Rebuilding Coral reefs: Does active reef restoration lead to sustainable reefs?

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Are U.S. Coral Reefs on the Slippery Slope to Slime?

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Coral reefs provide ecosystem goods and services worth more than $375 billion to the global economy each year (1). Yet, worldwide, reefs are in decline (1–4). Examination of the history of degradation reveals three ways to challenge the current state of affairs (5, 6). First, scientists should stop arguing about the relative importance of different causes of coral reef decline: overfishing, pollution, disease, and climate change. Instead, we must simultaneously reduce all threats to have any hope of reversing the decline. Second, the scale of coral reef seaweed (2, 7, 8). Overfishing of megafauna releases population control of smaller fishes and invertebrates, creating booms and busts. This in turn can increase algal overgrowth, or overgrazing, and stress the coral architects, likely making them more vulnerable to the slippery slope of coral reef decline (see bottom figure, this page), yet much less action has been taken. What is the United States doing to enhance its coral reef assets? In the Florida Keys National Marine Sanctuary, the Governor and the National Oceanic and Atmospheric Administration (NOAA) agreed in 1997 to incorporate zoning with protection from fishing and water quality controls (13). But only 6% of the Sanctuary is zoned no take, and these zones are not strategically located. Conversion of 16,000 cesspools to centralized sewage treatment and control of other land-based pollution have only just begun. Florida's reefs are well over halfway toward ecological extinction and much more impaired than reefs of Belize and all but one of the Pacific reefs in the figure below (6). Large predatory fishes continue to decrease (14), reefs are increasingly dominated by seaweed (15, 16), and alarming diseases have emerged (17).

Annual revenues from reef tourism are

A ROADMAP FOR REVERSING THE TRAJECTORY OF DECLINE OF U.S. CORAL REEFS

<table>
<thead>
<tr>
<th>Threat (time frame)</th>
<th>Critical first step</th>
<th>Results</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overfishing (years)</td>
<td>Immediate increase of cumulative no-take areas of all U.S. reefs to &gt;30%; reduce fishing efforts in adjacent areas</td>
<td>Increase in short-lived species, such as lobsters, conch, parrotfish, and sea urchins</td>
<td>Economic viability to lost or weakened fisheries; reduction in algal competition with corals</td>
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<td>Overfishing (decades)</td>
<td>Establishment of large fish, shark, turtle, and manatee breeding programs; mandatory turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs)</td>
<td>Increase in megafauna populations</td>
<td></td>
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<td>Pollution (years-decades)</td>
<td>Stringent controls over land-based pollution</td>
<td>Increase in water quality</td>
<td></td>
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<td>Coastal development (years-decades)</td>
<td>Moratorium on coastal development in proximity to coral reefs</td>
<td>Increase in coral reef habitat</td>
<td></td>
</tr>
<tr>
<td>Global change (decades)</td>
<td>International engagement in emission caps</td>
<td>Reduction in global sea surface temperatures and CO₂</td>
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Rapid climatic change has already caused changes to the distributions of many plants and animals, leading to severe range contractions and the extinction of some species.

The geographic ranges of many species are moving toward higher altitudes in response to shifts in the habitats to which these species have adapted. It already appears that some species are unable to disperse or adapt fast enough to keep up with the high rates of climate change. These organisms face increased extinction risk, and, as a result, whole ecosystems, such as cloud forests and coral reefs, may cease to function in their current form.....

Therefore, resource managers and policy-makers must contemplate moving species to sites where they do not currently occur or have not been known to occur in recent history.
The statements.....

- Coral reefs suffer worldwide decline/degradation
- This poor state of the reefs is due to (a) global changes and (b) anthropogenic activities
- This decline has raised the need for the development of adequate ‘rehabilitation’ methodologies
- Efforts to conserve degrading reefs have failed, in most of the cases, to produce significant results

- There is a need for active restoration measures
- The most effective approach is the concept of ‘gardening reef areas’
Tsunami impacts in Thailand

Placing corals into right position if possible!

Active vs. passive approaches

Silviculture
The Gardening Strategy

- Mariculture *(in situ or ex situ)* of coral colonies in protected nurseries (artificial substrates)
- Nursery grown coral colonies are transplanted to degraded reef areas

A two steps restoration measure:
Step I: mid-water floating nursery

sea level 0

-6 m

-20 m

sea bottom
Strategies for nursery types

Attached to the bottom.....

Leg fixed
Step II: nutrient enriched area

The location…
7 months of in situ growth......
Hundreds of nubbins in the size of a single to few polyps each, can be produced from a single branching coral colony.

Under proper farming conditions, most of the nubbins survive and produce new coral colonies.

Step III: source material - nubbins
Coral fragments, even partially dead, may be used as an excellent source for nubbins. The use of 'corals of opportunity'
An untrained person produces 100 nubbins/h
Development of monocultures
- Reduced genetic heterogeneity
- No negative ecological impacts
- High survivorship
- No impact on reproduction of donor colonies
- Unlimited source material
- Availability-year round
- High numbers of added colonies per genotype
- Lower growth rates
- Longer mariculture periods

Ex situ work
Step IV: large quantities, thousands
About 7000 nubbins and branches from 4 coral genera were farmed in a nursery (6 m depth), about 10 m from the fish cages.

here is the start....
Fast growth of an *Acropora* branch within 400 days of nursery time
Favia favus

Growth of 160% in size within 9 nursery months
After 2 years in the nursery: large colonies of 20 cm in diameter have developed from the nubbins.
Mid-water coral nurseries – a source for new coral colonies

Tens of thousands of nubbins and branches from >85 coral species were already farmed in various nursery types, worldwide (the Philippines, Singapore, Thailand, Eilat-the Red Sea, Tanzania-Zanzibar & Mafia Islands, Seychelles, Mauritius, Colombia, Jamaica)
Step V: different nursery types, different needs
Rope nursery
One year results

*Acropora hemprichi*

*Pocillopora verrucosa*
M. digitata

P. frondifera

Thailand nursery
Depth adjustable nursery in Jamaica
The nursery- oasis in blue waters...

Step VI : floating artificial reefs
Hundreds of invertebrates that settle, develop, and reproduce in the nursery.
Step VII: nursery maintenance
Drupella cornus
Corals grow faster in an enriched nutrient environment, but fouling organisms too, some of them may harm the corals.
Step VIII: nurseries as larval dispersion hubs

Tens of millions of larvae/ nursery/reproductive season
Principles for nursery

- A protected area from divers, storms
- Away from the reef
- Preferably in a nutrient enriched area
- The use of nubbins and small branches to produce huge numbers of coral colonies
- Mid water nursery
- Multi-deck nursery
- Various type of nurseries
- Maintenance – with the aid of grazers
Step IX: new transplantation methodologies
Even there is no ‘phase shift’, reefs of today are not reefs of yesterday ... or tomorrow- Eilat as a study case

Fig. 6. Total number of colonies of seven common stony coral species in nineteen 10-m transects in 1969, 1973, and 2001. Data for 1969 and 1973 are linear interpolations from Loya (1975), who surveyed 21 transects. Species abbreviations are given in Fig. 5 at the Eilat Coral Beach Nature Reserve (northern Red Sea).
How to transplant?

E. lamellosa
D1 = 6 cm
D2 = 13 cm
D3 = 50-40 cm

M. digitata
D1 = 15 cm
D2 = 10 cm
D3 = 50-40 cm

P. damicornis
D1 = 7.5 cm
D2 = 10 cm
D3 = 50-40 cm

‘PATCH’ vs. ‘ORDERED’ TRANSPLANTATIONS
MONO- vs. MULTI (mixed vs. uniform) GENOTYPES
Thailand- transplantation on metal mesh with cable ties

On rubbles, soft bottoms
Bolinao, soft substrate -1y After
Rope nursery translocation in Bolinao.

Corals' transplantation.

5000 colonies in 1d by a team of 6 people.
Rope nursery - Bolinao

Transplantation

10 months later
Blending rope transplantation into the reef
Transplantation processes:

3 sets of repeated transplantations

<table>
<thead>
<tr>
<th>Transplantation</th>
<th>Number of colonies</th>
<th>Coral species</th>
<th>Transplanted on</th>
<th>Distances between colonies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (November 2005)</td>
<td>554</td>
<td><em>Stylophora pistillata</em>&lt;br&gt;<em>Pocilopora damicornis</em></td>
<td>5 knolls</td>
<td>20 cm</td>
</tr>
<tr>
<td>2 (May 2007)</td>
<td>316</td>
<td><em>Stylophora pistillata</em>&lt;br&gt;<em>Pocilopora damicornis</em>&lt;br&gt;<em>Acropora sp.</em>&lt;br&gt;<em>Millepora dichotoma</em></td>
<td>2 of previously transplanted knolls</td>
<td>10 cm</td>
</tr>
<tr>
<td>3 (September 2008)</td>
<td>530</td>
<td><em>Stylophora pistillata</em>&lt;br&gt;<em>Pocilopora damicornis</em>&lt;br&gt;<em>Acropora sp.</em>&lt;br&gt;<em>Millepora dichotoma</em></td>
<td>2 of previously transplanted knolls and 1 new knoll</td>
<td>10 cm</td>
</tr>
</tbody>
</table>
Long term survivor of transplants: all species

T1: Survivorship of 554 farmed transplants and 76 natal controls over 6 ys

T2: Survivorship of 306 farmed transplants and 103 natal controls over 4.5 ys
Single vs. repeated transplantation scheme:

Improved survival following repeated transplantations

Transplants survival over 3.2 ys

<table>
<thead>
<tr>
<th>Months after transplantation</th>
<th>Survival (%)</th>
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<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
</tr>
<tr>
<td>12</td>
<td>80</td>
</tr>
<tr>
<td>18</td>
<td>70</td>
</tr>
<tr>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>36</td>
<td>40</td>
</tr>
</tbody>
</table>

- Colonies added to previously transplanted plots
- Colonies from a single transplantation act
July 2011, 5 years following the restoration of denuded knolls in Dekel Beach, Eilat
**Transplants: contribution to larval pool**

Improved reproductive capacity compared to natal colonies – maintained over time

Average number of planulae / colony collected from natal and transplanted *S. pistillata*

Average planulae / colony collected from natal and transplanted *S. pistillata*

0-2 vs. 15-23

\[ \pm SE; \text{Mann-Whitney } P<0.05 \text{ after Bonferroni correction} \]
Coral Reef Restoration (Bolinao, Philippines) in the Face of Frequent Natural Catastrophes

Lee Shaish,1,2,3 Gideon Levy,1,2 Gadi Katzir,4 and Baruch Rinkevich1

Restoration operation dates and major weather events

1, monitoring dates for nursery; 2, monitoring dates for transplanted colonies

Step X: Reef restoration and global changes
The ‘gardening concept’ has faced four major obstructions, all are satisfactorily deciphered:

- Developing the needed credentials for farming a wide variety of coral species in mid-water nurseries
- The ability to develop stocks of coral colonies; employing the ‘nubbins’ methodology
- Documentation that nursery farmed coral colonies perform well in their ‘new homes’, following transplantation
- Verification of the low cost gardening approach (down to 0.17 and 0.19 US$/coral colony for farming and transplantation, phases, respectively)

Fifth challenge:
- Performing a large, ecologically profound restoration act (hundreds of thousands of coral colonies/site) to reveal the ecological engineering capacities of large-scale transplantation acts.
Boosting reef services (e.g., artificial reefs for fisheries) aiming to increase biodiversity (e.g., the concept of ‘assisted colonization’).
Thank you