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EFFECTS OF LAND-BASED POLLUTION ON CENTRAL JAVA CORAL REEFS.

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ABSTRACT

Land-based pollution has severely damaged nearshore coral reefs in the Jepara area, Central Java. Effects described here include reduced coral cover and diversity, high coral mortality, reduced reef habitat complexity, and increased bioerosion intensity, compared to reference reefs in the Karimunjawa Islands National Marine Park, Central Java. Furthermore, the polluted reefs have negative net carbonate production, indicating net reef erosion. Reef health parametres based on coral cover and diversity and on net carbonate production are inversely correlated with chlorophyll A concentration, suggesting eutrophication of coastal waters as a key agent of reef degradation. Untreated sewage dumping, agricultural runoff, and aquacultural effluent all contribute to nearshore eutrophication in Central Java, but it is not possible from this study to determine which of these types of land-based pollution is most responsible for degradation of Central Java reefs. Efforts to restore the condition of degraded reefs must begin with controlling sources of land-based pollution.

I. INTRODUCTION

Two major types of coral reefs occur in Central Java. Fringing reefs and small coral cays occur along the north coast of central Java in places where siliciclastic sedimentation is not too great, for example near the town of Jepara. Fringing reefs also occur near Rembang, Kendal, and on rocky promontories between Semarang and Pekalongan. Platform reefs, developed as emergent or submerged coral cays, occur in the Karimunjawa islands and near the island of Bawean (Tomascik et al., 1997). The fringing reefs help support local artisanal fisheries, while the offshore platform reefs near Karimunjawa help to support the principal fishing grounds in Central Java. Karimunjawa reefs are nominally protected as part of the Karimunjawa National Marine Park. The biodiversity of these reefs is high, supporting approximately 75% of the coral genera (Hoeksema, 1997) and species (Edinger et al., submitted) present in eastern Indonesia. Eastern Indonesia, along with the Philippines and the north coast of New Guinea, forms the centre of diversity for Acropora (Wallace, 1997; Wallace & Wolstenholme, 1998) and other corals, with about 80 genera and 450 known species recorded (Veron, 1993). Eastern Indonesia is also the centre of diversity for reef fish

(Montgomery, 1990; Randall, 1998) mollusks (Paulay, 1997), and many other shallow water tropical organisms (Briggs, 1987).

Like coral reefs around the world (Birkeland, 1997), and throughout Indonesia (Suharsono, 1998), Central Java's coral reefs are threatened by various stresses, both acute and chronic. Acute stresses are intense one-time events, such as blast fishing, cyanide fishing, or ship groundings. Chronic stresses are continuous, and mostly result from land-based pollution, coral mining, or overfishing by non-destructive means, which removes grazing fish, allowing algae to take over the reef (c.f. Hughes, 1994, but see also Lapointe, 1997). This paper discusses the consequences of chronic stresses, particularly land-based pollution, for the coral reefs of Central Java. The field studies for this paper were conducted in Jepara and Karimunjawa, and the paper focuses on these two areas.

Land-based pollution comes in many forms. In waters surrounding Central Java coral reefs, the major types of pollution of concern are untreated domestic sewage, agricultural runoff, effluent from aquaculture ponds and shrimp hatcheries, and sedimentation associated with some or all of these activities (Whidden et al., 1996). Sewage contains high loadings of inorganic nutrients, dissolved and particulate organic matter (DOM/POM), and microorganisms, including human and animal pathogens. Agricultural runoff contains dissolved inorganic nutrients from fertilizers, particularly nitrogen from urea. Where animal manure is used as a fertilizer, pathogens may be transferred in agricultural runoff as well. Aquacultural runoff, specifically effluent from shrimp ponds (tambak) contains high loadings of inorganic nutrients, DOM/POM, shrimp feces, uneaten shrimp feed, and the carcasses of whatever organisms have died in the pond (Briggs and Funge-Smith, 1994). Furthermore, antibiotics, fungicides, and molluskicides used in the shrimp ponds are released into surrounding waters (Philips, et al., 1993). Shrimp hatcheries release many of the same types of contaminants into coastal waters. In the Jepara region, effluent from extensive woodworking operations, including wood preservatives, is released into coastal waters, and may be responsible for heavy metals contamination in local marine sediments (Dunn, 1995).

All of these pollution sources are present in the Jepara area, and influence local nearshore water quality. In Awur Bay and Jepara Bay, Jepara, nearshore waters are so polluted that backyard shrimp hatcheries must purchase clean seawater collected from other locations along the coastline.

Increased nutrient and DOM/POM loading over time is called eutrophication (Nixon, 1995). Eutrophication can damage reefs by favouring algae (Lapointe, 1997) and / or heterotrophic invertebrates over corals in spatial competition on reefs (Birkeland, 1977). Furthermore, eutrophication often leads to reduced rates of coral recruitment (Tomascik, 1991; Widjatmoko et al., 1996). Nutrients also stimulate the growth of phytoplankton, increasing water turbidity, thus decreasing the amount of light available to corals. DOM/POM, bacteria, phytoplankton, and zooplankton are food for the bioeroding animals that create dwellings within coral skeletons, making the corals more fragile in the process (Scott & Risk, 1988). Reduced coral cover and increased bioerosion lead to negative carbonate budgets, and net reef erosion

(Risk & MacGeachy, 1978; Hallock & Schlager, 1986; Glynn, 1997).

Here, we describe coral species diversity, cover, growth rates, bioerosion, and simple carbonate budgets for polluted and unpolluted coral reefs in Central Java. Our results suggest that many of the reefs of Central Java have been severely degraded by land-based sources of pollution, and that recovery of the reefs, and the fisheries dependent on them, will occur only after sources of pollution onto reefs are eliminated.

II. METHODS

Seven reefs were studied in Central Java: two polluted reefs in the Jepara area, and 5 reference reefs in the Karimunjawa islands, in Central Java Province, Indonesia. The Jepara area reefs were the coral cay at Pulau Panjang, and the fringing reef near Bondo, about 10km northeast of Jepara. The Karimunjawa reefs included three vegetated coral cays (Pulau Burung, Pulau Kecil, and Pulau Menjangan Besar & Menjangan Kecil combined), a submerged, unvegetated coral cay (Gosong Cemara) and a fringing reef adjacent to the mangroves in Lagun Marican, between P. Karimunjawa and P. Kemujan. P. Kecil and G. Cemara are reference reefs, P. Burung was affected by storm damage, and P. Menjangan are the sites of tourism development, and are the closest coral cays to Karimunjawa village. Reefs, the stresses on them, maximum depth of coral growth, and the water clarity at each site are presented in table 1. All of the reefs in Karimunjawa are subjected to intense fishing pressure, and large fish (>50cm) were rarely, if ever, observed in Karimunjawa.

Table 1. Study Site

Region	Reef Name (& Code)	reef morphology	max. depth	water clarity	source of stresses
Karimunjawa	Pulau Kecil (KC)	coral cay island	25m	20m	Reference, overfishing
	Gosong Cemara (CM)	coral cay, submerged	25m	20m	Reference, overfishing
	P. Menjangan (MJ)	Coral cay island	25m	15m	Tourism, close to village
	Pulau Burung (BR)	Coral cay island	25m	20m	Storm damaged
	Lagun Marican (LM)	mangrove fringe	4m	<3m	Carbonate sedimentation
Jepara	Pulau Panjang (PP)	coral cay island	8m	<3m	sewage, sediment, aquaculture
	Bondo (BND)	fringing reef	5m	<2m	Sedimentation, agricultural runoff

2.1. Coral Cover, Morphologies, and Species Diversity

On all 7 reefs, at least 6 non-overlapping 20m line intercept life-form transects were measured at 3m and 10m depth, according to the methods used for Indonesia's national coral reef monitoring program (English et al., 1994). The coral species occurring on each transect were listed in 5m increments, enabling us to construct species-area curves for each site, exposure, and depth. All coral cay reefs were sampled at both windward and leeward sides, and at both 3m and 10m depth, except at Pulau Panjang, Jepara, where transects were measured at 3m and 6m depth, because corals did not occur deeper than 8m. On the fringing reefs at Bondo and Lagun Marican, transects were measured on the windward side at 3m depth only.

Coral mortality indices were calculated as MI = dead corals / (live corals + dead corals) (Gomez et al., 1994). A high mortality index indicates a recent deterioration of conditions (Van Woesik & Done, 1997), causing many corals to die before they are broken down or buried (Pandolfi & Greenstein, 1997).

2.2. Coral Growth Rates, Skeletal Density, Calcification, and Bioerosion

Live Porites lobata massive corals were collected from 5 reefs at 1m depth to measure growth rate and bioerosion intensity using x-radiography. Coral skeletal density was measured by weighing 1 cm^3 blocks of coral, immersing the coral blocks in wax, and measuring the volume of water displaced. Coral calcification was calculated as the product of growth and density. Branching coral rubble was also collected on these 5 reefs assess to bioerosion intensity in the rubble (cf. Holmes 1997). Rubble bioerosion was then compared with bioerosion intensity measured from live massive corals. Details of sampling and analytical methods are described in Edinger (1998).

2.3. Net Carbonate Production

Net carbonate production of corals was estimated as a simple proxy for carbonate budgets for the five Java Sea reefs, according to Land (1979), where net carbonate production (P_n) = gross carbonate production (P_g) minus carbonate destruction (D_c) from bioerosion, using Porites lobata growth rate, density, calcification rate, bioerosion intensity data, and live and dead coral cover data from each reef (table 7). Gross carbonate production (kg $CaCO_3/m^2/$year) by corals was estimated as :

$$P_g = r_c \times C_l$$

where r_c = mean calcification rate, and C_l represents % live coral cover, assuming approximately equal calcification rates for all coral species on each reef. Carbonate destruction (kg $CaCO_3/m^2$/year) was estimated as :

$$D_c = ((b \times t \times \rho)/a) \times (C_l + C_d)$$

where b represents % bioerosion, t represents slab thickness (1cm), ρ represents skeletal density, a represents average age of corals, C_l represents % live coral cover, and C_d represents % dead coral cover, assuming approximately equal internal bioerosion rates for live and standing dead corals of all species. Age of corals was calculated as the height of each coral slab divided by the average growth (extension) rate of that coral.

2.4. Environmental Data

Environmental data collected from each reef included chlorophyll A concentration, suspended particulate matter concentration, and sediment traps deployed at 1m, 3m, and the base of the reef in Jepara, or 3m, 10m, and the base of the reef in the Karimunjawa sites (Table 2a). Chlorophyll A concentration measures phytoplankton biomass, and reflects overall biological productivity (Beer, 1997). High chlorophyll A concentrations typically indicate eutrophic conditions, especially if associated with organic matter loading (DOM/POM) from sewage or aquacultural runoff (Nixon, 1995). Light intensity was measured at the surface, 1m, 3m, 5m, 10m, and the base of the reef for 5 of the reefs; light extinction coefficients, k, were calculated as $I_z=I_o e^{-kz}$. (Table 2b).

Table 2: Environmental Data.

Table 2a. Environmental parameters measured for each reef

Reef Name **(units)**	**SST** **degrees C**	**Salinity** **Ppt**	**chl. A** **mg/m3**	**SPM** **mg/l**	**Sediment traps** **mg/cm2/day**
P. Kecil WW			0.33 (0.08)$_3$	9.75 (6.71)$_2$	2.03 (0.55)$_4$
P. Kecil LW	30.3 (1.1)$_4$	33.7 (0.6)$_4$	0.29 (0.17)$_5$	19.69 (18.27)$_4$	1.63 (1.31)$_3$
G. Cemara WW			0.40 (0.21)$_8$	22.98 (7.56)$_4$	4.21 (3.31)$_6$
G. Cemara LW	28.5 (0.7)$_4$	34.3 (0.5)$_5$	0.25 (0.14)$_5$	22.26 (7.56)$_7$	2.80 (3.62)$_5$
Lagun Marican	31.0 $_1$	33.5 (2.1)$_3$	1.24 (0.90)$_3$	26.39 (11.58)$_6$	
P. Panjang WW		33 $_2$	1.23 (0.54)$_5$	21.83 (8.40)$_9$	26.19 (24.42)$_8$
P. Panjang LW	28.7 (0.2)$_4$	32.6 (1.5)$_5$	1.09 (0.62)$_5$	28.91 (17.86)$_{12}$	31.69 (38.74)$_6$
Bondo			1.22 (0.52)$_5$	21.04 (7.60)$_8$	38.50 (43.70)$_3$

Table 2b: Light intensity, % of surface light, and light extinction coefficients

Reef Name (units)	**1m light intensity** **lumens/ sq. ft.**	**1m % surface light** **%**	**3m % surface light** **% sfc**	**light extinction** **K (unitless)**
Pulau Kecil LW	102.69 (45.85)$_{18}$	77	64	- 0.18
Gosong Cemara LW	146.87 (98.27)$_{25}$	59	35	- 0.22
Lagun Marican	71.73 (63.10)$_{19}$	18		- 0.37
Pulau Panjang LW	62.22 (14.85)$_{27}$	21	14	- 0.35
Bondo	93.47 (32.20)$_{62}$	23	9.7	- 0.27

III. RESULTS

3.1. Coral Species Diversity

Species-area curves are presented in figure 1. Within-habitat coral species diversity on the reefs affected by land-based pollution (P. Panjang and Bondo) was approximately 40% that of the most diverse unpolluted reefs (G. Cemara, P. Kecil; Edinger et al., 1998). Coral species diversity was higher on the leeward sides of Karimunjawa reefs than the windward sides (t-test, $p<0.05$), but there were no consistent diffe-rences in coral species diversity between 3m and 10m depth.

3.2. Live Coral Cover

Live coral cover was significantly lower on the reefs subject to land-based pollution than on the offshore reference reefs (table 3; ANOVA, $F=10.83$, $p<0.0001$). Conversely, the cover of algae and invertebrates was higher on the reefs subject to land-based pollution. Coral mortality index was significantly higher on the reefs subject to land-based pollution (P. Panjang & Bondo; MI = 0.48) than on the offshore reference reefs (G. Cemara, P. Kecil, & P. Burung leeward; MI = 0.25; $t=2.81$, $p<0.05$) or the fringing reef adjacent to the mangroves (MI = 0.18).

3.3. Coral Morphological Composition

The morphological composition of the polluted reefs was significantly different from that of the offshore reference reefs (two-way ANOVA, interactions $F = 4.97$, $p<0.0001$) . Nearshore reefs, including both the polluted reefs near Jepara and the mangrove fringing reef in Lagun Marican, were dominated by massive and submassive corals, with very low cover of branching corals, especially Acropora, which is highly sensitive to sedimentation (figure 2). The composition of coral morphologies on offshore reference reefs varied in response to depth. Most sites at 3m depth were dominated by Acropora corals, while most sites at 10m depth were dominated by branching non-Acropora corals, principally Porites cylindrica, and foliose corals, principally Montipora foliosa, Mycedium elephantotus, Pavona cactus, Echinopora lamellosa and E. gemmacea. Morphological composition was significantly different between 3m and 10m sites in Karimunjawa (two-way ANOVA, interactions $F= 3.61$, $p<0.0001$). Stout growth forms like corymbose, digitate, and tabular Acropora were most common on windward sites, while branching non-Acropora and foliose corals were most common on leeward sites. Nonetheless, there were no significant differences in coral morphological composition between windward and leeward reefs (two-way ANOVA, interactions $F= 0.91$, $p>0.5$).

3.4. Ternary Diagrams and Reef Conservation Value

Using ternary diagrams of ruderal (Acropora), competitve (branching non-Acropora and foliose), or stress-tolerating (massive and submassive) coral morphologies to classify the reefs (figure 3; Edinger & Risk, in press), the nearshore polluted sites and the mangrove fringing reef site were all class 1 reefs, while the offshore reference reefs in Karimunjawa included class 2, class 3, and class 4 reefs. Class 1 reefs are of lowest conservation value, harbouring the lowest coral diversity, lowest habitat complexity, and fewest rare coral species, while class 4 reefs are of highest conservation value, with the highest coral diversity, habitat complexity, and most rare coral species (Edinger & Risk, in press).

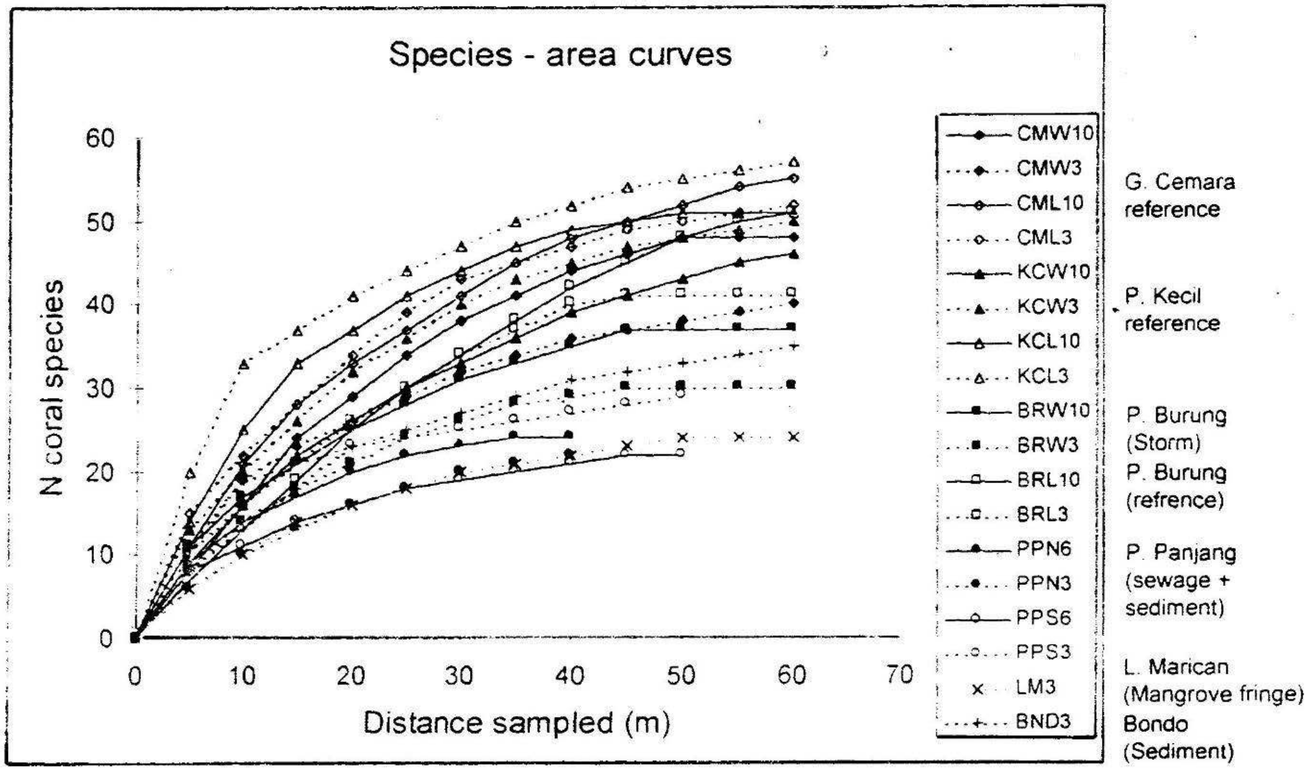
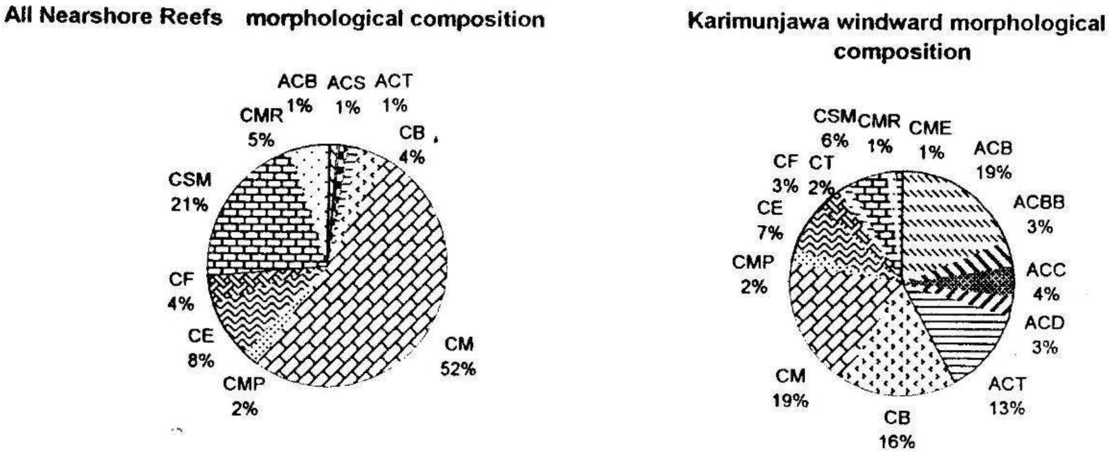


Figure 1 Species-area curves for Central Java reefs studied.

Table 3. Cover class values for all reefs studied. Table 2.3. W, L, 3, or 10 at ends of codes indicate aspect (windward/leeward) and depth.

Reef	**stress**	**site**	**lepth**	**% Acro-pora**	**% non-Acro-pora**	**% live coral**	**% deac coral**	**% algae**	**% othe fauna**	**% abiotic**	**Morta-lity index**
Cemara	Reference/ overfishing	CMW 10	10	18.15	37.65	55.80	24.35	0	0.75	16.85	0.30
		CMW 3	3	47.35	15.58	62.93	16.69	6.01	3.95	7.81	0.21
		CML 10	10	8.57	36.98	45.55	20.27	0.17	4.57	29.28	0.31
		CML 3	3	41.32	27.18	68.50	19.83	1.02	9.09	1.55	0.22
Kecil	Reference/ overfishing	KCW 10	10	6.72	34.70	41.42	24.54	4.92	5.35	17.80	0.37
		KCW 3	3	27.37	33.53	60.90	20.70	4.47	5.32	6.75	0.25
		KCL 10	10	2.40	62.10	64.50	25.88	5.53	0.33	3.61	0.29
		KCL 3	3	25.84	35.90	61.74	13.61	5.85	4.23	14.58	0.18
Menja-ngan	tourism Develop-ment	MJW10	10	15.56	41.99	57.55	21.06	0	1.81	19.58	0.37
		MJW3	3	28.08	13.75	41.83	19.08	1.00	11.92	25.83	0.62
		MJL10	10	3.35	56.99	60.34	16.72	1.53	1.5	19.91	0.34
		MJL3	3	18.6	61.58	80.18	13.70	0	0	6.13	0.20
Burung	storm	BRW 10	10	8.82	23.67	32.48	12.17	7.50	13.10	34.75	0.27
	storm	BRW 3	3	10.32	17.90	28.22	4.40	46.97	6.33	14.08	0.13
	Reference/ overfishing	BRL 10	10	22.23	33.58	55.82	9.80	13.47	11.05	9.87	0.15
		BRL 3	3	37.57	28.82	66.38	8.00	6.62	12.50	6.50	0.11
Marican	mangrove	MRCN 3	3	1.85	21.92	23.77	5.38	37.10	17.10	16.65	0.18
Jepara	Sewage + sediment	PPN 6	6	0	34.75	34.75	18.63	0	7.88	38.75	0.35
		PPN 3	3	0.63	31.89	32.51	15.35	3.24	26.39	22.51	0.32
		PPS 6	6	0	35.77	35.77	37.47	0	3.55	22.32	0.51
		PPS 3	3	0.50	20.68	21.18	58.93	0	0.80	18.63	0.74
Bondo	sediment	Bondo	3	0.55	27.48	28.03	21.22	3.85	10.10	36.80	0.43



A. Karimunjawa 3m

B. Karimunjawa 10m

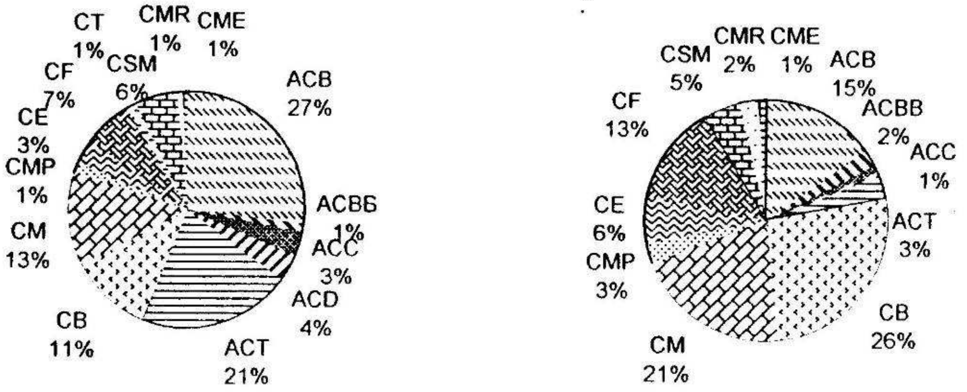


Figure 2 Coral morphology pie diagrams. Acronyms represent standard coral morphologies used in benthic life-form surveys (English et al., 1994). ACB: branching Acropora; ACBB: bottlebrush Acropora; ACC: corymbose Acropora; ACD: digitate Acropora; ACT: tabular Acropora; ACS: submassive Acropora. CB: branching coral (non-Acropora); CM: massive coral; CMP: massive-platy coral (mainly Euphyllia, Lobophyllia, Plerogyra); CE: encrusting coral; CF: foliose coral; CME: Millepora (hydrocoral); CMR: mushroom coral (mainly Fungia); CSM: submassive coral (non-Acropora); CT: tabular coral (non-Acropora; mainly Montipora). Significant differences in composition indicated between depths, but not between windward and leeward exposures.

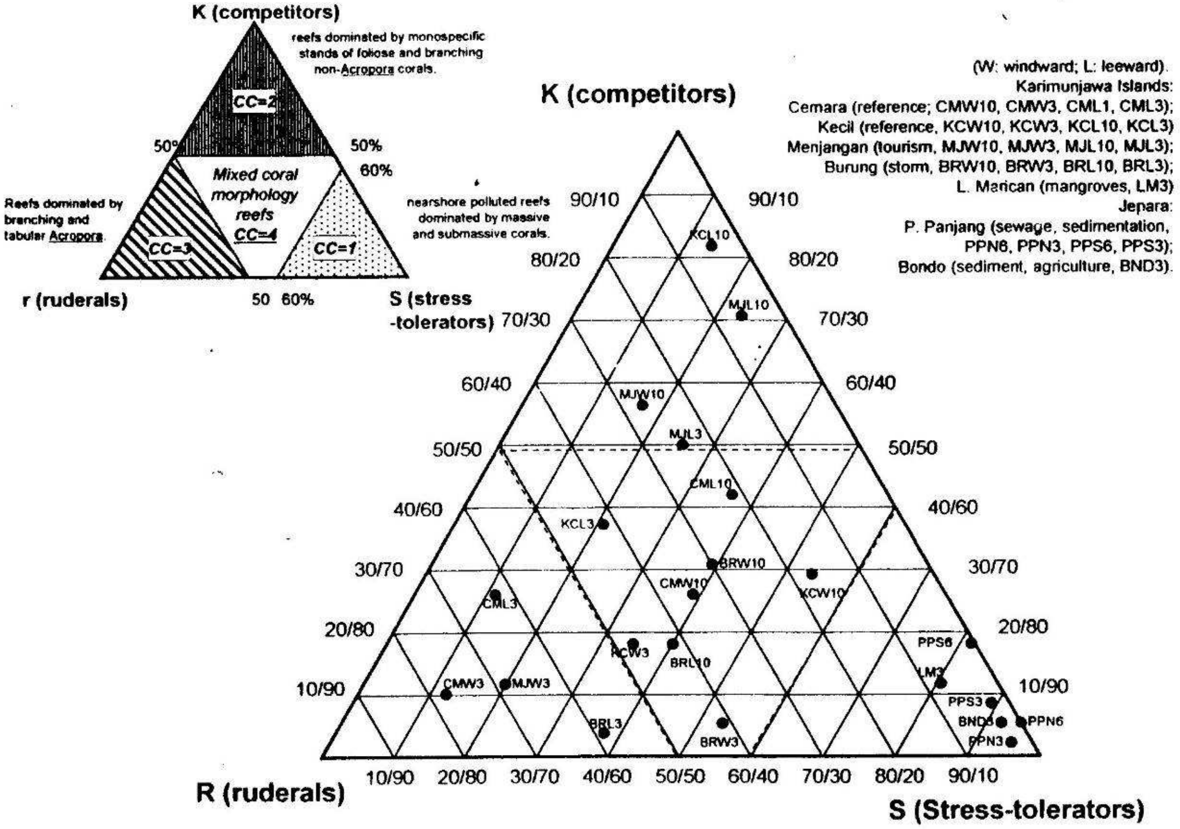


Figure 3 Upper left: reefs can be classified based on coral morphology into sites dominated by disturbance-adapted ruderals (Acropora), competitive dominants in more stable environments (foliose and non-Acropora branching corals) and stress-tolerators (massive and submassive corals, which are present in all environments, but become dominant only in highly stressed environments), or mixed coral assemblages. Conservation value of reefs, determined by coral species diversity, habitat complexity, and rare species occurrence, is highest on mixed assemblage sites, intermediate on class 3 and class 2 reefs, and lowest on class 1 reefs (Edinger & Risk, in press). Centre: Classification of Central Java reefs using coral morphology triangle diagrams. Polluted reefs and the mangrove fringing reef were all classified as 1 sites, while 8 of the Karimunjawa coral cay sites were class 4 sites, 4 were class 3 sites, and 4 were class 2 sites.

3.5. Coral Growth Rates, Skeletal Density, and Calcification Rates

Most corals from the offshore reefs had two high density-low density band couplets per year, as verified using $\delta^{18}O$ isotope ratios in the skeleton, which record the annual variation in water temperature experienced by the coral. By constrast, corals on the nearshore reefs, both the polluted reefs and the mangrove fringing reefs, had only 1 high density-low density couplet per year, also verified using $\delta^{18}O$ isotope ratios in the skeleton. Coral growth rates were highest on the offshore reference reefs, where they averaged 16.2 mm/yr., intermediate (mean 13.6 mm/yr.) but highly variable on the reefs subject to land-based pollution, and lowest (mean 11.7 mm/yr.) on the fringing reef adjacent to the mangroves (table 4). There were significant differences in growth rates between the offshore reference reefs and the fringing reef adjacent to the mangroves, but not between the offshore reference reefs and the nearshore polluted reefs (table 4). Average coral growth rates were negatively correlated with chlorophyll A concentrations ($r=-0.95$, $p<0.05$, $n=5$). No trends in average coral growth rate through time were evident (fig. 4).

Coral skeletal density was highest on the offshore reefs (1.30 g/cm^3), intermediate on the fringing reef adjacent to the mangroves (1.21 g/cm^3), and lowest on the nearshore polluted reefs (1.12 g/cm^3). Skeletal density was significantly lower at Pulau Panjang than at Gosong Cemara, but was not significantly different among the other reefs (table 5). Coral calcification rates were significantly lower at Lagun Marican 1.39 g/cm^2/yr) than at Pulau Kecil (2.19 g/cm^2/yr), but was not significantly different among the other reefs (table 6).

Table 4. Coral growth rates

Reef	Average	Variance	N corals
G. Cemara	16.0	2.22	4
Pulau Kecil	16.3	4.35	5
Lagun Marican	11.7	2.13	5
P. Panjang	13.5	10.21	8
Bondo	13.8	11.78	4

Marginally significant difference (F=2.69, p<0.06, d.f.=4,21) in coral growth rates between reference reefs and L. Marican indicated by Dunnett's T3 test assuming unequal variance. No significant differences between polluted reefs and other reefs.

Reef	Cemara	Kecil	Marican	Panjang	Bondo
Cemara					
Kecil	NS				
Marican	p<0.06	P<0.06			
Panjang	NS	NS	NS		
Bondo	NS	NS	NS	NS	

Nonparametric Kruskall-Wallis test and quartiles indicate a marginally significant difference in coral extension rates between L. Marican and P. Kecil (H=7.89, p<0.10).

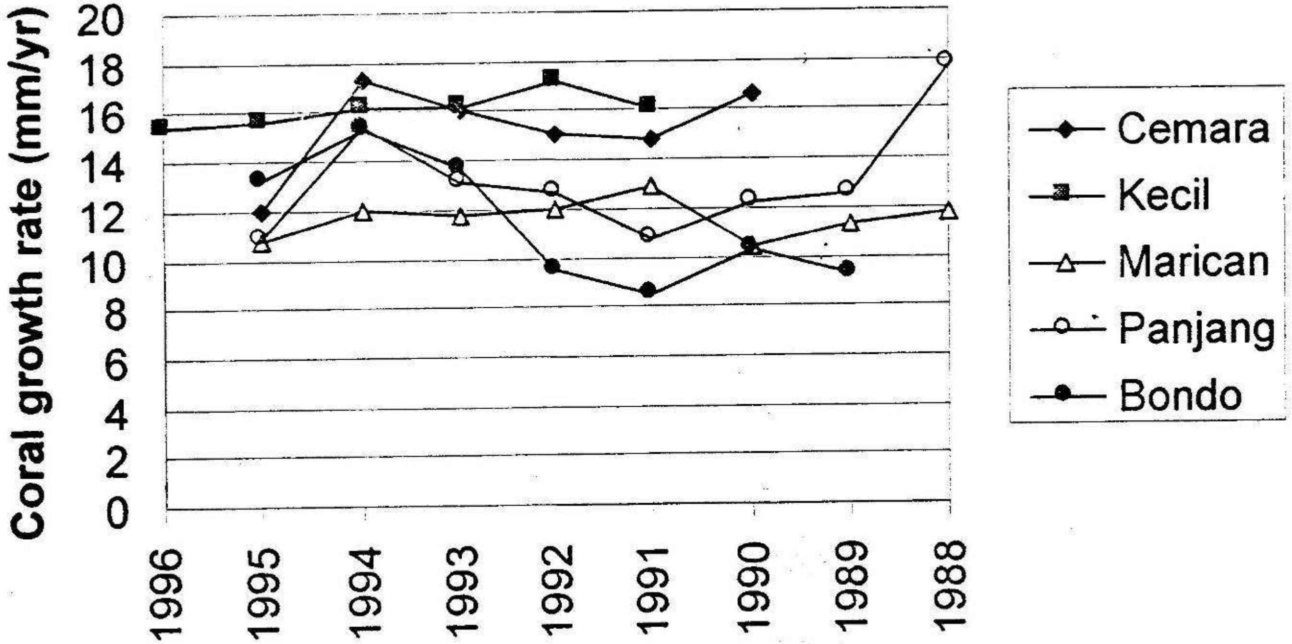


Figure 4 Coral growth rates through time at each reef. No temporal trends were observed within growth chronologies of individual corals.

Table 5. Coral skeletal density

Reef	Average	Variance	N corals
Gosong Cemara	1.33	0.39	4
Pulau Kecil	1.27	0.32	3
Lagun Marican	1.21	0.28	3
P. Panjang	1.08	0.26	4
Bondo	1.17	0.22	4

Significant difference (F=3.80, $p<0.05$, d.f.=4,13) in skeletal density only between G. Cemara and P.Panjang, as indicated by Tukey B test.

Reef	Cemara	Kecil	Marican	Panjang	Bondo
Cemara					
Kecil	NS				
Marican	NS	NS			
Panjang	p<0.05	NS	NS		
Bondo	NS	NS	NS	NS	

Table 6: Calcification rate

Reef	Average	Variance	N corals
Gosong Cemara	2.09	0.67	4
Pulau Kecil	2.19	0.48	3
Lagun Marican	1.39	0.51	3
P. Panjang	1.51	0.40	4
Bondo	1.54	0.60	4

Significant difference (F=4.58, $p<0.02$, d.f.=4,13) only between P. Kecil and L. Marican indicated by ANOVA and Tukey-B test.

Reef	Cemara	Kecil	Marican	Panjang	Bondo
Cemara					
Kecil	NS				
Marican	NS	P<0.02			
Panjang	NS	NS	NS		
Bondo	NS	NS	NS	NS	

3.6. Bioerosion

Massive coral bioerosion intensity was highest on the nearshore polluted reefs (8.5 %) and lowest on the offshore reference reefs (1.3 %; table 7). Similarly, branching coral rubble bioerosion was significantly higher on the nearshore polluted reefs than the offshore reference reefs (ANOVA, F=14.8, $p<0.0001$), and was positively correlated with chlorophyll A concentration in the water ($r=0.41$, $p<0.05$). Massive coral bioerosion and branching coral rubble bioerosion were positively correlated ($r=0.38$, $p<0.05$), showing that branching coral rubble can be used as a proxy measure for massive coral bioerosion. Branching coral rubble bioerosion was inversely correlated with live coral cover ($r=-0.37$, $p<0.05$), suggesting that branching coral rubble bioerosion can also be used as a proxy measure of reef health in general (cf. Holmes, 1997).

Table 7. Massive coral bioerosion intensity

Reef	Raw Average	Transformed average	Raw Variance	Transformed variance	N corals
Gosong Cemara	1.06	1.006	0.20	0.06	5
Pulau Kecil	1.62	1.25	0.59	0.09	3
Lagun Marican	1.74	1.22	2.36	0.32	5
P. Panjang	9.09	2.91	26.18	0.76	5
Bondo	7.92	2.72	25.70	0.67	4

Untransformed variance not homogeneous. (Levene statistic = 5.47, $p<0.005$). Data square-root transformed to homogenize variance, Levene statistic = 2.08, $p>0.12$).

Reef	Cemara	Kecil	Marican	Panjang	Bondo
Cemara					
Kecil	NS				
Marican	NS	NS			
Panjang	P<0.001	P<0.02	P<0.005		
Bondo	P<0.006	P<0.05	P<0.02	NS	

3.7. Net Carbonate Production

Net carbonate production was positive on the offshore reference reefs and negative on the nearshore reefs subject to land-based pollution (table 8, figure 5). Negative net carbonate production indicates that these reefs experience net reef erosion rather than net reef growth. Net carbonate production was strongly inversely correlated with chlorophyll A concentration ($r=-0.91$, $p<0.05$, $n=5$). This was stronger than the inverse relationship between light extinction coefficient and net carbonate production ($r= -0.78$, $p=0.12$, $n=5$), suggesting that nutrients and organic matter influence net carbonate production more than turbidity does. The net reef erosion experienced at Pulau Panjang is readily visible, as all sides of the island are eroding, and LandSat imagery shows that the island decreased in size between 1972 and 1990 (Kamiludin, et al., 1991).

Table 8. Net carbonate production

Table 8A. Gross Carbonate Production.

Reef	Calcification rate	% live coral cover	gross carbonate production
Gosong Cemara	2.09 (0.82)$_4$	68.5 (5.1)$_3$	14.3
Pulau Kecil	2.19 (0.69)$_3$	61.7 (17.8)$_5$	13.5
Lagun Marican	1.39 (0.71)$_3$	23.8 (5.9)$_3$	3.4
Pulau Panjang	1.51 (0.63)$_4$	21.2 (11.5)$_3$	3.2
Bondo	1.54 (0.77)$_4$	28.0 (8.2)$_5$	4.3

Gross carbonate production by corals is estimated as mean calcification rate of *Porites lobata* x percent live coral cover of all corals, assuming approximately equal calcification rates for all coral species on each reef. Standard deviations indicated (in brackets); numbers of measurements (in $_{\text{subscript}}$).

Table 8B. Carbonate Destruction.

Reef	Bioerosion	Density	Mean age	Live cover	dead cover	carbonate destruction
Gosong Cemara	1.06 (0.45)$_5$	1.33 (0.63)$_4$	9.4 (0.95)$_5$	68.5 (5.1)$_3$	19.8 (5.4)$_3$	1.32
Pulau Kecil	1.62 (0.77)$_3$	1.27 (0.57)$_3$	10.5 (3.22)$_3$	61.7 (17.8)$_5$	13.6 (5.0)$_5$	1.48
Lagun Marican	1.74 (1.54)$_5$	1.21 (0.53)$_3$	11.4 (2.27)$_5$	23.8 (5.9)$_3$	5.4 (4.9)$_3$	0.54
Pulau Panjang	7.91 (5.07)$_5$	1.08 (0.51)$_4$	7.8 (1.18)$_5$	21.2 (11.5)$_3$	58.9 (2.5)$_3$	8.77
Bondo	9.09 (5.12)$_4$	1.17 (0.47)$_4$	8.3 (3.37)$_4$	28.0 (8.2)$_5$	21.2 (6.5)$_5$	6.30

Standard deviations indicated (in brackets); numbers of measurements (in $_{\text{subscript}}$).

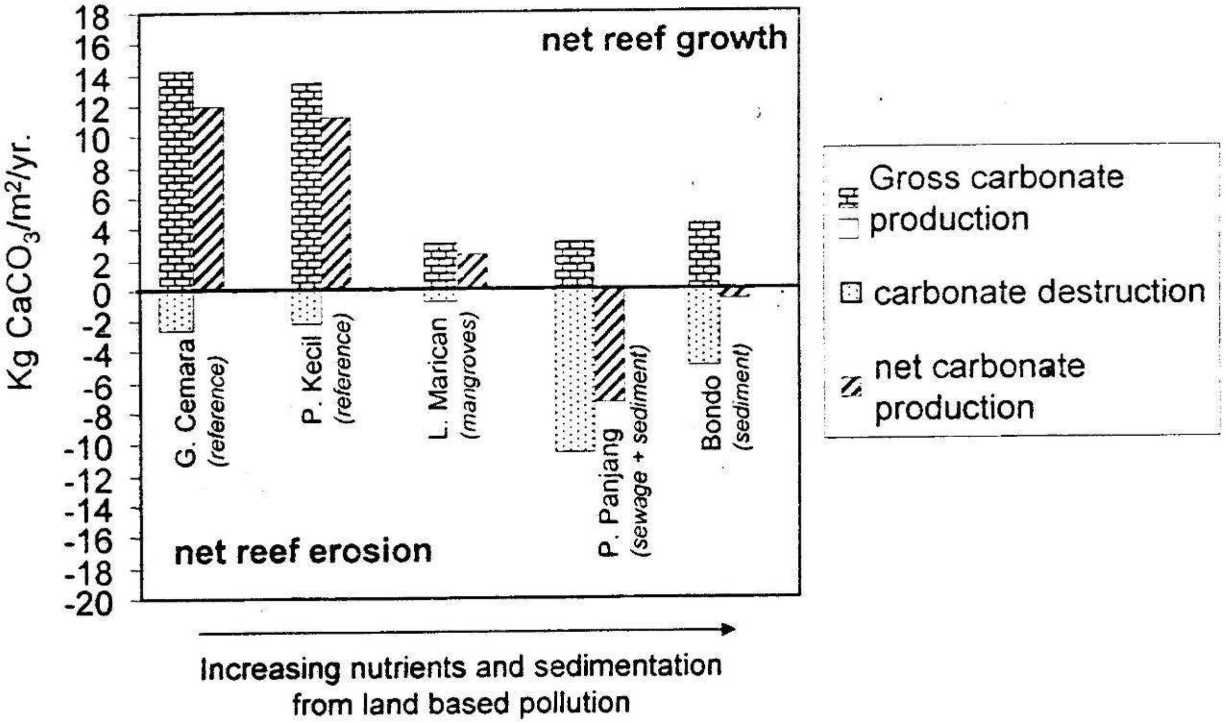


Figure 5 Gross & net carbonate production, Central Java reefs. Polluted reefs (P. Panjang, Bondo) both experienced net reef erosion, while reference reefs and the mangrove fringing reef all experienced net reef growth.

IV. DISCUSSION

Land-based pollution has had devastating impacts on the nearshore fringing reefs of Jepara, Central Java, similar to the reef degradation observed in Jakarta Bay and the Pulau Seribu (Tomascik et al., 1993). These effects are manifest in the transect data as low species diversity, low live coral cover, high coral mortality, and restricted coral morphological composition. From a carbonate budget standpoint, the polluted reefs are in very serious trouble, experiencing net reef erosion.

These reefs are unlikely to recover unless sources of land-based pollution are removed (Pearson, 1981; Tomascik et al., 1997). Reefs are capable of recovering from damage, given suitable conditions. Recovery from acute stresses like blast fishing is easier than recovery from chronic stresses, because the acute stresses do not cause deterioration of water quality (Pearson, 1981). Regardless of the type of stress, recovery requires that the stress be controlled or removed (Birkeland, 1997). Recovery after chronic stresses have been removed generally requires one to three decades (Tomascik, et al., 1997)

Determining which pollution sources are most responsible for the deterioration of nearshore reefs is difficult, because they overlap in space, and because chlorophyll A concentration, suspended particulate matter, sediment resuspension, and water clarity all covary. On the reefs sampled in this study, linear regression suggested that coral diversity, cover, and growth rates, and reef net carbonate production were more strongly related to chlorophyll A concentration than to the other environmental factors measured. Many of the corals at Pulau Panjang have lesions and infections, suggesting an impact of pathogenic organisms from sewage and aquaculture effluent. Similarly, the high bioerosion intensities observed at both Bondo and Pulau Panjang, are a typical consequence of organic matter loading, particularly sewage and animal waste (Rose & Risk, 1985). Conversely, bioerosion intensity was low on the fringing reef adjacent to the mangroves, even though Lagun Marican had the highest average chlorophyll A concentration of the sites studied. These data suggest that organic matter loading from sewage and shrimp ponds has contributed strongly to the deterioration of nearshore reefs in Jepara and Bondo.

The coral reefs in the Karimunjawa National Marine Park are mostly not affected by land-based pollution, as populations in the islands are small, and there is no industry. The increasing number of shrimp ponds on Karimunjawa island is cause for great concern, however, as the shrimp ponds are among the chief causes of reef decline on the mainland reefs near Jepara. Various water quality parameters worsened on a fringing reef in Karimunjawa when a shrimp pond was drained into adjacent waters (G. Llewellyn, unpublished data). Other threats to the reefs in illegal cyanide fishing, remnant coral mining, and overfishing, as evidenced by the lack of large fish, either herbivores or piscivores on most Karimunjawa reefs (Rao, 1998).

Our results also suggest that the current system of estimating reef health in Indonesia needs revision. Currently, reefs are evaluated as in poor, fair, good, or excellent condition based solely on live coral cover, accordingly to a linear scale. Reefs with less than 25% live coral cover are considered in poor condition; those with

25-50%, fair condition; 50-75%, good condition; and >75%, excellent condition (Gomez & Yap, 1988). According to this scale, the polluted reefs in Jepara and Bondo would be classified as "fair condition", while the mangrove fringing reef in Karimunjawa would be considered as in "poor condition". Our carbonate budget results, however, suggest that the mangrove fringing reef maintains net reef growth, while the polluted reefs undergo net reef erosion. Furthermore, the site with the highest live coral cover, MJL3, had very low species diversity, equivalent to that observed on the polluted reefs. Reefs could be more effectively classified for conservation purposes using the combination of live coral cover, coral mortality indices, and coral morphology triangles (Edinger and Risk, in press).

The implications of this study for coral reef management in Central Java are three-fold. First, the Jepara area reefs have been badly damaged by land-based pollution. Second, the chronic stress caused by land-based pollution can only be mitigated by cleaning up the sources of pollution. Third, overfishing threatens the Karimunjawa reefs, and has exacerbated the degradation of the Jepara reefs, but does not bear primary responsibility for their demise. Attempts at reef restoration, such as coral transplants, artificial reefs, or, fisheries restrictions, which do not address the land-based pollution sources will be futile.

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