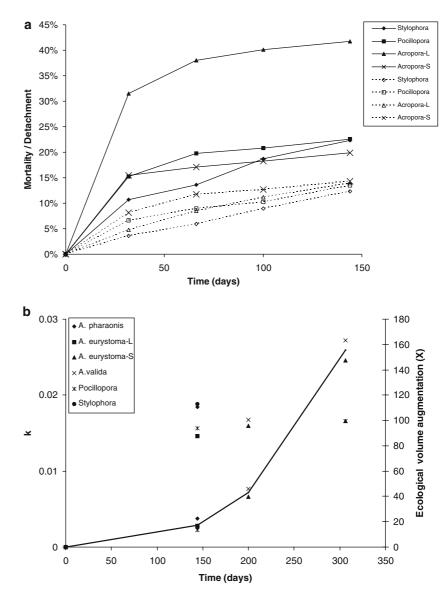
During the first 144 nursery days, 1,441 ramets (21.2%) were detached from the plastic pins. Most fragments ($n = 953$, 66.1%) detached during the first month (Table 1; Fig. 2a) because of unsuccessful adhesion. Much of the subsequent loss was due to mechanical force by fish activities, by accidental detachment, and by researchers during monitoring and cleaning sessions. A major loss was recorded for the long and thin fragments

Table 2 Ramet sizes at preparation (mean ± SD; L, S, see legend to Table 1)

Coral species	No.	Size of ramets						Height/Diameter
		Height (mm)			Diameter (mm)			
		Average	Maximum	Minimum	Average	Maximum	Minimum	
A. pharaonis-L	36	23.6 ± 6.6	39.6	6.6	10.0 ± 5.6	26.6	5.6	2.9 ± 1.4
A. eurystoma-L	37	22.1 ± 7.7	37.1	4.2	12.3 ± 6.8	30.8	3.7	2.2 ± 1.2
A. eurystoma-S	54	6.2 ± 1.9	11.0	2.2	6.3 ± 2.4	13.8	2.1	1.2 ± 0.7
A. valida-S	51	7.3 ± 2.6	17.9	2.7	8.6 ± 2.6	15.1	3.7	0.9 ± 0.4
Pocillopora	51	15.8 ± 7.8	35.8	3.2	11.8 ± 4.0	29.9	5.4	1.4 ± 0.6
Stylophora	48	11.7 ± 4.3	25.6	4.3	8.0 ± 1.9	17.6	2.9	1.5 ± 0.7

Fig. 2 a Detachment (*solid line*)
and mortality (*broken line*) rates
of coral fragments during 144
nursery days. *Acropora*
fragments: *L* large, > 2 cm; *S*
small, < 1 cm. **b** Parameters of
ecological volume increase in
nursery-farmed branching
corals. *Left axis* denotes the
growth rate constant (*k*)
following 144, 200 and 306
nursery days. *Right axis*
represents size augmentation (*X*
times from initial) of colonial
ecological volumes

of *A. pharaonis* and *A. eurystoma* (43.1 and 40.5%,
respectively, Table 1) characterized by high H/D ratios
(Table 2). These long branches were probably subjected
to increase shearing forces (not measured), as the rela-
tively narrow glued surface areas failed to hold the long
branches attached to them. Again, most detached from
the plastic tips within the first month (77.5 and 73.0%
from total loss, respectively). When comparing detach-
ment rates of large versus small fragments originating
from the same coral colony (*A. eurystoma*; Table 1), 40.5
vs. 23.9% loss, respectively, was recorded after 144 days
of nursery (*P* < 0.05; χ^2 *G*-test). The smaller but wider
fragments with low H/D values (Table 2) obtained from
A. eurystoma, *A. valida*, *S. pistillata* and *P. damicornis*
colonies revealed reduced detachment rates (21.0, 10.0,
8.6, and 12.1%, respectively, Table 1), possibly resulting
from being more resistant to mechanical forces. Most of
the loss was recorded during the first month (87.8, 62.5,
48.0, and 65.8% of total loss, respectively), pointing

again to failures in the gluing procedure. Only 702 coral
fragments (13.1%) died during the first 144 days of
nursery period (Table 1), less than half of the detached
branches (Fig. 2a). Significant fragment mortality
(*n* = 335, 47.7%; Fig. 2a) occurred during the first
month, reflecting the impact of stress imposed during the
preparation and transportation of the fragments. Mor-
tality rates did not differ between the three coral genera
throughout the observations (one-way ANOVA, *P* > 0.1),
but indicated high variations (up to threefold differ-
ences) within species analysed. After 144 nursery days,
the three *S. pistillata* colonies showed 10.7, 19.5, and
6.7% mortality rates, respectively (one-way ANOVA,
P < 0.05), and the four *P. damicornis* colonies, 9.4, 11.0,
12.9, and 20.7%, respectively (one-way ANOVA, *P* < 0.05).

The remaining coral fragments developed into colo-
nies at an impressively fast rate. Within the first month
in the nursery, the ramets grew horizontally over the
plastic pinheads forming a "ring" (up to 15 mm diam-

Table 3 Growth rates of farmed coral ramets after 144, 200 and 306 nursery days *A. eurystoma* ramets were divided into two groups (*L* large, > 2 cm; *S* small, < 1 cm)

Coral species	No.	Days	Measurements			Size augmentation (×)			Growth Rates Constant (%/d)
			Height (mm)	Diameter (mm)	Ecological volume (cm³)	Height	Width	Ecological volume	
A. pharaonis	36	0	23.6 ± 6.6	10.0 ± 5.6	2.4 ± 2.8				
		144	41.7 ± 14.4	26.0 ± 14.1	34.3 ± 48.9	1.8 ± 0.6	2.9 ± 1.6	22.3 ± 27.4	1.86
A. eurystoma-L	37	0	22.1 ± 7.7	12.3 ± 6.8	3.4 ± 3.3				
		144	36.9 ± 10.3	28.0 ± 9.2	27.8 ± 23.5	1.8 ± 0.7	2.8 ± 1.2	16.9 ± 17.4	1.46
A. eurystoma-S	54	0	6.2 ± 1.9	6.3 ± 2.4	0.2 ± 0.2				
		200	18.2 ± 6.5	17.0 ± 4.9	4.9 ± 4.0	3.1 ± 1.3	3.0 ± 1.4	39.8 ± 60.0	1.60
	18	306	35.5 ± 8.4	31.4 ± 8.8	31.8 ± 23.7	5.7 ± 1.9	5.0 ± 1.9	147.4 ± 130.3	1.66
A. valida	51	0	7.3 ± 2.6	8.6 ± 2.6	0.5 ± 0.4				
		200	23.3 ± 7.2	25.5 ± 7.4	14.3 ± 11.2	3.5 ± 1.5	3.2 ± 1.2	46.2 ± 49.8	1.68
	29	306	43.9 ± 8.3	46.0 ± 9.1	79.4 ± 44.8	6.0 ± 2.1	5.4 ± 1.9	163.3 ± 142.5	1.66
Pocillopora	51	0	15.8 ± 7.8	11.8 ± 4.0	2.3 ± 2.4				
		144	24.1 ± 9.0	29.6 ± 9.4	21.9 ± 23.4	1.7 ± 0.6	2.4 ± 0.8	13.2 ± 9.2	1.56
Stylophora	48	0	11.7 ± 4.3	8.0 ± 1.9	0.6 ± 0.5				
		144	22.0 ± 6.1	21.0 ± 6.2	9.0 ± 7.5	2.0 ± 0.5	2.4 ± 1.1	15.7 ± 10.6	1.88

eter, Fig. 1b) of tissue and deposited skeleton on the substrate. Two months later, most of the coral material had covered the entire pinhead, thereby anchoring the developing coral colony to the plastic pin (Fig. 1c). A follow up of 277 colonies (Table 3) revealed that on the average, height nearly doubled after 144 days (*n* = 172 colonies), tripled after 200 days (105 colonies) and multiplied by a factor of six after 306 days (47 colonies). Colony diameters tripled between 144 and 200 days and multiplied by a factor of five after 306 days, as compared to the initial diameters. The ecological volumes of colonies increased 13–22 fold during the first 144 days, 40–46 fold after 200 days, and 147–163 fold after 306 days (Table 3), revealing an exponential rate (Fig. 2b). This represented an average ecological growth rate constant of 1.67% per day in the first 10 months of nursery maintenance (Fig. 2b). After 5–7 months in the nursery, small colonies of *Acropora*, *Pocillopora* and *Stylophora* developed (Fig. 3) from small single-branch (0.6–2.4 cm) fragments forming the typical colonial shapes of species.

We routinely (every 3–4 weeks) checked the nursery, and monitored and documented dead, detached and partly dead colonies. Photographs were taken as needed. In the crowded in situ setup (80–110 fragments/plastic frame), the fast-growing coral fragments came within a few months into direct contact with each other. In many cases, these isogenetic contacts were followed by colony fusions (Fig. 1e), forming morphologically distorted super-colonies. Since several thousands coral fragments were simultaneously farmed and observed, we were unable to clean the fragments, except for a few cases where a cleaning protocol was tested (Fig. 1f). In this preliminary trial, the pins were easily and efficiently cleaned by scraping them with a dental tool to remove all encrusting organisms. This procedure, however, cannot be performed routinely because of the extensive labor required. During our monthly visits, we found that rapidly waving our hands above the colonies was an efficient protocol for removing debris, unattached organisms and algal blades covering the colonies during periods of alga blooms. Natural removal of algae and
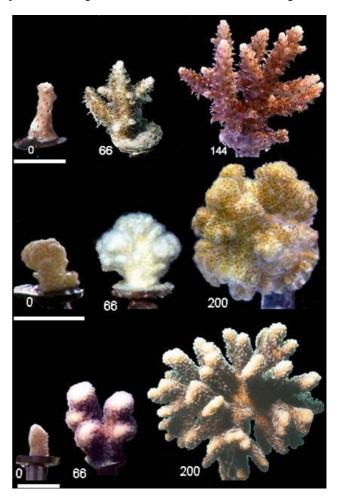

Fig. 3 Examples of nursery-cultured colonies. **a** *Acropora eurystoma*, **b** *Pocillopora damicornis*, **c** *Stylophora pistillata*, (66, 144, and 200 days). Bar = 2 cm (Photo by D. Gada)

other settled organisms was performed by fish, mostly by resident schools of *Siganus rivulatus* that appeared one month after the construction of the nursery, and by individual sea urchins *Diadema setosum* that settled from the plankton (Fig. 1g, h). Cleaning was less efficient in areas where pins were densely placed. In time, we reduced the number of colonies to 40–50 per plastic frame. Wider spacing of the pins led to more intensive grazing and to the removal of most large settling organisms and to the reduction of fusion events between ramets.

Numerous species of invertebrates appeared within 1–2 months and settled on or between the farmed colonies. The developed branching structures were colonised by the host's species-specific assemblages (i.e., in *Stylophora* colonies: *Trapezia* crabs and boring *Lithophaga lessepsiana*), all originating from the plankton. A dense population of the sea anemone, *Boloceroides memurrichi*, developed between crowded pins during the first 4 months of nursery operation (Fig. 1h), without harming the coral fragments. The sea anemone disappeared because of predation after the pins were reallocated at reduced densities. Many corallivorous snails (*Drupella cornus*) appeared 6–7 months after the construction of the nursery. They settled particularly on colonies of *S. pistillata*. Manual removal of the snails under and above the water (Fig. 1f) during the monthly observations led to recovery of damaged coral colonies and reduced predation pressure.

The construction and maintenance of nursery was relatively cheap. The cost did not exceed $2 per 100 coral colonies installed in the nursery ($0.01 per plastic pin, $0.05 for glue and $0.05 for small appliances). The entire nursery (a rope net 10×10 m) cost $250, ropes, anchors and buoys $100, and each plastic frame $5. Labor was also minimal. Preparation of 100 fragments from *Acropora* colonies that possess long and thin branches or those that secreted considerable amounts of mucus required 4 h of labor as compared to only 1 h for colonies (i.e., *Stylophora*) with thicker branches. Routine maintenance time for 100 colonies was 1 h/month.

Discussion

The need for restoration practices specifically adapted to the coral reef ecosystem has led to a number of recent initiatives. Initial efforts focused on the establishing of artificial reefs (Pickering et al. 1998; White et al. 2000) to enhance fisheries production (Ortiz-Prosper et al. 2001; Sherman et al. 2001; Abelson and Shlesinger 2002; Schumacher 2002). Other reef restoration efforts mainly concentrated on direct, whole coral colony transplantation or on coral fragments transplantation (Raymundo 2001; Fox et al. 2002, 2003; Lindahl 2003). While these approaches are still being employed, recent initiatives have specifically been directed to restoring degraded reefs by novel approaches that inflict minimal detrimental impact on existing coral colonies and reef areas. These measures include the "gardening" and the "electric reef" concepts (Hilbretz and Goreau 1996; Rinkevich 1995, 2000; van Treeck and Schuhmacher 1999; Epstein et al. 2001).

The present prototype coral nursery addresses several methodological issues that are important for feasibility evaluations of large in situ coral nurseries. Major topics are (1) the general shape of the nursery with an eye to working conditions; (2) the temporary substrate on which the coral colony develops during the nursery phase; (3) the realistic number of fragments/new colonies that can be generated and maintained; (4) the duration of the nursery phase; (5) the growth and mortality rates of fragments; (6) the farming applicability of branching forms under in situ nursery conditions. Other aspects such as how and where to transplant the coral colonies, the optimal size for transplantation, rates of mortality/growth in the reef after transplantation and other post-nursery acts were not studied here.

This study demonstrates that a successful nursery can be a simple structure, cheaply built from easily procured material and with low technical manipulations. Preferably, it should be situated in a protected area since mechanical forces may significantly reduce operational success. A shallow location for the nursery (here at 6 m depth) in mid-water (here 14 m above the sea bottom) and in a nutrient-enriched site are recommended for obtaining faster growth rates of shallow coral species. Attaching ramets to substrates by super glue is an easy and cheap way to construct thousands of nubbins by untrained workers within a few days. Production of a 1,000 fragments required 10–20 h for an untrained worker and almost half this time for a highly trained employee (Shafir, personal observations). Based on these observations, it is estimated that a single worker can produce more than 50,000 fragments (from about 50 donor colonies) per year, which could result in the net development of 35,000–40,000 new colonies after the deduction of coral mortality and detachment.

We found that the first month of the nursery period is critical for reducing the number of detached and dead coral fragments. Therefore, special attention should be given to the preparation of the fragments (separation from donor colony, attachment to substrate, placement in the underwater nursery) and the initial fragment size. Working with nubbins will generate, within a specific timeframe, smaller colonies amenable for transplantation (the optimal size for coral transplantation was not tested here). This will reduce the stress inflicted on the donor colonies, which in turn could increase colony production. Under the set of conditions tested here, the main cause for coral loss was detachment from the substrate of, especially, larger coral fragments. We estimate that the use of smaller coral fragments and nubbins will increase the nursery output to about 90% of the initial farmed fragments (but would also increase nursery time). Monthly maintenance of the nursery (observations, replacement of plastic frames and relocation of crowded coral colonies within plastic frames, removing

dead corals fragments and detached samples) requires about ten diving hours per month.

The use of plastic pins for individual coral colonies is an easy and inexpensive ($0.01/pin) way to mass-produce fragments. Initially, 80–110 plastic pins were included within each plastic net (30×50 cm). However, we found that the crowded pins prevented herbivorous fish and grazing invertebrates from naturally cleaning the nets and pins from settled organisms. Spacing the pins proved to increase the efficiency of this "natural" cleaning. Moreover, the use of plastic pins enabled the manual cleaning of each colony in a fast and easy way without harming the developing coral (Fig. 1f). The pins could also act as an efficient attachment device during transplantation.

In a previous study, we found that the nutrient-enriched environment near the fish cages resulted in enhanced growth of coral fragments (Bongiorni et al. 2003). Indeed, incubation under nutrient-rich conditions in this study has shortened (compare with Rinkevich 1995) the nursery period and the ramets' ecological volume increased 13–46 times during 144–200 days and 147–163 times after 306 days. The corals are therefore growing at a high rate of 1.67% per day, which rivals growth of algae at these high ambient nutrient concentrations. Short nursery time reduces nursery costs and increases restoration efficiency. It also reduces the threats of predation and competition caused by coral-livorous snails and settling organisms. However, in an established nursery, where stocks of farmed coral colonies are continuously cultured, the invasion of new organisms originating from the plankton should be considered. As with the cultured corals, some of these organisms (such as sea urchins, reef fishes, symbiotic, and mutualistic organisms residing between branches of coral colonies) may also be a focus of interest for transplantation onto denuded reef areas.

It should be noted that part of the success of this nursery trial was due to the location of the nursery. The mid-water nursery examined in this study was located in an isolated, nutrient-enriched area at a distance of 6–8 km from the natural reef. The area is protected from the impacts of tourists (e.g. skin and scuba divers) and the site was not subjected to predation by corallivorous fish, common in southern Eilat reef. The crucial experiment of transplanting the nursery-grown corals to the natural, non-nutrient-enriched reef environment with all its additional biological and physical pressures is now in progress.

Worldwide extensive reef degradation calls for active remediation and restoration measures in addition to the traditional measures for reef protection. The continuous loss of biological and economical benefits from reefs due to their destruction emphasizes the need for maintaining this ecosystem and, where degraded, activating restoration practices. Restoration measures that use new coral colonies will generate additional habitats for reef-dwelling organisms, help in biodiversity preservation, reduce the impact of commercial and recreational activities and may enhance ecotourism. Much remains to be learned about the proper management and restoration of coral reef ecosystems. Establishing this new ecological discipline will generate approved technologies for better use of existing coral reefs worldwide, including those that are regarded as "paradise lost" sites (Risk 1999).

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