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RECOVERY FROM BLAST FISHING ON CORAL REEFS: A TALE OF TWO SCALES

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Abstract. Dynamite or "blast" fishing is one of the most immediate and destructive threats to coral reefs worldwide. However, little is known about the long-term ecosystem effects of such blasts or the dynamics of recovery. Here, we examine coral reef recovery in the simplest case of acute single blasts of known age, as well as recovery from chronic blasting over greater spatial and temporal scales. Rubble resulting from single blasts slowly stabilized, and craters filled in with surrounding coral and new colonies. After five years, coral cover within craters no longer differed significantly from control plots. In contrast, extensively bombed areas showed no significant recovery over the six years of this study, despite adequate supply of coral larvae. After extensive blasting, the resulting coral rubble shifts in ocean currents, forming unstable "killing fields" for new recruits. While recently tested rehabilitation methods might be feasible on a small scale, human intervention is unlikely to be effective on large spatial scales, highlighting the need for effective management to prevent blast fishing in the first place.

Key words: conservation; coral reefs; disturbance; dynamite or bomb fishing; Indonesia; marine ecology; recovery.

Introduction

Disturbance is a natural structuring force in both terrestrial and aquatic communities, with disturbed patches undergoing cycles of removal and recovery leading to spatial heterogeneity (Sousa 1984, 2001, Done 1992, Connell 1997). Whether a disturbance is acute or chronic has significant implications for the disturbed ecosystem's time frame for recovery, with lower chances for recovery after chronic, long-term disturbances (Connell 1997) or after a phase shift from one major community to another (e.g., from coral-dominated to algal-dominated reefs [Hughes et al. 2005]). Hard corals (primarily Scleractinia) form the biological and structural foundations of coral reef ecosystems, and can recover rapidly if communities are adapted to high disturbance regimes or if stable and complex substrate remains to facilitate recruitment (Colgan 1987, Dollar and Tribble 1993, Tomascik et al. 1996). However, blast fishing is an anthropogenic disturbance that physically alters the reef structure. The detonation of homemade bombs not only kills fish but also shatters the coral skeletons, creating expanses of unstable coral rubble (Alcala and Gomez 1987) that reduces survival of coral recruits (Fox et al. 2003). Furthermore, the removal of the targeted herbivorous fish is likely to reduce the resilience of the reefs to climate change and other impacts, further hampering recovery (Hughes et al. 2003). Blast fishing is illegal but widespread, and a major threat to reefs (McManus et al. 1997, Erdmann 2000), with destructive fishing estimated to threaten over 50% of reefs in Southeast Asia (Burke et al. 2002). Coral fragments that are not killed by the blast directly may experience further post-disturbance mortality in the shifting rubble (Knowlton et al. 1981, Munro et al. 1987).

Other impacts on reefs, both anthropogenic and natural, can result in similar broken reef framework and rubble, including ship groundings, "meting" or reef gleaning, coral mining, trampling, severe hurricane damage, and tsunamis. However, the recent Sumatra-Andaman Tsunami caused far less damage to coral reefs than past destructive fishing had (Baird et al. 2005). Estimates of recovery from severe storm damage range from 10 years if the substrate remains intact (Connell 1997) to 40–70 years (Dollar and Tribble 1993). Although little is known about the long-term ecosystem effects of blast fishing or the dynamics of recovery (Jennings and Lock 1996, Connell 1997), the recovery

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period for blast and ship grounding sites is estimated at 100–160 years (Riegl 2001), and may well be extended to centuries or more in high current areas.

Although recovery from blasting has been modeled (Saila et al. 1993, McManus et al. 1997) and levels of biological or economic impact have been assessed (Riegl and Luke 1998, Pet-Soede et al. 1999), field studies of recovery from blast fishing are rare. Here we report empirical results from a remote area in Indonesia where fishing with homemade bombs still occurs. In early April 1999, we observed two bomb fishermen in Pulau Tiga using a kerosene–fertilizer mix in 300-mL glass soda bottles with homemade fuses. The fishermen collected several kilograms of the targeted reef fish per blast (Fox and Erdmann 2000). Hours after the blasts, we surveyed the reef using SCUBA, marked the approximate center of each of the resulting six craters, and measured the size of damaged areas. We returned to these sites repeatedly over the subsequent five years to measure the dynamics of coral recovery.

Cases of single, isolated bombs are rare in Southeast Asia, however. We therefore also examined natural recovery in nine rubble fields created by chronic blasting in Komodo National Park (KNP), where blasting had taken place over a number of decades, impacting more than half the coral reefs before the start of The Nature Conservancy's involvement in KNP (Holthus 1995).

METHODS

Study sites.—Single blasts of known age were studied in an area known locally as Pulau Tiga (00°52′ N, 123°48′ E) ~135 km southwest of the city of Manado, Sulawesi, Indonesia. Research on large rubble fields produced by chronic blasting was conducted in Komodo National Park, between the islands of Sumbawa and Flores (08°29–38′ S, 119°33–43′ E). Although the sites vary in latitude by ~9°, we believe the differences in physical impacts of single vs. chronic blasting override any differences due to geography; also, more closely matched sites were not feasible given field logistics.

Small scale: single blast studies.—Blasts occurred in water ~5–10 m deep, and we infer that the bombs detonated on the substrate. Within a radius of approximately 0.5–1.5 m from the blast epicenter (hereafter, the "rubble zone"), the impact of the explosion shattered scleractinian corals into small rubble (1–10 cm). Surrounding the rubble zone, coral colonies had broken into larger pieces (10–50 cm) 1.5–4.0 m away from the epicenter ("the broken zone"). To track crater size, we measured the radial distance from the epicenter to the edge of the rubble and broken zones at 30° increments. The porosity of the rubble was assessed by measuring penetration depth of a pointed metal skewer (~0.5×30 cm; Good Cook Metal Skewers, Bradshaw International, Rancho Cucamonga, California, USA) inserted vertically through the rubble until it could be pushed no further ($n = \sim 20$ per crater). We also visually surveyed the rubble and surrounding broken zones for new coral recruits, and recorded the taxon, size, location, and distance from the epicenter of each recruit. In each crater, we measured hard coral cover in six to eight quadrats (0.5×0.5 m), positioned uniformly, radiating out from the epicenter to the edge of the crater (~2–3 m in diameter). Four to six control quadrats were similarly surveyed in nearby, unblasted areas three months post-blast. We surveyed sites comprehensively three, seven, 11, 17, and 24 months post-blast, measuring crater size, rubble porosity, recruitment, and hard coral cover. Three years post-blast we measured size and porosity, and five years post-blast, we measured size, porosity, and hard coral cover in blasted and control quadrats. Data were square-root transformed to homogenize variances and ANOVAs were used to compare change in coral cover over five years.

Large scale: rubble fields.—Oral histories date the beginning of fishing with dynamite in KNP to the 1950s; blast fishing is continued in the region today using homemade bombs, although it has greatly diminished in KNP due to park patrols supported by The Nature Conservancy. We examined recovery from chronic blasting in nine large (>300 m^2) rubble fields, also 5–10 m deep. The precise history of each rubble site studied is unknown, but data from park patrols and expert judgment indicate that the rubble fields were caused by blast fishing. Based on the weathering of the rubble, we estimate the rubble study sites to be up to several decades old. Point estimates of flow speed at each site (General Oceanics flowmeter, model 2030R; General Oceanics, Miami, Florida, USA) showed varying current speeds ranging from <5 to >90 cm/s. Sites were divided into low, medium, or high current (three each) based on relative dissolution rates of blocks of dental cement (Jokiel and Morrissey 1993). Natural recruitment was assessed annually in six of seven years (1998–2004) by visually surveying location, number, size, and taxon (if known) of hard coral recruits within six to 10 random 1×1 m quadrats per site. Numbers and sizes of recruits over time were compared using repeated-measures ANOVA on natural-log-transformed values. Small-scale rubble movement was measured by painting and tracking individual rubble pieces (analyzed using generalized linear models of natural-log-transformed values of mean total distance moved; compared using current [low, medium, and high] as a model factor). Large-scale rubble movement was measured as the changing depth of the rubble field overall, monitored by the changing height above the substrate of nine stakes driven into the rubble to an initial depth of 40 cm and evenly spaced in a 10×10 m grid at each site (compared using repeated-measures ANOVA on natural-log-transformed values).

RESULTS AND DISCUSSION

The acute blasting had an immediate and dramatic impact on the reef community (Fig. 1). The pulverized rubble zone was overlain with a layer of silt and mucus,

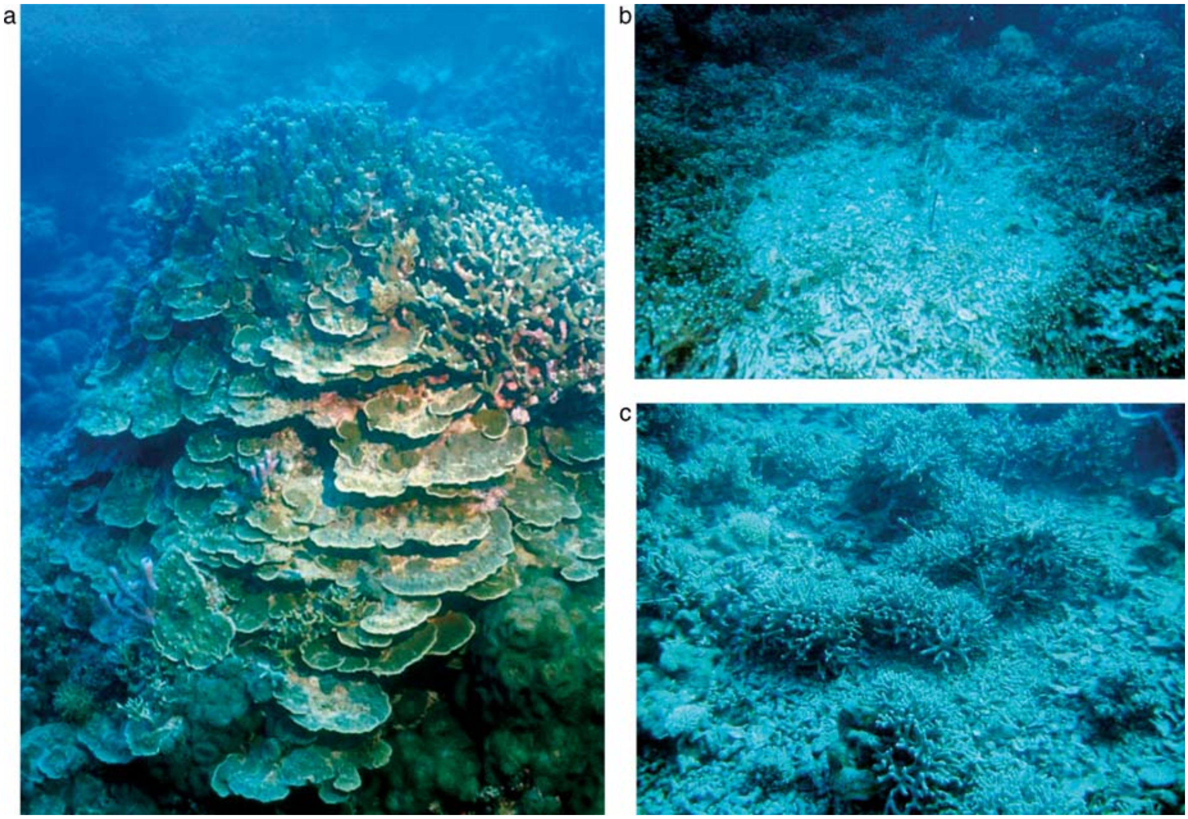

FIG. 1. The impact of a single 300-mL bomb transforms a coral reef with complex and three-dimensional structure into a large crater. The reef in (a) is adjacent to the crater in (b), which is ~2 m in diameter and two years old. (c) The crater in (b) five years post-blast. It has filled in considerably.

surrounded by larger fragments of broken coral, many of which had shifted downslope. The initial size of the entire affected area ranged from 9 to 31 m^2. Blasting killed approximately 70% of the live coral and further mortality occurred during the first year, but we observed significant recovery over time in both of these zones (Fig. 2). After five years, the broken zone was no longer distinguishable (Fig. 2a), and the rubble zone, while still visible (Figs. 1c and 2b), had filled in with growth of surviving corals and additional recruitment. Numbers and size of coral recruits increased over time, and recruitment tended to occur at the edges of the dead rubble zone (Table 1). Total hard coral cover no longer differed significantly from that of pre-blast levels (Fig. 2c, Tukey's hsd on ANOVA, $P > 0.05$). Porosity of the rubble bed also decreased over time as settling occurred (Fig. 2d). Even after five years, however, a top layer of loose rubble 5–10 cm deep persisted, comparable to values found in large rubble fields (Fig. 2d). Therefore, we found that isolated, small bombs had persistent effects over the time scale of this study, although craters recovered considerably in several respects (Fig. 1c).

In contrast, many bombs on larger spatial and longer temporal scales create unstable fields of broken and dead coral (Burke et al. 2002, Wilkinson 2002) that showed no evidence of natural recovery. In large rubble fields, we found no significant increase in the area covered by naturally recruiting corals over six years; in fact, mean coral cover in the rubble fields *decreased* over time (Tukey's hsd on ANOVA, $P < 0.0001$; Fig. 3).

This lack of recovery is unlikely due to recruitment limitation. Using terra cotta settlement tiles to measure early recruitment of coral, previous work found an abundance of early recruits settled on tiles in both blasted and unblasted areas (Fox 2004). Instead, it appears that the motion of unconsolidated substrate leads to abrasion or smothering of any surviving fragments or recently settled coral colonies (Brown and Dunne 1988, Clark and Edwards 1995). We monitored rubble movement in all nine sites over the same two- to three-week period and found that the mean movement of rubble pieces during that time ranged from 15 to 46 cm, with high current sites having statistically greater rubble movement (Tukey's hsd on GLM, $P < 0.05$). This lateral movement of 1–3 cm/d caused changes in the depth of the entire rubble field of several centimeters every month, more than enough to bury new coral recruits. Again, higher current strength led to greater variance in rubble depth (repeated-measures ANOVA, $P < 0.05$); earlier experiments also found

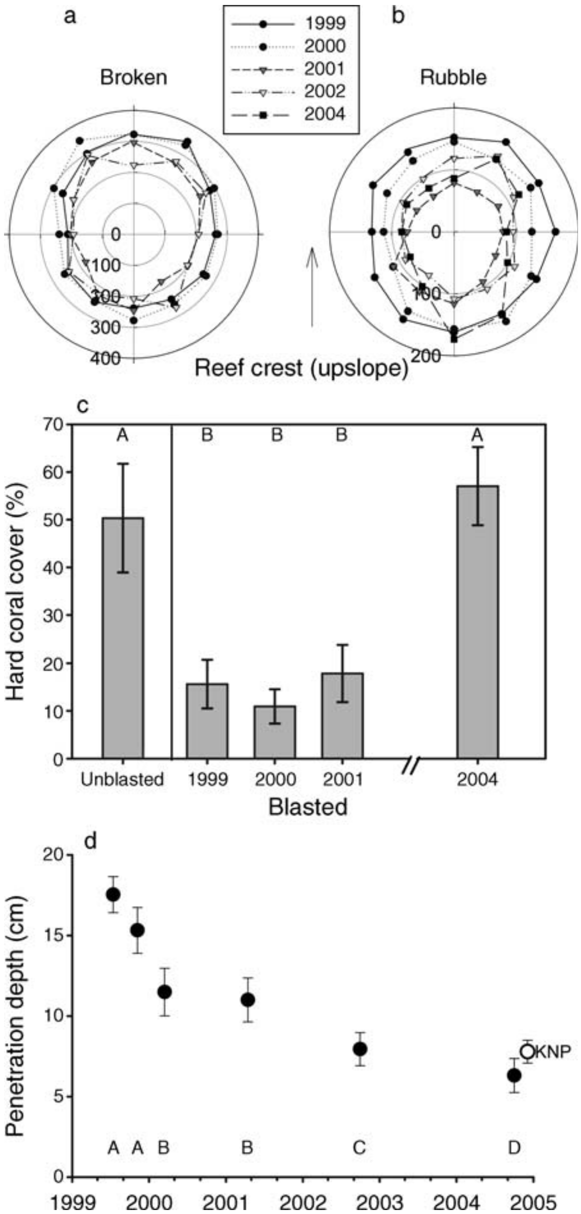

Fig. 2. Single blasts have long-term physical and biological effects. Immediately after the blast (1999), (a) broken and (b) dead rubble zones extend to ~300 cm and 150 cm, respectively (mean radii of six craters); these zones contract over time, and by five years post-blast, a broken zone is no longer distinguishable. (c) Percent cover (and 95% CI) of hard coral on unblasted and adjacent blasted reef over five years. Groups that share letters are not statistically different. (d) Depth of penetration (mean and 95% CI) into the rubble bed as a proxy for substrate stability (see *Methods: Small scale: single blast studies*). The rubble bed gradually becomes less porous (groups that share letters are not statistically different) and, after five years, is comparable to that of the large rubble fields in Komodo National Park (labeled "KNP," open circle).

Table 1. Number of scleractinian coral recruits per crater, distance from epicenter (not measured in November 1999), and colony area for the six large blast craters in the protected reef habitat.

Months post-blast	Date	No. recruits/ crater	Distance from epicenter (cm)	Colony area (cm^2)
3	Jul 1999	0	†	0
7	Nov 1999	0.83 (0.54)	†	6.82 (2.64)
11	Mar 2000	4.50 (1.82)	76.36 (8.63)	12.49 (2.57)
17	Sep 2000	6.00 (0.89)	107.78 (10.24)	46.30 (9.09)
24	Apr 2001	10.67 (0.92)	114.05 (5.48)	20.62 (5.25)

Notes: The larger mean colony area at 17 months vs. 24 months is primarily due to the presence of several large colonies of *Seriotopora hystrix*, a rapidly growing colonizer with poor persistence, during the September 2000 survey. Values are means (SE).

† Not measured.

increased rubble movement to be correlated with decreased survival of small corals transplanted into rubble fields (Fox et al. 2003).

Our results suggest that while coral reefs can recover over 5–10 years from single blasts isolated in the reef matrix, extensive blast fishing as it is often practiced transforms these complex, biodiverse ecosystems into persistent expanses of shifting rubble. Because corals appear unable to survive within these rubble fields, we expect recovery to take several decades to centuries, even if reefs are protected from further blasting. Indeed, recovery may follow a different trajectory, resulting in an altered community (Hughes et al. 2005). This study supports the general hypothesis that reefs are very slow to recover from intense physical disturbance (whether by blasting, mining, "reef gleaning," or hurricanes [Brown and Dunne 1988, Clark and Edwards 1995]), in contrast

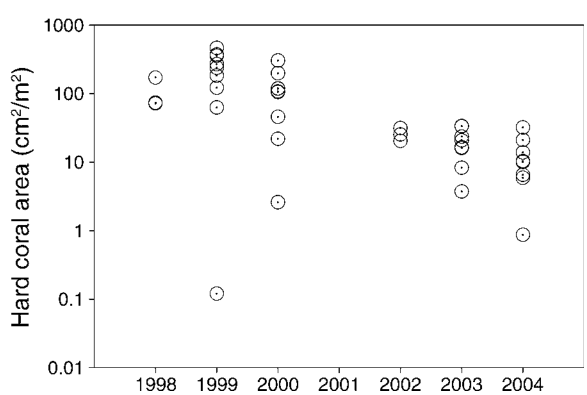

Fig. 3. "Killing fields" for corals in extensively blasted areas. Total area of available substrate covered by hard coral colonies, surveyed annually in six of seven years (n = 6–10 random quadrats in each of nine large rubble field sites, except 1998 [three sites] and 2002 [four sites]).

to relatively rapid recovery (<20 yr) from disturbances that leave the reef framework intact, such as crown-of-thorns starfish (Colgan 1987). While work to develop effective rehabilitation methods (e.g., Lindahl 2003, Fox et al. 2005) might be feasible on a small scale, human intervention is unlikely to be a viable solution on large spatial scales. These findings should serve as additional incentive to invest in effective reef management that, among other things, halts this destructive fishing practice.

Acknowledgments

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