# Experimental Assessment of Coral Reef Rehabilitation Following Blast Fishing

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**Abstract:** *Illegal fishing with explosives has damaged coral reefs throughout Southeast Asia. In addition to killing fish and other organisms, the blasts shatter coral skeletons, leaving fields of broken rubble that shift in the current, abrading or burying new coral recruits, and thereby slowing or preventing reef recovery. Successful restoration and rehabilitation efforts can contribute to coral reef conservation. We used field experiments to assess the effectiveness of different low-cost methods for coral reef rehabilitation in Komodo National Park (KNP), Indonesia. Our experiments were conducted at three different spatial scales. At a scale of 1 × 1 m plots, we tested three different rehabilitation methods: rock piles, cement slabs, and netting pinned to the rubble. Significantly more corals per square meter grew on rocks, followed by cement, netting, and untreated rubble, although many plots were scattered by strong water current or buried by rubble after 2.5 years. To test the benefits of the most successful treatment, rocks, at more realistic scales, we established 10 × 10 m plots of rock piles at each of our nine sites in 2000. Three years after installation, coverage by hard corals on the rocks continued to increase, although rehabilitation in high current areas remained the most difficult. In 2002 rehabilitation efforts in KNP were increased over 6000 $m^2$ to test four rock pile designs at each of four rubble field sites. Assuming that there is an adequate larval supply, using rocks for simple, low-budget, large-scale rehabilitation appears to be a viable option for restoring the structural foundation of damaged reefs.*

**Key Words:** coral reef recovery, Indonesian reefs, reef restoration

Evaluación Experimental de la Rehabilitación de Arrecifes de Coral Después de Pêsca con Explosivos

**Resumen:** *La pesca ilegal con explosivos ha dañado a arrecifes de coral en el sureste de Asia. Además de matar a peces y otros organismos, las explosiones destruyen esqueletos de corales, dejando campos de escombros rotos que se mueven con la corriente, erosionando o enterrando a reclutas de coral nuevos y por lo tanto disminuyen o previenen la recuperación del coral. Esfuerzos exitosos de restauración y rehabilitación pueden contribuir a la conservación de arrecifes de coral. Usamos experimentos de campo para evaluar la efectividad de diferentes métodos de bajo costo para la rehabilitación de arrecifes de coral en el Parque Nacional Komodo (PNK), Indonesia. Desarrollamos nuestros experimentos en tres escalas espaciales diferentes. A una escala de parcelas de 1 x 1 m, probamos tres métodos de rehabilitación: pilas de rocas, losas de cemento y redes sobre el escombro. Crecieron significativamente más corales por metro cuadrado sobre rocas, seguido por el cemento, redes y escombro sin tratamiento, aunque muchas parcelas fueron dispersadas por la fuerte corriente de agua o enterradas por escombros después de 2.5 años. Para probar los beneficios del tratamiento más exitoso, rocas, a escalas más realistas, en 2000 establecimos parcelas de 10 x10 m con pilas de rocas en cada unos de nuestros nueve sitios. Tres años después, la cobertura de corales duros sobre las rocas continuó incrementando, aunque la rehabilitación en áreas con corrientes fuertes fue la más difícil. En 2002, los esfuerzos de rehabilitación en PNK se incrementaron a 6000 $m^2$ para probar cuatro diseños de pilas de rocas*

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*Paper submitted June 12, 2003; revised manuscript accepted May 18, 2004.*

*en cada uno de los cuatro sitios con escombros. Asumiendo que hay una adecuada existencia de larvas, la utilización de rocas para rehabilitación simple, de bajo costo y gran escala parece ser una opción viable para la restauración de la base estructural de arrecifes dañados.*

**Palabras Clave:** arrecifes de Indonesia, recuperación de arrecife de coral, restauración de arrecifes

## Introduction

The island archipelagos of Indonesia and the Philippines contain the world's highest diversity of coral species and many reef-dependent organisms (Veron 1994; Burke et al. 2002). Unfortunately, reef ecosystems throughout Southeast Asia are severely threatened by increased pressures from rapid population and economic growth (Chou 1997). Furthermore, few of the designated marine protected areas are effectively managed (Wilkinson et al. 1994; Gomez 1997; Wilkinson & Chou 1997; Spalding et al. 2001). It is estimated that Indonesia's coral reefs comprise 18% of the world's total, yet more than 85% of Indonesian reefs are threatened by anthropogenic impacts (Richmond 1993; Burke et al. 2002). Many of these impacts, which include pollution and eutrophication (Tomascik & Sander 1987; Edinger et al. 1998; Kinsey 1988), cyanide fishing and overfishing (McManus et al. 1997; Mous et al. 2000; Jackson et al. 2001), and bleaching (Hoegh-Guldberg 1999), leave the underlying skeletal framework of the reef intact, so future settlement and recruitment could potentially lead to reef recovery if the stresses were removed. In contrast, dynamite or blast fishing is an especially insidious form of destructive fishing (Mous et al. 2000) that removes the resource itself (fish and invertebrate stocks) and destroys the coral reef (Pauly et al. 1989). Blast fishing was banned in Indonesia in 1985 but is still widespread (Djohani 1995).

One of the most serious impacts of extensive blast fishing is that new scleractinian coral colonies are slow to grow back in the shifting fields of dead coral rubble that result, even when an area is protected from further blasting (Alcala & Gomez 1987; Yap & Gomez 1988; McManus et al. 1997; Fox et al. 2003). Large areas of shifting rubble hinder successful coral recruitment, especially in areas with strong currents or wave action (Pearson 1981; Yap & Gomez 1988; Clark & Edwards 1995; Fox et al. 2003). In addition, few fish recolonize the area because of the lack of coral structure after blasting (Jones & Syms 1998).

## Reef Rehabilitation as a Potential Solution

Coral reefs are among the most complicated habitats to restore (Yap 2000), and reef restoration projects number in the tens, as compared with the thousands that have been implemented for terrestrial and wetland systems (Precht 2001). Techniques that have been explored to restore damaged coral reefs include transplantation of living coral colonies or cultivation of coral "gardens" (Harriott & Fisk 1995; Rinkevich 2000), branching ceramic stoneware modules (Moore & Erdmann 2002), and electrolysis to accelerate the deposition of calcium carbonate and enhance the growth of transplanted coral (Hilbertz 1992; van Treeck & Schuhmacher 1997, 1999). Restoration techniques for ship groundings, which produce rubble substrate similar to blasting, include reef framework stabilization, topography rebuilding with specialized cement, and transplantation (Hudson & Diaz 1988; Precht 1998; Hudson & Spadoni 2000). Reef community rehabilitation has also been attempted through removal of macroalgae (McClanahan et al. 2001) or bioeroding urchins (McClanahan et al. 1996).

Unfortunately, most rehabilitation techniques are expensive and labor intensive, and can still result in high mortality of coral transplants (Clark & Edwards 1995; Harriott & Fisk 1995; Edwards & Clark 1998). Researchers comparing various coral restoration methods found that costs could range from US$13,000 to more than US$100 million/ha (Spurgeon & Lindahl 2000). Not surprisingly, the most expensive methods are unsuitable for the limited conservation resources of developing countries, although there are some less expensive techniques that rely on "low-tech" transplantation of fast-growing *Acropora* fragments (Lindahl 1998; Bowden-Kerby 2001). However, most transplantation techniques are inappropriate for the shifting rubble fields created by blast fishing in high-current areas. Clark and Edwards (1995) found that stabilizing rubble substrate with concrete mats (onto which new coral larvae settled) resulted in recovery comparable to that of transplanting coral colonies to the concrete mats.

Management options include rehabilitation (i.e., enhancing natural recovery through substrate stabilization) and restoration (i.e., reestablishing the structural, geological, biological, and aesthetic aspects of the reef) (Precht 1998). We believe that rehabilitation is more pragmatic and cost-effective in the long term. For such rehabilitation efforts to be merited, criteria that should be met include cessation of the damage (i.e., effective enforcement of the blast fishing ban), low natural recovery, adequate source of coral larvae, and good water quality (Edwards & Clark 1998). Komodo National Park (KNP) in Indonesia meets these criteria. Despite decreased blast fishing, high coral recruitment to settlement tiles, and little land-based pollution, recovery of blasted corals in KNP is slow. The strong currents in the park cause rubble motion, which in turn damages juvenile corals and inhibits natural recovery (Fox et al. 2003). Because most of the park's reefs are not recruitment-limited (Fox 2004), transplantation was considered unnecessary. In addition, KNP has high biodiversity, tourism potential as a premier dive destination, and park management personnel who are committed to conservation and rehabilitation of damaged areas (Pet & Yeager 2000), all of which make reef rehabilitation worth pursuing.

## Methods

### Study Area and Research Sites

The KNP is located in eastern Indonesia between the major islands of Sumbawa and Flores (Fig. 1). It is a large (>170,000 ha) and unusually diverse park that encompasses areas where blast fishing has occurred at varying levels since the early 1950s (Pet 1997). The diverse underwater environments within a relatively small area make studies of coral reef regeneration under a range of conditions possible. In 1995, at the request of the Indonesian government, The Nature Conservancy (TNC) conducted a rapid ecological assessment of the region. They found very high coral and fish diversity (253 and 734 species, respectively), and even higher biodiversity has been estimated (Holthus 1995). The assessment also showed that more than 50% of the coral reefs inside the park had suffered damage from destructive fishing practices, primarily blast fishing but also cyanide fishing and reef gleaning or "meting" (harvesting organisms that hide among corals) (Holthus 1995; Pet 1997).

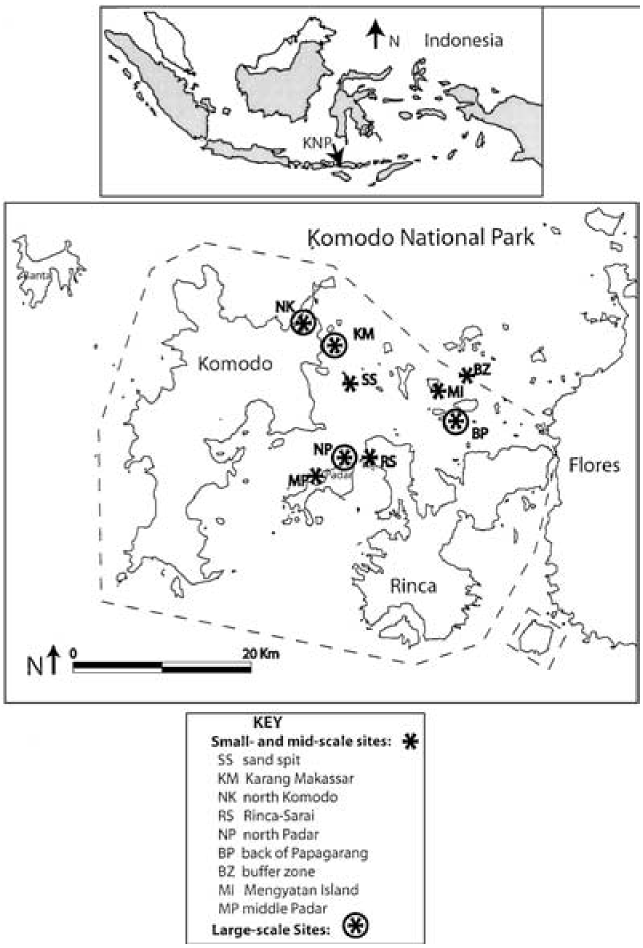


*Figure 1. Maps of Indonesia and Komodo National Park showing locations of sites for small-, mid-, and large-scale rehabilitation of blasted coral reefs (asterisks and circled asterisks). Park boundary is marked with dashed lines.*

In 1996 TNC began assisting authorities in protecting the marine areas of KNP. Weekly patrols were established to monitor marine resource extractive activities in the park and enforce the ban on destructive fishing practices. Based on resource use surveys, dynamite fishing in the park decreased by 75% in 1996, the year regular patrolling began (Pet 1999). These patrols effectively reduce other destructive fishing practices, such as cyanide fishing for the aquarium and live reef fish trades (Pet 1999). The increased law enforcement and community awareness has resulted in a shift from low-income fishing for local markets (dynamited fish) to high-income fishing for export markets (live reef fish and fresh chilled pelagics) (Cesar 1996; Pet 1999). The Nature Conservancy and park staff can effectively protect sites in the no-take zones, which makes coral rehabilitation at ecologically significant scales a sensible approach. Nine sites were selected from rubble fields with areas of ~500–3000 $m^2$ and ~6–10 m deep, that were presumed to have been created by chronic blasting (identified from TNC's coral monitoring program, see Fox et al. 2001). These sites spanned the northeastern quadrant of the park and represented a variety of current strengths (Fig. 1). To the best of our knowledge, no additional blasting occurred at any of our research sites.

Currents in KNP are tidal, and at most sites the current reverses direction with the semidiurnal tides (although because of local topography, current at some sites flows predominantly in only one direction). Relative current strength (low, medium, or high; three sites each) was measured using dissolving plaster-of-paris blocks (~45 g initial weight, three hemispherical blocks per site at each of three separate 24-hour time periods) (Jokiel & Morrissey 1993). Point estimates of flow speed were taken opportunistically at each site with a standard mechanical flow meter (General Oceanics, Miami, Florida; model 2030R); current speeds at the different sites varied from <5 cm/second to >90 cm/second.

The Indonesian Archipelago is governed by southeast and northwest monsoon systems (approximately March to October and November to February, respectively), but for brevity, field seasons that occurred in March and April are referred to as "spring" and those in October and November are designated as "fall."

### Small-Scale Experiment (1 m$^2$)

We compared three substrate stabilization treatments in replicate ~1 × 1 m pilot plots: (1) wide-mesh fishing net (~5 cm mesh) attached to the rubble with U-shaped rebar pins; (2) cement slabs pinned to the rubble; (3) piles of rocks on top of the rubble. Rocks were not attached to the rubble; piles were 20–40 cm high (individual rocks were 20–30 cm diameter, on average). Each substrate was made of locally available materials and varied in the extent to which it stabilized loose rubble, projected above the rubble surface, and increased substrate complexity. We installed two to four replicates of each treatment and four untreated control plots (1 × 1 m permanently marked bare rubble quadrats) at each blast site. Plots at sites NK, BZ, and NP were established in March and April 1998 and established at the remaining 6 sites (SS, KM, RS, BP, MI, MP) in October and November 1998. We monitored sites every 6 months until spring 2001. Location, size, life-form, and taxon of all visible hard corals recruiting to the different treatments and the control untreated plots were recorded (English et al. 1997). Cover of soft coral or other dominant benthos was also estimated. We recorded material costs, time, and labor necessary to install each treatment for cost-benefit analyses. Nonparametric statistical analyses (Kruskall-Wallis test) were performed to determine differences in coral recruitment and coverage on each substrate stabilization treatment from spring 1999 to spring 2001 (Fig. 2).

### Mid-Scale Study (100 m$^2$)

Because many of the small pilot treatments broke apart or were buried after 2.5 years (see Results) and because any serious rehabilitation effort would need to work at scales >1 m$^2$, larger substrate stabilization treatments were initiated with the most practical and successful small-scale treatment. The rock piles were the best candidates for the mid-scale studies because they had the highest coral recruitment, were easiest to pile above the surface of the rubble, and were the most natural substrate. They were less expensive than cement and required no advance construction.

Replicate rock piles (three or four per site) were installed within a 10 × 10 m area near the plots for the small-scale experiment in each of the nine blast sites in April and May 2000. The rocks, limestone and lithic sandstone (G. Brimhall, personal communication) were quarried from nearby sources in western Flores and transported via a local cargo boat. The boat anchored over a preselected rubble site with little live coral nearby. The

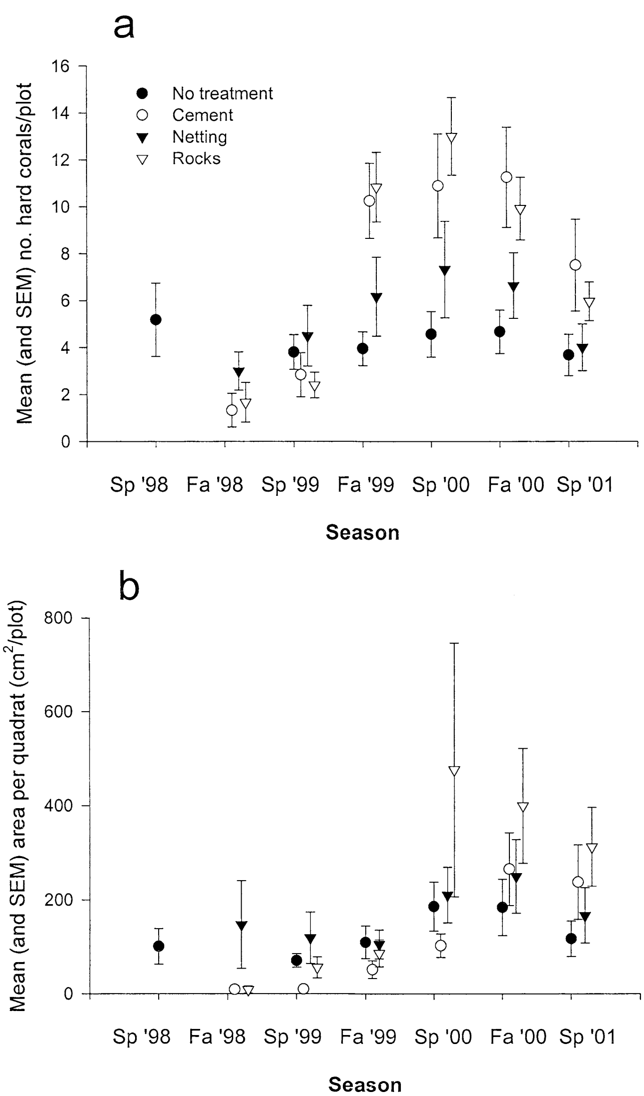


*Figure 2. Recruitment and growth of corals onto the three small-scale pilot treatments (cement, netting, and rock piles) and control plots over 3 years: (a) mean (and SEM) number of coral recruits per plot and (b) mean (and SEM) total area (cm$^2$) of coral recruits per plot (abbreviations: Sp, spring; Fa, Fall).*

site was marked with a small, temporary buoy, and rocks were thrown overboard and then consolidated by scuba divers to form piles. The rock mounds (0.5–2.0 m$^3$ total volume, spaced 2–4 m apart) were piled 70–90 cm high in an attempt to prevent them from being buried by rubble as had occurred at some of the small pilot plots.

The rock piles were surveyed every 6 months after installation until May 2002 and again in March 2003 (Figs. 3 & 4). The number, size, life-form, and taxon of scleractinian coral recruits were recorded for six 1 × 1 m quadrats per site (1–3 per rock pile) by one of four observers trained in recognizing coral life-form categories (margin of error <10%; English et al. 1997). Cover of soft

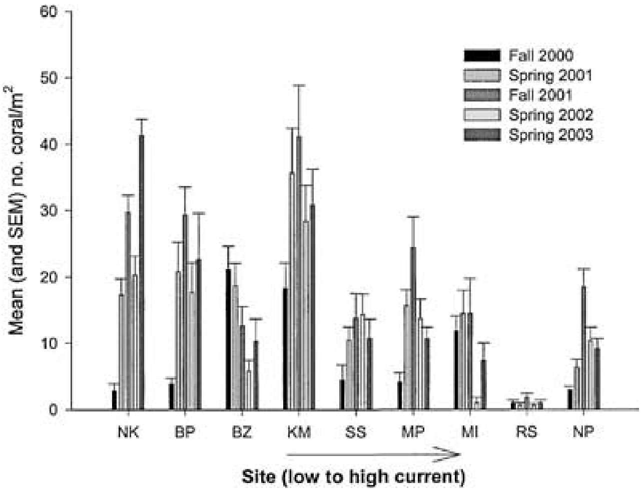


*Figure 3. Mean (and SEM) number of coral recruits onto the mid-scale rock piles from fall 2000 to spring 2002. Piles were installed spring 2000. Site abbreviations defined in Fig. 1 key.*

coral and other prominent benthic colonizers was also noted. Size of the rock piles (length, width, height, and circumference) was measured during each survey, except spring 2002, to calculate rock pile volume and thus measure persistence of the piles. Data from the six quadrats within a site were pooled for analyses. We square-root transformed data to homogenize variances (Zar 1984) and performed two-way analyses of variance (ANOVAs) to investigate differences in area covered by hard corals over time.

### Large-Scale Study (>1000 m$^2$)

The areas surrounding the rock pile sites were surveyed in November 2001 for suitability for large-scale installation (i.e., large stretches of rubble with little live coral cover so rocks could be unloaded from the cargo boats with a minimum of damage to live coral). Based on these surveys and the recruitment and soft coral data, four sites were chosen for large-scale substrate stabilization (Fig. 1). Installation took place from March to September 2002. We tested four rock pile designs, each with the same total volume of rock (~140 m$^3$), to determine the configuration that best resists rubble encroachment and gives the best ecosystem recovery for the same cost. The four designs installed at each site were (1) complete coverage (~75 cm high), (2) rock piles (1–2 m$^3$ spaced every 2–3 m), (3) "spur and groove" morphology parallel to the prevailing current, and (4) spur and groove perpendicular to the current (spurs ~75 cm high, 2 m wide, spaced every 2–3 m). These latter two designs were based on the fact that on some reefs with high wave energy, spurs and grooves naturally form perpendicular to the waves, with the spurs, or ridges, breaking the force of the waves and the grooves, or valleys, allowing the channeling of sand.

The large-scale study sites were surveyed in March 2003. At each of the four sites, the area covered by the rehabilitation treatments was measured. We video recorded transects to assess coral cover on each treatment and a control (bare rubble field) at each site. We filmed stationary video to assess fish populations at each treatment and at a control plot at each site (Fig. 5). To avoid disturbances to the fish, no diver was nearby during the filming. Coral recruitment was surveyed (using methodology described in the mid-scale study) in six 1 × 1 m quadrats at the design installed first at each site (site abbreviation [Fig. 1] and treatment: BP, complete coverage; KM, parallel to current; NK, perpendicular to current; NP, rock piles).

## Results

### Small-Scale Experiment

Stabilizing the substrate had a significant effect on coral recruitment. Initially there was no difference between treatments, but recruitment to the substrate stabilization treatments diverged over time. During the first 3 years, the rock stabilization plots had the highest hard coral recruitment and cover, followed by cement and netting, and last, by untreated rubble (Fig. 2; Kruskal-Wallis test on counts: $H = 43.64$; df = 3, 524; $p < 0.0001$; areas: $H = 11.75$; df = 3, 524; $p < 0.01$). After 2.5 years, some coral colonies on rock and cement piles were 20–30 cm in diameter. With increased time since installation, however, many of the treatment plots became degraded. Many of the netting plots, which had the lowest profile, were scoured or buried by shifting rubble. Rock piles became scattered, cement slabs flipped over or were broken by the current, and all treatments were vulnerable to being overgrown by soft coral or buried by the shifting rubble. In the untreated rubble control plots, the numbers and sizes of coral juveniles were consistently low over 3 years. Neither numbers nor area covered by small scleractinian colonies increased at rubble sites from spring 1999 to spring 2001 (Fig. 2 and ANOVA on log-transformed counts: $F = 0.355$; df = 4, 181; $p = 0.85$; area: $F = 0.726$; df = 4, 181; $p = 0.58$).

### Mid-Scale Study

Recruitment of hard coral and cover increased significantly in the mid-scale studies. The rock piles quickly developed a "biofilm" and were colonized by coralline algae and other encrusting organisms. Scleractinian recruits had settled on the rock piles by the first survey (5 months after installation). Within 1 year there were many hard coral recruits 2–4 cm in diameter. For the first 18 months, most sites had increasing numbers of coral recruits (Fig. 3). After 2 years, the numbers of colonies had stopped increasing and in most cases decreased, although

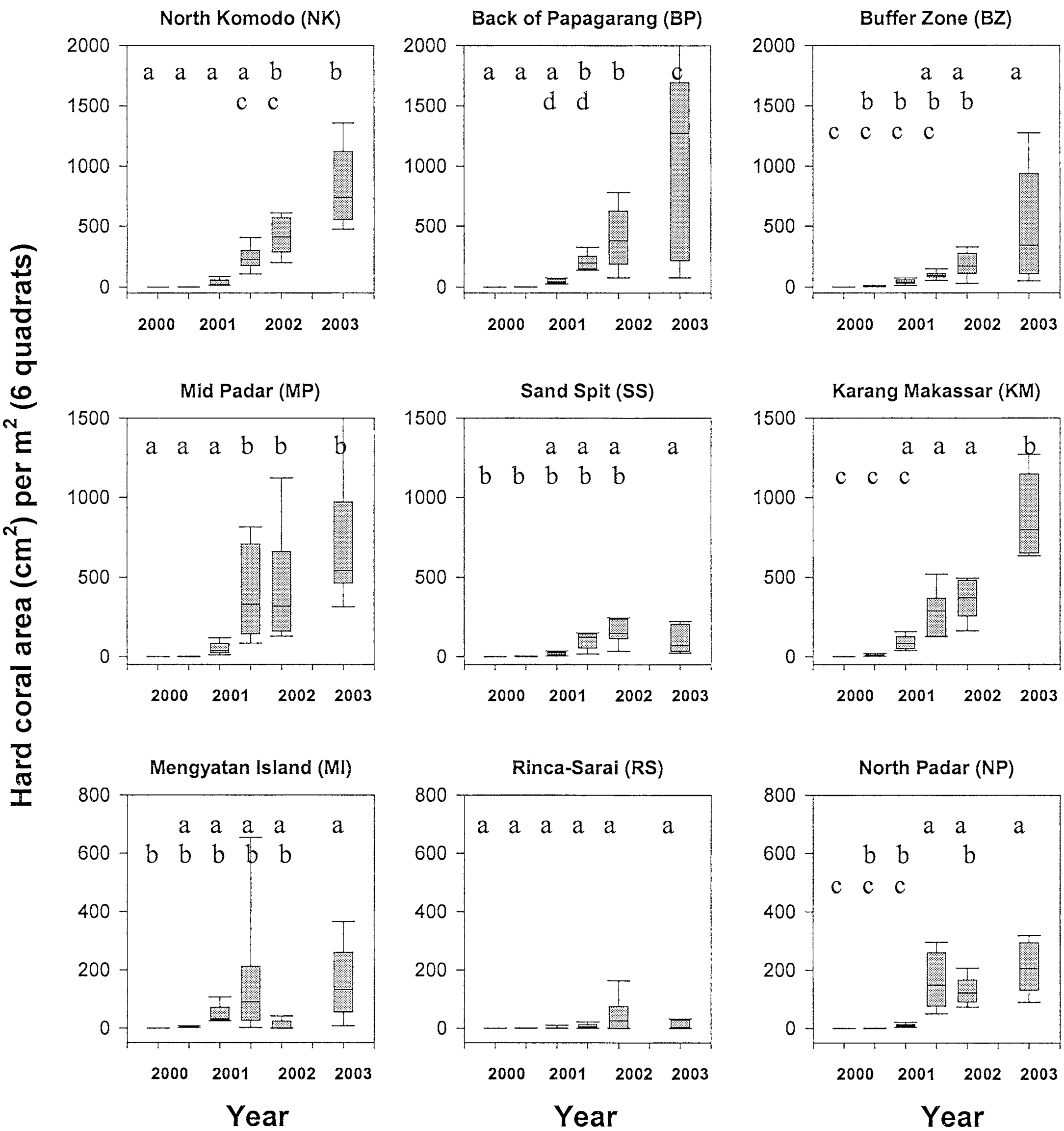


*Figure 4. Hard coral area on mid-scale rock piles in six 1 × 1 m quadrats from spring 2000 (date of rock installation, thus zero hard coral area) to spring 2003. Sites were surveyed in spring and fall in 2000 and 2001 and in spring only in 2002 and 2003. The boundary of the bar closest to zero indicates the 25th percentile, a line within the bar marks the median, and the boundary of the bar farthest from zero indicates the 75th percentile. Whiskers above and below the bars indicate the 90th and 10th percentiles. Graphs are arranged by current level: low current, top row; medium current, middle row; high current, bottom row. The scales are different on the y-axis. High current sites have lower coral cover. Also shown is the summary of significant differences in mean area covered by hard corals per square meter on each rock pile (square-root transformed) between seasons at each site (Tukey's honestly significantly different). Seasons that share letters (top of each graph) are not significantly different from one another.*

the total coral area continued to increase. The range in numbers of recruits across the sites was wide, from an average of <1 colony/m$^2$ (site RS) to > 40/m$^2$ (site NK) in the spring 2003 survey (Fig. 3). Scleractinian recruits to the rock piles were primarily branching corals, dominated by the family Pocilloporidae and the genus *Acropora*, with fewer *Montipora*, Poritidae, or other massive coral recruits.

Although the numbers of recruits had decreased by spring 2002, on average colonies were larger. The total area covered by hard corals on the large rock piles continued to increase over time, with total area increasing at each survey and reaching the highest area in spring 2003, the most recent survey, at most sites. Area increased on average 464% from spring 2001 to fall 2001, 77% from fall 2001 to spring 2002, and 216% from spring 2002 to

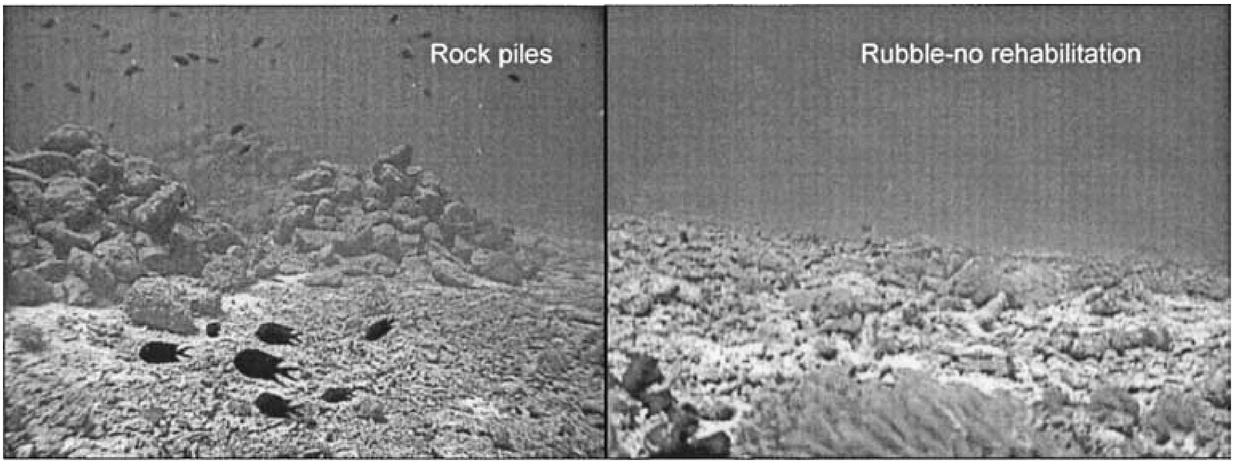


*Figure 5. Pictures from a videotape of a rehabilitation treatment (rock piles) and rubble control at site BP (back of Papagarang). No diver was present during the filming.*

spring 2003 (Fig. 4; Table 1). During the same time period, no increase in coral cover was detected in control rubble quadrats.

At some high-current sites, however, the 2002 and 2003 surveys showed a decrease in hard coral area. In general, sites with the highest current (MI, NP, and RS) had low coral cover on rocks or decreased cover with time, or both (Fig. 4). Volume of the rock piles did not decrease significantly 3 years after initial installation across all sites (one-way ANOVA, df $= 4$, $F = 1.82$, $p = 0.13$), although there was a decrease at high-current sites.

In addition to rubble burying the rock piles, at some sites soft corals (primarily *Xenia* spp.) colonized and grew very quickly. Although no correlation existed between soft coral cover and hard coral cover during the same season ($p = 0.38$, Pearson correlations), a significant negative correlation existed between soft coral cover in fall 2001 and numbers of hard coral recruits the following season ($p < 0.05$, Pearson correlations). Many other sessile and mobile organisms colonized or utilized the rock piles, including algae; sponges; tunicates; echinoderms (crinoids, echinoids, and holothurians); *Trochus; Octopus cyanea;* various fishes; and in one case, an anemone ~1 m in diameter.

### Large-Scale Study

The large rock rehabilitation treatments, designed to minimize the problems of burial or scattering encountered in the pilot studies, transformed large areas of rubble into more structured habitats. Approximately 6430 m$^2$ of dead coral rubble was covered with the four designs at the four locations. Scleractinian recruits quickly settled on the rock piles, with considerable recruitment of hard corals after approximately 1 year (mean 7.3 recruits/m$^2$; mean size of recruits 7.5 cm$^2$ across all sites). By site, the mean number of recruits per square meter ranged from 3.5 (site NP) to 14.2 (site BP); maximum sizes ranged from a mean of 2.7 cm$^2$ (site KM) to 10.7 cm$^2$ (site NP). Observations of fish populations showed higher numbers and diversity at the rocks than on the rubble (Fig. 5). Fish appeared to be using the rocks as refuge. Taxa observed included grouper (Serranidae), anthias (Anthiinae), damselfish and chromis (Pomacentridae), surgeonfish (Acanthuridae), parrotfish (Scaridae), stonefish (Scorpaenidae), fusilirs (Caesionidae), and Moorish idols (*Zanclus cornutus*).

## Discussion

Our results indicate that coral recruitment can be greatly enhanced by creating stable, spatially complex structures that are high enough above reef rubble to minimize burial and abrasion. At all nine sites, chosen to broadly represent rubble fields in the park, coral recruitment was greater at rock and cement pilot treatments compared with untreated bare rubble or netting treatments. In some cases, recruitment (number of colonies per square meter) was

**Table 1. Two-way analysis of variance of the effect of site and season[a] on mean area covered by hard corals (cm$^2$/m$^2$) on mid-scale rock piles.[b]**

| *Source* | *df* | *SS* | *MS* | F | p |
|---|---|---|---|---|---|
| Season | 5 | 14504 | 2900.8 | 140.83 | <0.001 |
| Site | 8 | 4004.3 | 500.5 | 24.3 | <0.001 |
| Season × site | 40 | 4351.4 | 108.8 | 5.28 | <0.001 |
| Error | 269 | 5540.6 | 20.6 | | |
| Total | 322 | 28400.4 | | | |

[a] *Measured every 6 months from installation in spring 2000 to spring 2002 and again in spring 2003.*
[b] *Data are square-root transformed. See Fig. 4 for pairwise comparisons.*

more than 20 times higher in the experimental plots than on untreated rubble. Both cement slabs and rocks, however, were eventually broken up or encroached on by rubble because of strong currents. The mid-scale rock piles, designed to minimize the problems of burial or scattering encountered in the small-scale experiment, showed better persistence than the small plots. Hard corals showed considerable recruitment after only 6 months (Fig. 3), with 10–20 recruits/$m^2$ at some sites. This rapid colonization confirms that transplantation is probably unnecessary in KNP and that creating stable, three-dimensional substrate may be sufficient to enhance natural coral recruitment, as suggested by Edwards and Clark (1998). At some sites, soft coral impeded hard coral recruitment because few hard coral colonies were found beneath the soft coral canopy. The significant negative correlation between soft coral cover in fall 2001 and numbers of hard coral recruits the following season may suggest that existing soft coral impedes hard coral recruitment more than growth. Other differences between sites may play a greater role in determining coral cover.

The average number of recruits across all sites (12.46/$m^2$ after 2 years) was comparable to that found in a comparison of several methods in the Maldives (11.9–13.0 recruits/$m^2$ after 3.5 years [Clark & Edwards 1999]). In a study of coral recruitment onto a concrete pillar near Singapore, 16.4 corals/$m^2$ covered ~31% of the surface after 11 years (Chou & Lim 1986). More important than increasing numbers of corals to the rock rehabilitation treatments, the total area covered by hard corals also increased at all sites except those with the strongest currents, suggesting that the process of rebuilding the reef has begun (Fig. 4).

Rehabilitation in areas with coral rubble and strong currents, steep slopes, or wave action is especially challenging because the motion of the rubble, which impedes natural coral recovery, also fills in or buries the substrate stabilization treatments (Clark & Edwards 1999). Despite the difficulties this loose rubble and sand caused, it was clear after initial inspection of the sites that it would not have been feasible to remove the rubble from the seabed because of the extent and depth of the rubble fields. Although no predisturbance baseline data on coral cover exist, data from park patrols, oral histories, and eyewitness accounts suggest that these extensive rubble fields resulted from blast fishing, rather than other causes. Observers familiar with blast damage concur that the rubble fields point to chronic blast fishing in the past. Furthermore, KNP is not within a cyclone belt, and is generally well protected from major storm damage. This means that not only are the rubble fields unlikely to have been created by storms, but that the rehabilitation treatments are unlikely to be disturbed by cyclonic storm events in the future.

Our results indicate that there is good potential to rehabilitate destroyed reefs in KNP by enhancing coral recruitment with stabilization of the loose rubble and re-creation of solid, structurally complex substrate. The gradual failure of our small-scale, 1-$m^2$ treatments showed that we need continued monitoring of recruitment to and persistence in the mid-scale treatments, which have appeared successful thus far. Our large-scale manipulations also suggest great promise for rock piles as a rehabilitation strategy, albeit with some caveats. At this early stage we cannot determine which treatment design will result in the greatest long-term coral recovery or fish abundance.

The different large-scale designs had different potential strengths and weaknesses. A relatively high solid coverage of rocks (method 1) may keep rubble out, but this method covered the least area per cubic meter of rock. Piles of rock (method 2) covered the most area per cubic meter but left the most rubble free to move in the stabilized area. A spur and groove system parallel to the direction of flow (method 3) might allow the buildup of coral on the spurs and the “flushing through” of rubble in the grooves where rubble motion is fairly unidirectional (as with a steep slope or some currents). Alternatively, a spur and groove system perpendicular to the direction of flow (method 4) might generate turbulent flow and eddies as they block the current, enhancing settlement of coral larvae from the water column. The different configurations of rocks resulted in different areas covered, for a total of ~1500 $m^2$ stabilized at each site. By testing the different large-scale rock designs, further insight can be gained into the variables important for reef recovery in rubble fields.

Economically, substrate stabilization using locally available rock compares favorably with other methods. Specially formulated cement used to restore ship-grounding sites in Florida costs more than US$1500/$m^3$ (Hudson & Spadoni 2000). Extrapolating from experimental studies, rehabilitation treatments in the Maldives cost from US$40 to US$160/$m^2$, and rehabilitation projects in the Florida Keys National Marine Sanctuary cost from US$550 to more than US$10,000/$m^2$, clearly unreasonable for large-scale rehabilitation in developing countries (Spurgeon & Lindahl 2000). EcoReefs, which are branching ceramic stoneware modules, cost ~$US70/$m^2$ for materials alone (Moore & Erdmann 2002), and comparably sized hollow cement Reef Balls cost more than US$40/$m^2$ for materials and ~US$1000 for each mold (Reef Ball Foundation 2004). In our study, rocks were the least expensive treatment at an approximate cost of US$5/$m^2$, including materials, transportation, boat rental, and labor. Costs could be reduced in larger scale application through economy of scale, potentially decreasing these costs by half or more (by, for example, negotiating a better rate or having a boat built and a crew hired specifically for the project). Admittedly, these costs are considerably cheaper in Indonesia than in other parts of the world, and projects in low-lying atolls, such as those in the Maldives, would not have access to rock quarries.

Dynamite fishing has been calculated to cause a net loss of income from fisheries, coastal protection, and tourism potential of between US$33,900 and US$306,800/km$^2$ of coral reef over 20 years (Pet-Soede et al. 1999). Estimates of total lost income for all of Indonesia range from >US$570 million (Burke et al. 2002) to >US$3 billion (Pet-Soede et al. 1999). Programs that successfully decrease this destructive fishing practice and restore value to the ecosystem are critical, both economically and biologically.

In addition to the ultimate goal of increasing coral and fish biomass, coral rehabilitation projects can have further benefits. Involving the community and park rangers can create a necessary sense of responsibility for managing and protecting coral reef resources and educate people about the importance of healthy reefs. Reef stabilization treatments also have tourism potential for divers and snorkelers. Rehabilitation is more likely to be effective in conjunction with other restoration techniques such as fisheries reform and reduced fishing pressure (Maragos 1992). Given that marine reserves are widely accepted as one of the most practical and effective methods of managing coral reef fisheries and preserving coral reef resources (Birkeland 1997; Roberts 1997), it makes sense to concentrate efforts to rehabilitate damaged areas in existing parks and to successfully enforce regulations and implement alternative livelihood programs. The relatively inexpensive and effective method for stabilizing rubble and enhancing coral reef recovery described in this paper could be incorporated in park reef-management programs and aid in restoring economic and ecological value to these remarkable ecosystems.

## Acknowledgments

We thank the Indonesian Institute of Sciences (LIPI), R. Dahuri, and the staff of KNP and TNC, Komodo Field Office. This work was funded by grants from The Packard Foundation, The Nature Conservancy/Mellon Foundation Ecosystem Research Program, the University of California's Pacific Rim Research Program, and the International Society for Reef Studies, as well as by National Science Foundation grant INT98-19837. E. Maloney and C. Huffard provided excellent assistance in the field; R. Caldwell, W. Getz, M. Gleason, P. Karieva, C. Roberts, R. Robison, W. Sousa, and two anonymous reviewers provided helpful comments on the manuscript.

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