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Long-term environmental impact of coral mining at the Wakatobi marine park, Indonesia

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ABSTRACT

Coral mining for use as construction material is a major cause of reef degradation in several coastal nations. We studied the long-term impact of coral mining at the Wakatobi marine park, Indonesia, where a substantial mining event was undertaken two decades ago in order to supply building material for a jetty. The mined area shows significant differences in reef viability compared to a control reef 1000 m away: the percentage of dead coral in the substrate, the percentage of live coral coverage, the species richness and abundance of hard corals are all greatly reduced. For the most part, soft corals and other (non-coral) invertebrates do not show significant differences in richness, abundance or diversity, but their species composition differs greatly: the control site abounds giant clams, whereas these are absent at the mined site; instead, the dominant species there is *Strombus*, an algae-grazing gastropod associated with stressed reefs. We conclude that the mined reef flat failed to recover from the severe mining event, despite being un-mined for over 20 years. Our results demonstrate that without effective management and enforcement, coral mining may cause a long-term, destructive impact on the coral reef ecosystem. We propose the following management steps: first, law enforcement measures must become more stringent; second, alternative income sources such as aquaculture, ecotourism, or even land-based alternatives need to be actively promoted and financed; third, alternative building materials such as landrock and concrete should become more accessible and affordable; and fourth, education and awareness regarding both the MPA regulations and the environmental impact of coral mining have to be strengthened.

1. Introduction

Coral reefs are the ‘rainforests of the sea’, containing the richest biodiversity of all marine ecosystems. In addition, they are of major economic benefit to many countries, supporting millions of people living in coastal, tropical environments; the value of resources and services derived from reefs was estimated at $375 billion per year [7]. However, these ecosystems are in serious decline worldwide [34] due to human impact (e.g. global warming, water acidification and unsustainable resource use; [27]). The future survival and regeneration of coral reef ecosystems requires an improved understanding of their dynamics and of the processes that support or undermine their resilience, coupled with stronger, more innovative management efforts [1]. Threats to coral reefs increase daily, and the need for the protection of these habitats is at an all time high. In South East Asia, anthropogenic stresses are at their most destructive. High population pressure, especially in coastal communities, intensifies pressure on near shore resources, often producing an unsustainable outcome. Singularly among the factors affecting reefs, coral mining is a largely unstudied subject. The effect on coral community, adjacent fisheries and recruitment/recovery levels are not well understood. Coral mining for use as construction material is cited as a major cause of reef degradation in a number of tropical coastal regions, including East Africa [11], South Asia [3], South East Asia [4] and in the Pacific [29]. Extraction of corals has a detrimental effect on the reef: it decreases the abundance and richness of the corals and fish (e.g. [11]), increases land retreat and sedimentation (e.g. [29]), and decreases shoreline protection against Tsunami waves [12]. Thus, coral mining creates a significant long-term loss to society and economics, including a loss in fisheries value, coastal protection, and tourism. The skeletal framework of reefs, which is removed through mining of coral and rock, is built up over hundreds to thousands of years and will take as long to grow back and recover. When considering these factors, the cost of destroying or mismanaging one square kilometer of reef results in losses of up to US $6.6 million [22].

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The extraction of solids from the sea might sound like a peculiar option-why mine in water when land is made of solid materials? To understand this, one needs to understand the demographic make-up of the studied area. Two very different societies share the sea's resources. The Bajo ('sea gipsies') do not associate themselves with land at all. Traditionally practicing a maritime nomadic lifestyle and building seasonal stilt-suspended houses on the reef flat, they have in recent years been forced by the Indonesian government into permanent villages. Therefore, current Bajo dwellings are constructed atop solid platforms on the reef flat. Due to their reluctant contact with land, the Bajo turned to the reef flat for obtaining building materials for these solid platforms [24]. The size of a Bajo house's foundation platform serves as a reflectance of its inhabitants' financial status; moreover, coral solids are used by the Bajo people as a financial commodity much like currency. Sadly, an alternative building material - fossilised coral rock, which is found in abundance along the coastline - is much denser and harder to break, extract and transport, and therefore seldom used. The other community residing in the area is villages of Kaledupans, whose inhabitants (unlike the Bajo) are predominantly Indonesian with a land-based culture. Their coral mining is usually limited to the production of lime, which is used for creating mortar and also in sewage (cess) pits and white wash [24]. Here too, the alternative material-inland fossilised coral rock–is not used since it produces lower-grade lime which is also less white, an important disadvantage when marketing the whitewash. Corals are collected in shallow water, broken into smaller pieces and then burned in a kiln or open fire until only lime remains. A relatively low conversion ratio of about 1.8:1, corals to lime by weight, is obtained after burning the coral skeletons (i.e. every kilogramme of lime that is produced requires at least 1.8 kg of coral [2]). Although the practice of small-scale coral burning appears to be widespread in Indonesia, it is perhaps best known from Bali where these practices led to a dramatic decrease in coral cover, richness and abundance. Although coral mining in Bali has now largely ended, it led to significant and expensive beach erosion problems, and subsequent monitoring has shown very little recovery of mined sites throughout Bali [30].

Throughout coastal Indonesia, corals are used for construction, either as building blocks for walls and foundations or crushed and fired to produce lime (an important constituent of cement). Their use in construction is reported from Java, Kalimantan, Bali, Lombok, Sulawesi, and Maluku [5,25] and consists mainly of genera with dense calcium carbonate skeletons such as Platygyra, Porites and Favia [30]. Our preliminary anthropological and ecological field observations, as well as interviews with local miners, revealed that although referred to as 'coral mining', the actual materials being mined at the reef flat do not necessarily consist of live corals. There are two main sources for materials: the first is 'coral rock' or 'coral rag' - fossilised limestone which constitutes the foundation for most of the substrate on the reef flat. Typically found as flat slabs of loosely packed conglomerated calcium sand, it is usually covered with sand and rubble and can be dislodged using a lever (Fig. 1). The second mining material is hard coral, which may be alive or dead. As corals and coral rock dwindle around the village, mining expands along the reef flat. Mining is confined to low-tide time and is done mostly on an opportunistic basis; the collectors do not rely on it for a dominant fraction of their income. However, in the event of high demand, a shift into more mining can be observed and with it evidence of less particular or choosy collection. The building of the jetty at Hoga Island, 20 years ago, provides a good example: it is constructed predominantly of now-dead corals that were collected alive, as evidenced by their polyp structure which is still visible. The jetty represents temporary shifts from random, opportunistic collection of rock material to fast gleaning, non selective aggregation of solids from reef flats close to the construction site.

Fig. 1. Miner using a crowbar on a reef flat at Hoga Island, Indonesia.

2. Materials and methods

We compared two sites at the Hoga island reef flat (Fig. 2). The first site, named 'buoy-2' (coordinates: 9394878, 584032), was an area within close proximity to the jetty, which – 20 years ago – served as the main source of corals and solids for the jetty's construction. The second site, named 'Pak-Kasim' (coordinates: 9395496, 583812), was located approximately 1 km north of 'buoy-2' and served as a control group which only suffered sporadic, low-intensity mining but was not affected by the massive mining event associated with the jetty's construction. Both study sites were very similar in depth, vertical relief and distance from the crest (see [9]). At each of the two sites, four 50 m-long transects were marked on the reef. At each transect, at high tide, we surveyed the following reef parameters: (1) Rugosity: along the transect lines, a 10 m metal chain was laid and allowed to acquire the vertical relief of the reef. Rugosity was then calculated as the horizontal length of the chain in situ, divided by the actual length of the chain. (2) Reef substrate: along each transect, at 25 cm intervals, the substrate directly below the transect line was recorded. Additionally, where sessile flora/fauna was detected, its growth form, species and colony size were noted. (3) Coral surveys: along each 50 m transect, ten 5×5 m quadrates were surveyed for hard and soft corals. Each colony was identified to genus level and measured. (4) Invertebrates: a 5 m-wide belt (2.5 m on each side of the 50 m transect line) was surveyed for invertebrates which were identified as specifically as possible (to at least the family level). For each of the above-mentioned reef parameters, differences between the two sites were analyzed for statistical significance using one-way ANOVA tests. Since there were four 50 m transects (i.e. repeats) at each site, the degrees of freedom for each test (except when marked n.a.) are 1 (between groups) and 6 (within groups).

3. Results

The results of the study are summarised in Table 1. Although the rugosity is similar at the two sites, the composition of the substrate of the reef is significantly different: at buoy-2, it is about equal parts dead corals and inorganic material (sand and rubble) while at Pak-kasim the substrate is mainly dead corals. Significant differences also exist in the overall percentage of live coverage which is doubled at Pak-kasim, and the percentage of hard corals' live

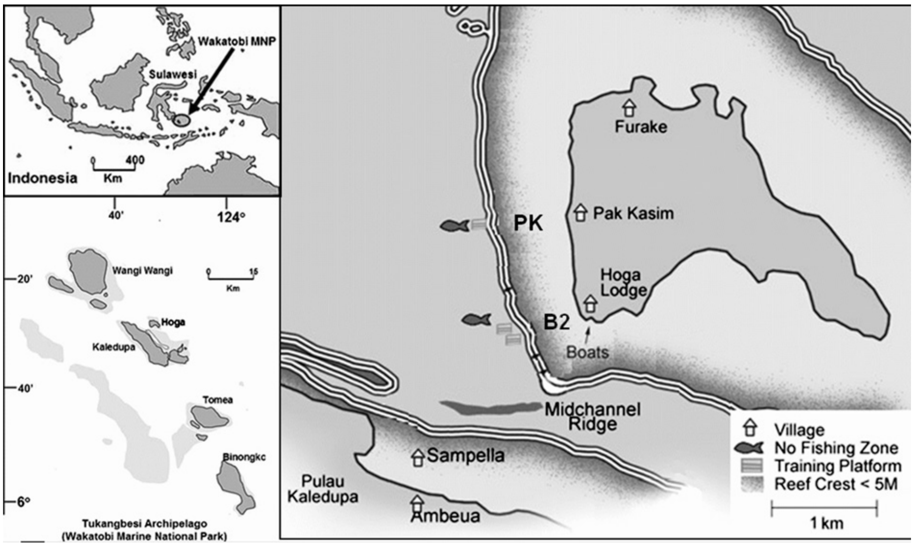

Fig. 2. The study sites at Hoga Island, Wakatobi marine national park, Indonesia. B2, "Buoy-2"; PK, "Pak-kasim".

Table 1
reef parameters at the two study sites.

	Buoy-2 (severe mining)	Pak-kasim (opportunistic)	Significant difference?
Rugosity (%)	59 ± 5	60 ± 3	No ($P = 0.69$)
Reef substratum			
Dead coral (%)	47.8 ± 18.3	78.1 ± 13.9	Yes ($P = 0.04$)
Sand + rubble (%)	52.2 ± 18.3	21.9 ± 13.9	Yes ($P = 0.04$)
Reef live cover			
Hard corals (%)	6.9 ± 4.3	18.5 ± 3.3	Yes ($P < 0.01$)
Soft corals (%)	3.2 ± 4.5	4.0 ± 3.4	No ($P = 0.80$)
Other (seagrass, algae, sponges)	6.2 ± 6.4	12.8 ± 4.9	No ($P = 0.15$)
Total live cover (%)	16.4 ± 3.6	35.3 ± 6.2	Yes ($P < 0.01$)
Hard corals			
No. of species per transect	9.5 ± 1.7	16.3 ± 4.0	Yes ($P = 0.02$)
No. of colonies per transect	49.8 ± 15.3	157.8 ± 59.3	Yes ($P = 0.01$)
Total no. of species	18	25	n.a.
Total no. of colonies	199	631	n.a.
Shannon–Wiener diversity index	1.4 ± 0.3	1.4 ± 0.3	No ($P = 0.98$)
Simpson diversity index (1/D)	2.6 ± 0.5	2.2 ± 0.4	No ($P = 0.29$)
Soft corals			
No. of species per transect	2.0 ± 0.0	2.8 ± 0.5	Yes ($P = 0.02$)
No. of colonies per transect	10.3 ± 7.6	21.5 ± 16.7	No ($P = 0.27$)
Total no. of species	3	4	n.a.
Total no. of colonies	41	87	n.a.
Shannon–Wiener diversity index	0.2 ± 0.3	0.2 ± 0.3	No ($P = 0.48$)
Simpson diversity index (1/D)	1.2 ± 0.4	1.3 ± 0.5	No ($P = 0.56$)
Invertebrates (except corals)			
No. of species per transect	11.5 ± 0.6	11.0 ± 2.9	No ($P = 0.75$)
No. of organisms per transect	64.8 ± 75.7	54.3 ± 14.2	No ($P = 0.79$)
Total no. of species	24	21	n.a.
Total no. of organisms	259	217	n.a.
Shannon–Wiener diversity index	1.7 ± 0.9	1.5 ± 0.2	No ($P = 0.70$)
Simpson diversity index (1/D)	5.4 ± 3.4	3.1 ± 1.1	No ($P = 0.24$)

coverage which is almost tripled at Pak-kasim (Fig. 3). In addition, the community of hard corals at Pak-kasim enjoys a significantly larger species richness and colony abundance (×1.5 and ×3 than at Buoy-2, respectively). All the studied parameters of soft corals and other invertebrates did not show significant differences between the sites, except for species richness which was slightly higher at Pak-kasim. The biodiversity indexes of hard corals, soft corals and other invertebrates do not differ significantly between the two sites (Table 1).

The hard-coral community of both sites is dominated by corals of the genus *Porites* (Fig. 4), which comprises more than 60% of the total colony abundance. The composition of communities of soft corals and other invertebrates, however, despite not showing significant differences in either the Shannon–Wiener or Simpson diversity index, exhibit marked differences. The most abundant soft coral at Buoy-2 is *Sinularia* sp while at Pak-kasim *Sinularia* is joined by *Sarcophyton* sp. The 'other invertebrates' community at buoy-2 is dominated by *Strombus* sp., whereas at Pak-kasim the dominant species is *Tridacna* sp. (Fig. 4).

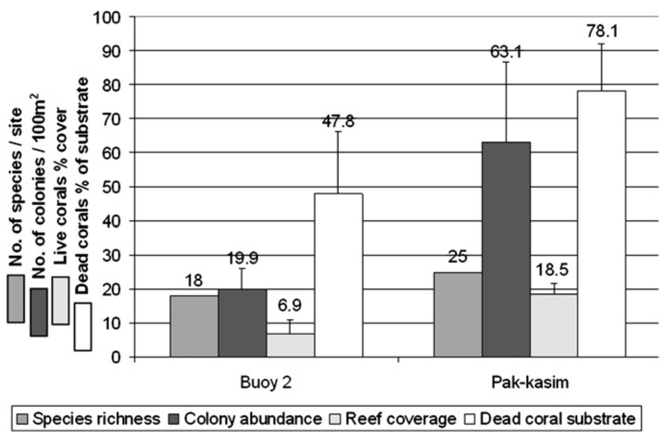

Fig. 3. Main differences of hard-coral community between the two sites.

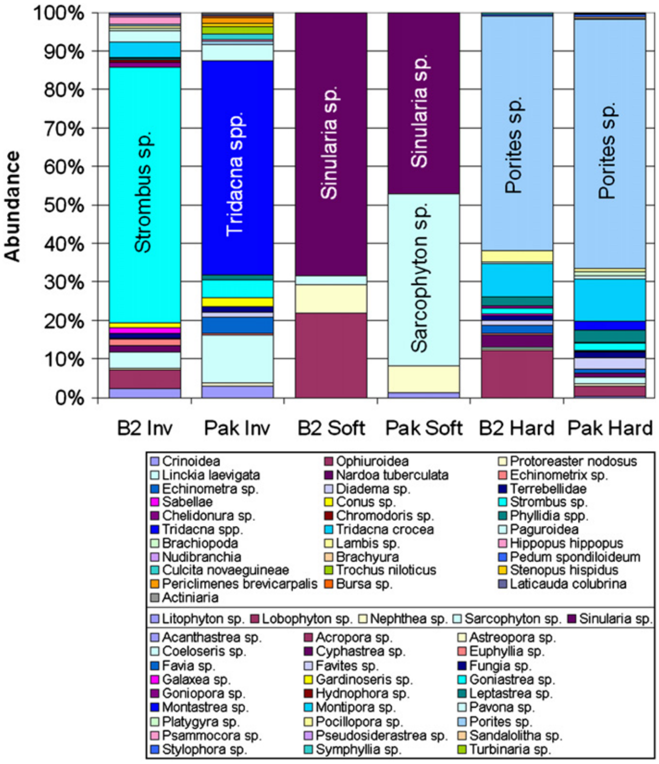

Fig. 4. Composition of species at the Buoy-2 and Pak-kasin study sites. Color legends: top, invertebrates; middle, soft corals; bottom, hard corals.

4. Discussion

The results demonstrate a significant difference between the two study sites, clearly showing that the "Buoy-2" reef flat, where a massive mining event occurred 20 years ago, still has not recovered despite being un-mined since. The reef substrate, which in the past was composed mainly of dead and live hard corals, was taken away to serve as building material; as a result, the reef substrate is currently dominated by sand and rubble. This, in turn, affects the rate of recovery as coral settlement is effected by the lack of stable favourable substrates [13]. Currently, low live coverage as well as low richness and abundance of hard corals are recorded in the mined area compared to the control site just a kilometer away; if we assume that both these reef sites were similar prior to the mining event, it is logical to deduce that very little recovery occurred at the mined reef during the past two decades. Our findings are in agreement with those reported from the Maldives, where live coral cover, diversity and abundance at reefs subject to coral mining were all very low compared to un-mined reefs. Moreover, little recovery was seen at intensively-mined sites even 16 years after the mining has stopped [3]. To explain the reasons for this failure to recover, we may first compare coral mining to another practice which is superficially similar - coral harvesting, e.g. for the aquarium industry. Harvesting usually involves only live colonies or "live rock" that are of a certain size and "quality". Moreover, because coral harvesting relies on intact coral heads, relative care is taken not to damage their surrounding. Hard coral populations that are harvested can recover by re-growth of "pruned" colonies, growth from fragments, or larval settlement. Survival and growth of fragments has been demonstrated for many species, with the probability of survival dependent on the size of the fragment [20]. Scleractinian corals grow relatively slowly: the relationship between colony size and age is not always clear [23], but as a general estimate, colonies of branching species such as *Acropora* grow in radius at up to 10 cm y^{-1}, *pocilloporids* at up to 3 cm y^{-1} and massive species such as *faviids* and *poritids* at about 1 cm y^{-1} [16]. Coral mining, as opposed to harvesting, removes all coral colonies indiscriminately as well as its entire solid foundation, leaving very little coral fragments or damaged colonies behind. Moreover, at least at Wakatobi, not only corals are collected but also the rocks on which they rest [24]. This is the marine equivalent of forest clear-cutting, resulting in a massive disturbance that affects not only the current coral growth but also its chance for recovery. Additional stress is imposed on the surviving corals via trampling by miners as well as massive clouds of sediment raised by the mining activity. As the main avenue for rehabilitation of the reef flat is through larval recruitment, the destruction of potential substrate may dramatically impair settlement and thus increase the recovery time. Most corals reproduce by release of eggs and sperm, or brooded larvae [17]. Larval vitality in the water column supports their dispersal for long periods [19]. Availability is high in many Indo-Pacific reefs, although not all reefs receive large numbers of coral recruits [16]. The key difficulty in reef recovery, however, is recruitment success: since mining usually leaves a wasteland of sand and rubble, coral larvae that arrive at a mined area find little suitable settlement substrate. Even if they manage to settle, the chronic substrate disturbance (i.e. mechanical abrasion of loose, mobile rubble, turning over of substrate, high sediment load and exposure to predators) decreases their post-settlement survival rates, all leading to a very low recovery [13]. The substrate instability is similar to that in areas affected by dynamite fishing, a practice common in Wakatobi and other areas close to our study site where the result is seemingly similar.

Mined reef flats apparently fail to recover, even many years after the mining has stopped. The loss is not limited to the reef substrate and hard corals: the richness and abundance of reef fish also deteriorate, with severe economic repercussions [10]. In the current study, the composition of the invertebrate community at the mined site was dramatically different than the control site. While the control reef was dominated by giant clams, the mined reef had almost no giant clams; instead, it was dominated by *Strombus*, a genus of gastropods that mostly inhabit sandy areas. As an algae grazer, *Strombus* sp. is often associated with stressed reefs (Caras, personal data). Giant clams (*Tridacna* sp.) occupy a narrow ecological niche, displaying a symbiotic association with photosynthetic algae (Zooxanthellae) and inhabiting rocks or corals (mostly *Porites*) in shallow waters up to 30 m depth. Giant clams are often used as an 'indicator species' of healthy reef (e.g. [18]): they are fixed (i.e. do not change their location), long-living, and grow to large sizes. In addition, due to their method of reproduction, they are highly vulnerable to stock depletion, with populations becoming non-sustaining when densities fall below certain levels. The two sites studied at Hoga did not differ significantly in the Shannon–Wiener or Simpson biodiversity indexes; however, by comparing the contrasting invertebrates community composition that inhabited each site, it is clear that while the Pak-kasim reef was healthy and thriving, the Buoy-2 reef was quite the opposite.

Our results confirm that mining of corals as building material can have a devastating, long-lasting impact on the ecosystem. Thus, the damage of mining can be paralleled to that of other destructive substrate-disintegrating practices such as clear-cutting on land or dynamite fishing, indiscriminate anchor laying and sea-bottom dredging at sea. The implications of this study for management of the area can be divided into three main categories: wildlife protection, promotion of alternative income sources, and promotion of alternative building materials. As for wildlife protection, many countries have banned coral mining, including Indonesia. The Wakatobi area was designated a Marine National Park (MNP) in

1996 and a Marine Protected Area (MPA) in 2002, but due to lack of education, enforcement and management, this had very little effect on the destructive practices of the inhabitants [6]. Between 2002 and 2007, average hard coral cover at the Wakatobi MNP declined by half (suggesting an 8% decrease per year), from $46.7 \pm 3.4\%$ to $22.2 \pm 4.0\%$ [32]. The total live cover also suffered a sharp decrease, from $80.5 \pm 3.2\%$ in 2002 to $51.3 \pm 5.0\%$ in 2007 [32]. The deterioration in the state of the reefs was observed at all sites except the protected no-take area (NTA) at Hoga, indicating an anthropogenic cause for the general decline within the park. In 2007, a new zoning system was implemented, which comprises various no-take and no-entry zones, tourism zones, and a zone where traditional pelagic fishing is allowed. Enforcement of these rules is performed by park rangers, local police, local community, local district fisheries, the Wakatobi Marine & Fisheries Agency and the Indonesian navy; however, the enforcement and surveillance efforts of all these bodies combined still manage to encompass only ca. two weeks of every month [26]. Clearly, enforcement efforts have improved recently, but are still lacking.

Poverty and resource degradation are intimately linked in many coastal communities around the world, with poverty sometimes driving people to break management rules [6], thus making it more difficult to reach conservation goals [33]. We believe that in addition to enforcement, management plans must emphasize the alleviation of poverty and the promotion of alternative income sources. Potential solutions need to take into account local traditions and focus on the socio-economic place coral mining takes in the community. For example, East African coral mining is predominantly aimed at lime production for which coral rock may be an adequate and reasonable direct alternative [14,15]. For the Wakatobi Bajo, coral and solids are used as they are without treatment, for which land mining formulates a range of social conflicts. In Wakatobi, basic services such as sanitation, healthcare, and education are often rare [8]. The infant mortality rate can be so high that many mothers cannot remember the number of children they have lost, and the average number of years in school is four [31]. Alternative income sources are desperately needed for such people, especially in instances where traditional livelihoods (e.g. by coral mining) become illegal. *Agar agar* farming seems to be the most widespread alternative source of income, and its implementation is succeeding in some areas [21]. In the case of the Bajo people, their reluctance to board the land for work or resourcing, makes agar farming a good option as it is a solely sea-based alternative. The main problem with Agar farming in Wakatobi is that people perceive it as unreliable and seasonal [24]. Roumasset [28] put forward the 'Safety first principle' whereby people at subsistence level will stay with the incomes they know to be reliable; seasonality may cause the majority of Agar farmers to have another job, in many cases coral mining which provides an instant source of income. In order for an Agar farm to provide stable, year-round income, people need (1) aquaculture education, and (2) enough start-up money to create a farm that is large enough. Any sound management plan must attempt to provide both these things, along with political persuasion for adopting this new source of income. Credit associations and other cooperative schemes, deployed through women's social and kin networks, have had considerable success in other parts of the world, notably West Africa [21]. Social networks among the Bajo and similar peoples do, indeed, tend to be organized around the women, and women have traditionally controlled household finances, so this sort of strategy holds promise [8].

As important as poverty alleviation may be, the main coral mining problem at Wakatobi stems from the social traditions of the Bajo people. It is important to highlight the Bajo community's deeply rooted traditional reluctance for land-based solutions. Changing these traditions would require a successful educational campaign promoting a very basic switch in the pattern of thinking. The platform for a single Bajo house may reach sizes of 280 m^3 (Caras, pers. obs.); this platform is composed of a very large amount of corals taken from the reef. This represents the Bajo equivalent of land ownership and symbolises the entire worldly possessions of the Bajo family. Conversely, conservation-wise, if mining a healthy 1 m^2 of reef can supply 0.2 m^3 of solid rock and coral, one of the above platforms may 'cost' a staggering 1400 m^2 of reef.

The main alternatives for corals as building material are landrock and cement. Beyond cultural reservations, the problems with these are (1) expense and (2) transport, which tie in together: coral is free, can be collected over a long period of time, can occupy off-season periods and employ the entire family (it is often the main source of income and social status for young, unmarried men). Landrock, on the other hand, is expensive, requires hard cash and dependency upon land-based suppliers. Additionally, coral can be brought to the doorstep from the surrounding reef by boat, whereas landrock must be purchased from the inland and transported by a car, of which are precious few in the area [24]. Local government should encourage an increase in the number of transportation vehicles (cars, trucks and boats) in the area, thus helping to lower the price of alternative building materials. Another problem is that many of the Bajo people still believe that cement is not as strong as coral [24], and this point of view needs to be changed, perhaps by public demonstrations of the strength of concrete. Combined with subsidies to the price of cement and vigorous educational campaign, this can cause a dramatic shift from corals to cement as the main building material in Bajo villages. Moreover, the Bajo have traditionally built their houses on wooden stilts, moving towards coral platforms only in the second half of the 20th century. Therefore, it may be socially possible to promote a "return to earlier traditions" by producing cheap, standardized concrete pillars on which they can build their houses. Pillars can be locally produced, sold and deployed, and may provide an immediate alternative to coral mining. In the case of the Bajo at Wakatobi, cement pillars were implemented successfully in the building of a local walkway.

In summary, in order for coral mining to decline at Wakatobi, the following steps are recommended: first, law enforcement measures must become more stringent; second, Agar farming needs to be actively promoted and financed; third, landrock and concrete should become more accessible and affordable, and concrete pillars should be locally available and socially acceptable; and fourth, education and awareness regarding both the MPA regulations and the environmental impact of coral mining have to be strengthened. Coral reefs are invaluable resources to local communities around the world, and while coral mining provides some economic benefits, it is destructive and undermines the important long-term benefits provided by reefs. In a case study in Lombok, Indonesia, it was estimated that for every $10 net profit gained through coral mining, there was a net loss of $245, through loss of fisheries, coast protection, and tourism [5]. Without effective management, coral mining may jeopardize the potential of coral reefs to sustain local communities and future generations.

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