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Reef Degradation and Coral Biodiversity in Indonesia: Effects of Land-based Pollution, Destructive Fishing Practices and Changes Over Time

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Species–area curves calculated from line-intercept transect surveys on 15 reefs in three regions of Indonesia allow estimation of the relative decrease in within-habitat coral species diversity associated with different types of reef degradation. Reefs subject to land-based pollution (sewage, sedimentation, and/or industrial pollution) show 30–50% reduced diversity at 3 m, and 40–60% reduced diversity at 10 m depth relative to unpolluted comparison reefs in each region. Bombed or anchor damaged reefs are *ca* 50% less diverse in shallow water (3 m depth) than are undamaged reefs in the same region, but at 10 m depth the relative decrease is only 10%. Comparison reefs in the Java Sea are *ca* 20% less diverse than their counterparts in Ambon, Maluku. The results, compared with a previous survey in the Spermonde Archipelago found a 25% decrease in generic diversity of corals on two reefs resampled after 15 years. The decreased diversity on reefs subject to land-based pollution implies a dramatic, rapid decrease in Indonesian reef-based fisheries resources.

Keywords: biodiversity; reef degradation; Indonesia.

1. Introduction

Indonesia's coral reef resources are among the richest and most diverse in the world. Eastern Indonesia lies at the centre of diversity for corals (Veron, 1993), molluscs, reef fishes and other reef organisms, along with the Philippines (McManus, 1985) and the north coast of Papua New Guinea (Pandolfi, 1992). This wealth in biodiversity emphasizes Indonesia's importance in global efforts to conserve marine resources and preserve biodiversity (BAPPENAS, 1993).

Threats to Indonesia's coral reef resources can be divided into two main types: acute threats; and chronic stresses. Acute threats cause dramatic damage in a short period of time. Examples include destructive fishing practices, such as blast fishing, as well as other forms of mechanical damage, like anchor damage, ship groundings, cyclones or *Acanthaster* outbreaks. Acute threats cause significant damage, but do not persist; the reef can, and usually will, recover if protected from further assaults (Pearson, 1981). Chronic stresses, on the other hand, alter the physical or biological environment on a long term basis, and cause long term damage to coral reefs. Examples in Indonesia include sewage pollution, increased sedimentation, nearshore eutrophication, and industrial pollution (Tomascik *et al.*, 1993). Non-point source pollution, such as sewage and agricultural/aquacultural runoff, is an increasingly important type of stressor in Indonesia (McManus, 1988; Cesar, 1996). Reefs normally will not recover from chronic stresses until the stressor is removed, that is, the pollution is cleaned up (Grigg, 1995).

This study quantitatively evaluates several threats to Indonesian coral reefs with respect to their impact on coral reef biodiversity. The implications of this study for coral reef biodiversity conservation and manage-

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ment are simple: to understand what threats to reefs deserve most attention it is necessary to evaluate which threats have the greatest impact on biodiversity. The results suggest that the severity of the threats to Indonesian reefs are greater than previously thought, and that many of these problems will be difficult to address.

2. Methods

2.1. Study areas

This study was conducted in three areas within Indonesia [Fig. 1(A)]: Ambon [Moluccas; Fig. 1(E)], the Spermonde Archipelago [South Sulawesi; Fig. 1(B)] and Central Java [Fig. 1(B and C)]. In eastern Indonesia, four reefs in each region were sampled (Table 1), one comparison site and three sites subjected to varying forms of degradation. Comparison sites are operationally defined – they are the reefs within each region least affected by anthropogenic stress, usually by virtue of being located away from centres of habitation. The degraded sites included three subject to land-based pollution (Wailiha, Wayame and Kayangan) and three subject to various forms of mechanical damage (Hila, Samalona and Barang Lompo). Further details on the Eastern Indonesian sites are presented in Jompa (1996) and Limmon (1996).

The Java Sea sites (Table 1) include two comparison reefs in the Karimunjawa islands national marine park [P. Kecil, G. Cemara; Fig. 1(C)], one reef affected by storm damage (P. Burung, windward), one fringing reef adjacent to mangroves (L. Marican), and two nearshore reefs in Jepara [P. Panjang, Bondo; Fig. 1(B)], both subject to high levels of land-based pollution. The comparison reefs in the Karimunjawa islands

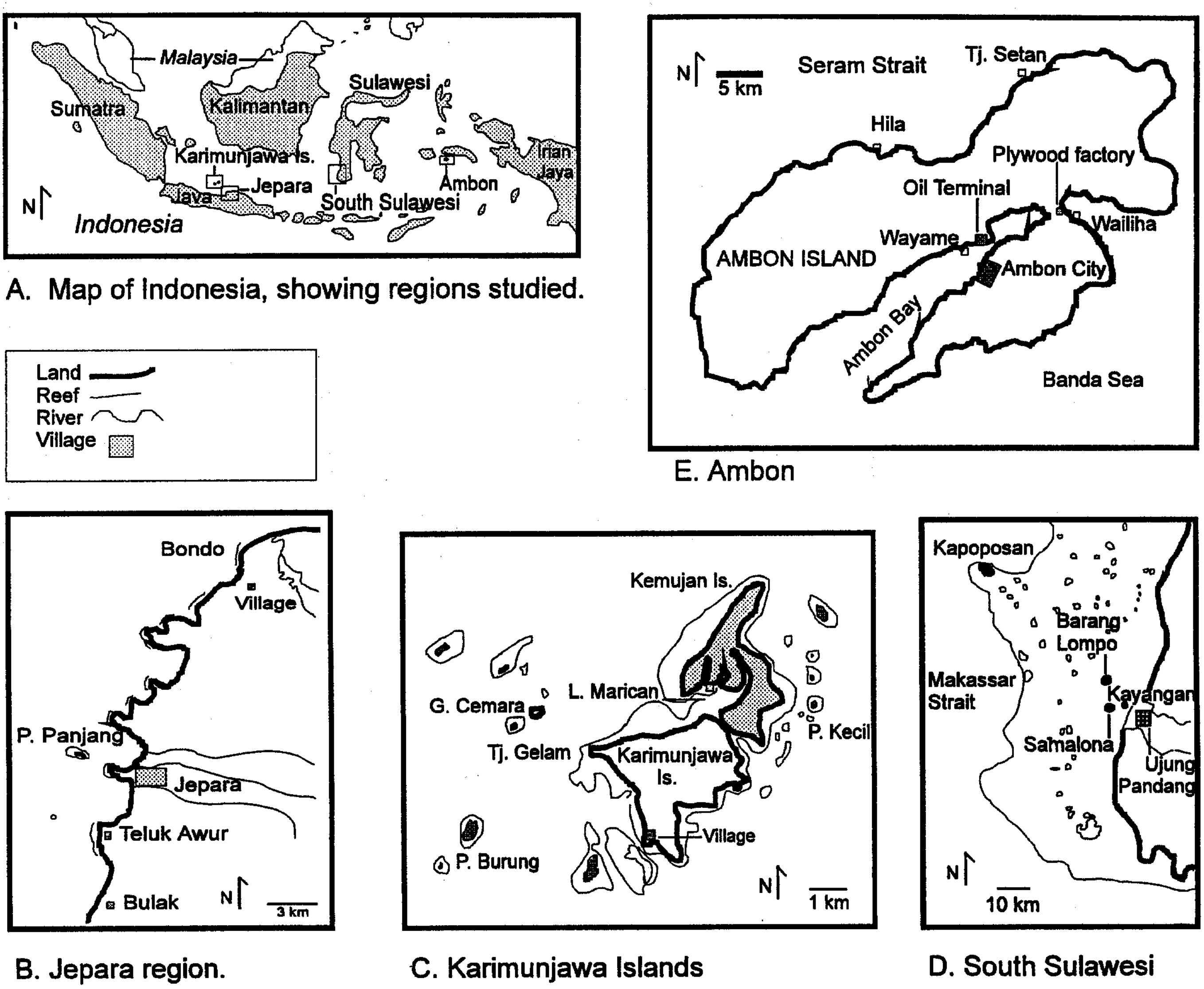

Fig. 1 Maps to study sites. (A) All Indonesia, showing regions studied, including Jepara (B), Karimunjawa (C), both in the Java Sea, and two areas in eastern Indonesia, the Spermonde Archipelago in South Sulawesi (D), and the island of Ambon (E), in the Moluccas.

TABLE 1
Study site regions, names, morphologies and summaries of stresses.

Region	Reef name	Reef morphology	Maximum depth (m)	Source of stresses
Ambon	Tanjung Setan	Fringing reef/wall	40	Unaffected sites (10 m, 3 m)
	Hila	Fringing reef	20	Bombing, construction, rubble bottom
	Wayame	Fringing reef	15	Harbour, sewage, sedimentation
	Wailiha	Fringing reef	6	Sediment, plywood factory
So. Sulawesi	Kapoposan	Coral cay/wall	50	Unaffected (10 m), bombed (3 m)
	Barang Lompo	Coral cay island	25	Bombing, local sewage pollution
	Samalona	Coral cay island	25	Anchor damage, pollution from city
	Kayangan	Coral cay island	11	Harbour, industry, sewage, sedimentation
Karimunjawa	Pulau Kecil	Coral cay island	25	Java unaffected, overfishing
(Central Java)	Gosong Cemara	Coral cay, submerged	20	Java unaffected, overfishing
	Pulau Burung	Coral cay island	25	Storm damage (windward only)
	Lagun Marican	Mangrove fringe	4	Carbonate sedimentation
Jepara	Pulau Panjang	Coral cay island	8	Sewage, sediment, aquaculture
(Central Java)	Bondo	Fringing reef	5	Sedimentation, agricultural runoff

Max. depth: maximum depth of coral growth. Source of stresses summarizes impacts on each reef. More detailed descriptions of each reef can be found in Limmon (1996), Jompa (1996) and Edinger (1998).

are far from pristine; they are subject to intense fishing activity by non-destructive means, with attendant effects (Roberts, 1995). Nonetheless, they provide the best local comparison for degraded Java Sea reefs. Further description of Java Sea sites is presented in Edinger (1998).

The reef names, morphological types, maximum depth of coral growth, and primary stresses are listed in Table 1. Environmental data characterizing each site are listed in Table 2; methods for measuring environmental data are discussed in Section 2.2.

2.2. *Environmental data: methods*

The nature of the stresses at each site were determined by qualitative observations (notes on bomb craters, etc.) and by a series of environmental measurements including chlorophyll A, suspended particulate matter (SPM) concentrations, and sediment resuspension rates and water clarity or light penetration, measured by secchi disk extinction depth. All measurements were repeated on at least three occasions for each reef; averages and standard deviations are reported in Table 2. Raw environmental datasets are presented in Jompa (1996), Limmon (1996) and Edinger (1998). Ambon and Sulawesi sampling was conducted in May–August 1995; sampling in the Java Sea was conducted in November–December 1994, July–November 1995 and August–November 1996. Ambon chlorophyll sampling was repeated in May–July 1997.

2.2.1. *Chlorophyll A concentrations*

Chlorophyll A concentrations were measured using standard filter methodology (Parsons *et al.*, 1984). Filters were frozen and transported on ice to Canada,

TABLE 2
Environmental parameters measured for each reef in the study. Water Clarity: water clarity as measured by average secchi disk extinction depth.

Region	Reef name	Depth (m)	Chloro. A (mg m^3)	SPM (mg l^{-1})	Resuspension (mg cm^{-2} day^{-1})	Water clarity (m)
Ambon	Tanjung Setan	All	0.39 (0.18)	4.49 (1.40)	0.08 (0.02)	> 20
	Hila	All	0.44 (0.21)	4.91 (2.66)	0.19 (0.14)	20
	Wayame	All	0.38 (0.06)	11.15 (3.40)	0.55 (0.23)	10
	Wailiha	All	0.46 (0.14)	15.3 (10.21)	3.08 (3.13)	<4
So. Sulawesi	Kapoposan	All	0.47 (0.05)	5.26 (1.24)		> 20
	Barang Lompo	All	.075 (0.07)	8.62 (1.60)	0.7 (0.2)	17
	Samalona	All	0.82 (0.05)	8.22 (1.30)	0.6 (0.1)	18
	Kayangan	All	1.52 (0.53)	19.25 (4.61)	2.8 (0.2)	<5
Karimunjawa	Pulau Kecil W/W	3	0.33 (0.08)	9.75 (6.71)	2.03 (0.55)	20
(Central Java)	Pulau Kecil L/W	3	0.29 (0.17)	19.69 (18.27)	1.63 (1.31)	18
	G. Cemara W/W	3	0.40 (0.21)	22.98 (2.98)	4.21 (3.31)	20
	G. Cemara L/W	3	0.25 (0.14)	22.26 (7.56)	2.80 (3.62)	16
	P. Burung W/W	All	0.40 (0.01)	4.45		22
	P. Burung L/W	All	0.22 (0.01)	19.69		18
	Lagun Marican	3	1.24 (0.90)	26.39 (11.58)		<3
Jepara	P. Panjang W/W	3	1.23 (0.54)	21.83 (8.40)	26.19 (24.42)	<4
(Central Java)	P. Panjang L/W	3	1.09 (0.62)	28.91 (17.86)	31.69 (38.74)	<2
	Bondo	3	1.22 (0.52)	21.04 (4.60)	57.5 (83.7)	<2

All values are averages (standard deviations) of a series of measurements. Ambon measurements are wet season, while Sulawesi and Java measurements are mostly dry season or transitional (November). Methods are described in text.

where they were analysed using the method of Burnison (1980).

2.2.2. Suspended particulate matter

Suspended particulate matter was measured at all reefs by filtering 1 l of seawater onto a pre-weighed glass fibre filter, which was subsequently oven-dried and weighed (Cortes and Risk, 1985).

2.2.3. Sediment resuspension

Sediment resuspension was measured using sediment traps, consisting of 30 cm long PVC tubes, 5 cm in diametre. In Ambon and Sulawesi, these were deployed in arrays 25, 50 and 75 cm above the bottom, at 3 m depth on each reef (Cortes and Risk, 1985). In Central Java, these were deployed on the reef surface at three depths: 3 m, 10 m and at the base of the reef (Karimunjawa), or 1 m, 3 m and at the base of the reef (nearshore reefs). Sediment traps were collected weekly in Ambon and Sulawesi, and twice a month or monthly in Central Java. Accumulated sediment was oven dried, weighed and subsampled for carbonate content and constituent analysis, for use in other studies. The values reported here are average sediment resuspension rates at 3 m.

2.2.4. Water clarity

Water clarity was estimated using standard secchi disk extinction depth measurements. These were repeated on at least three occasions at each reef, noting weather and sea conditions.

2.3. Sampling methods

In Ambon, all reefs sampled were fringing reefs. In Sulawesi, all coral cays were sampled on the leeward side, which generally had the most luxuriant coral growth, except at Kayangan, where the leeward reef is dead, and the windward reef was sampled. In Java, all reefs were sampled on both windward and leeward sides, except the fringing reef at Bondo and the reef fringing the mangroves at Lagun Marican. Transect locations were non-adjacent, non-overlapping and dispersed over at least 200 m laterally along each reef, such that the reef areas sampled would incorporate variation on each reef. Windward vs leeward replication in the Java Sea, and replication of disturbance on nearby reefs in Sulawesi ensured that kilometre scale heterogeneity (Edmunds and Bruno, 1996) was accounted for, while replication of disturbance regime within and between regions helped to account for larger scale biogeographic variation.

2.3.1. Coral morphology and reef cover classes

At least six replicate 20 m line intercept transects (Risk, 1972; Loya, 1978) were measured at 3 and 10 m depth at each of the sites, totalling a minimum of 12 transects, or 240 m cumulative transect length, per reef, in most cases. For three reefs on which coral growth did not continue beyond 6 m depth (Wailiha, Bondo, L. Marican), transects were measured at 3 m only. Ambon and Sulawesi sampling took place in May–August 1995; Java Sea transect sampling took place in July–November 1995 and August–November 1996. Life form transects were measured for cover of live corals, separated by morphological life forms and cover of dead coral, algae, other invertebrates and abiotic substrates (e.g. sand and rubble). Mortality index (Gomez, 1994) was calculated as:

$$\mathrm{MI} = \frac{\text{live coral cover}}{\text{live coral cover} + \text{dead coral cover}}$$

2.3.2. Coral species diversity

Of a total 146 transects measured, 94 were recorded with coral species identifications, and were used for compiling a total of 32 species–area curves (Loya, 1978). During intensive sampling in August–November 1995 and 1996, all coral species occurring on each 20 m transect were noted, as were the positions of the first occurrence of each species along each transect. In nearly all cases, species–area curves asymptotically approached horizontality within a cumulative sampling distance of 40 m; the exceptions were the highly diverse reefs in Ambon (Fig. 2), which approached horizontality by 60 m cumulative transect length.

All corals except *Acropora* were identified using Veron (1986). Field parties did not have sufficient experience in *Acropora* taxonomy to allow species identifications underwater, and due to the impoverished nature of many of the stressed reefs, the authors were reluctant to collect large suites of specimens for later identification. Rather, *Acropora* corals were identified to species group (Veron and Wallace, 1984; Veron, 1986) in the field, and representatives of each species group were collected for provisional identifications, and subsequent verification by Dr C. C. Wallace.

2.4. Data analysis

Line intercept transect data were pooled for each reef to compute average percent covers of six basic categories: Acroporid corals; non-Acroporid corals; total live corals; dead corals; algae; other invertebrates; and abiotic substrates. Morphology data are discussed in more detail elsewhere (Edinger, 1998).

Coral species–area curves were compared statistically using two methods. First, because nearly all species–area curves were observed to approach horizontality by 40 m cumulative length (Figs 2–4), coral diversity was compared among reefs by counting the number of coral species sampled in the first 40 m of each species–area curve. Next, the distance axes of species–area curves from each reef were $\log_{10}$ transformed, converting the curves to lines, *N* spp. vs. $\log_{10}$(distance), passing through the origin. The slopes of these lines were calculated using linear regression ($r^2 > 0.90$ in all but one case, where $r^2 = 0.83$), and were compared using one-way ANOVA (Sokal and Rohlf, 1973). Slopes of these diversity lines were also used in regression analyses of diversity vs live coral

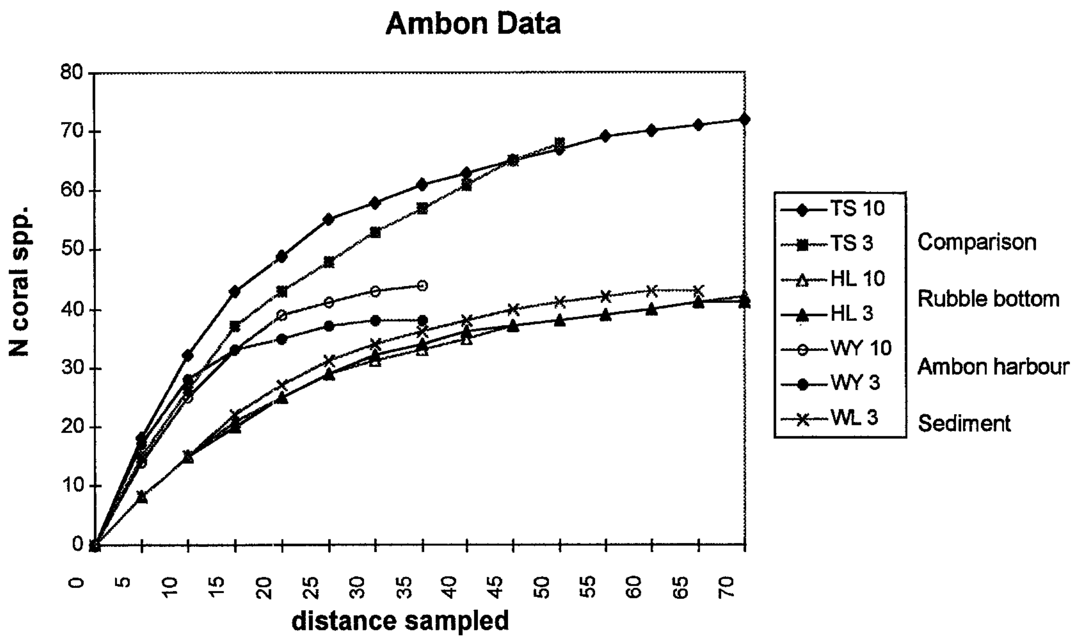

Fig. 2 Ambon species-area curves. Site codes follow Tables 1 and 3; stresses listed at margin. Within-habitat diversity is significantly less at affected sites than at comparison site.

cover (Aronson and Precht, 1995; Cornell and Karlson, 1996) and environmental parameters (Fraser and Currie, 1996).

These two methods yielded nearly identical results, and were very highly significantly correlated with one another ($r^2 = 0.95$, $P < 0.0001$, $n = 32$). Species–area curves are presented in Figs 2–7; these are intuitively more understandable than the the $\log_{10}$ transformed slopes (Figs 8 and 9) which are used in statistical analyses.

3. Results

3.1. Species–area curves

Within biogeographic regions, species–area curves clearly show reduced species diversity on reefs

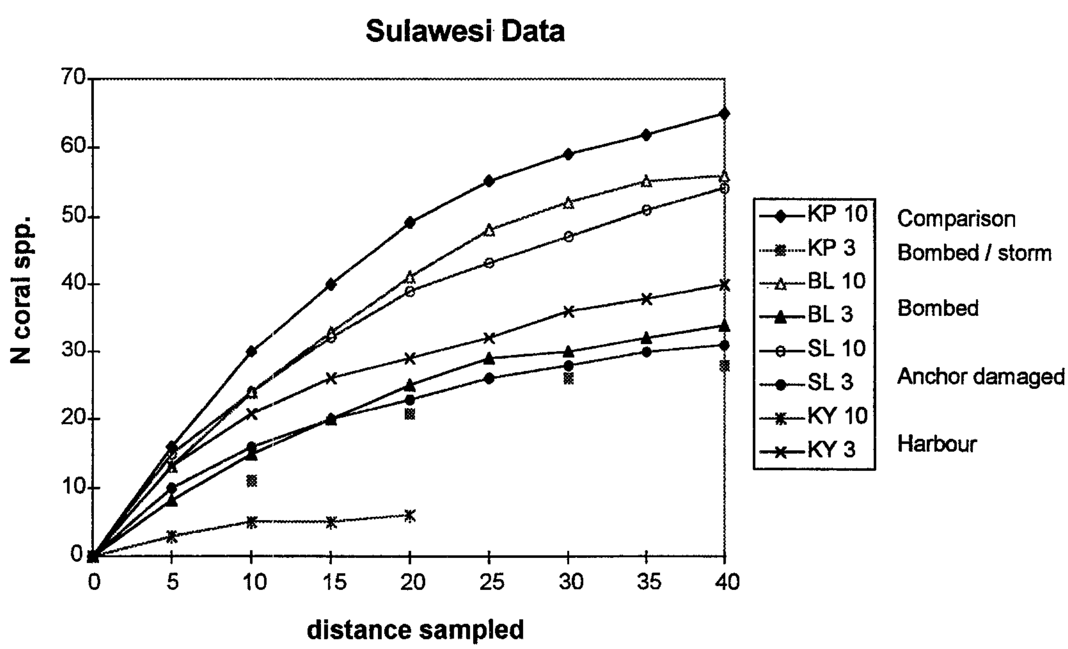

Fig. 3 Sulawesi species-area curves. Site codes follow Tables 1 and 3; stresses listed at margin. Within-habitat diversity is significantly less at affected sites at 3 m than at comparison site (KP 10) but not at 10 m (Barang Lompo and Samalona).

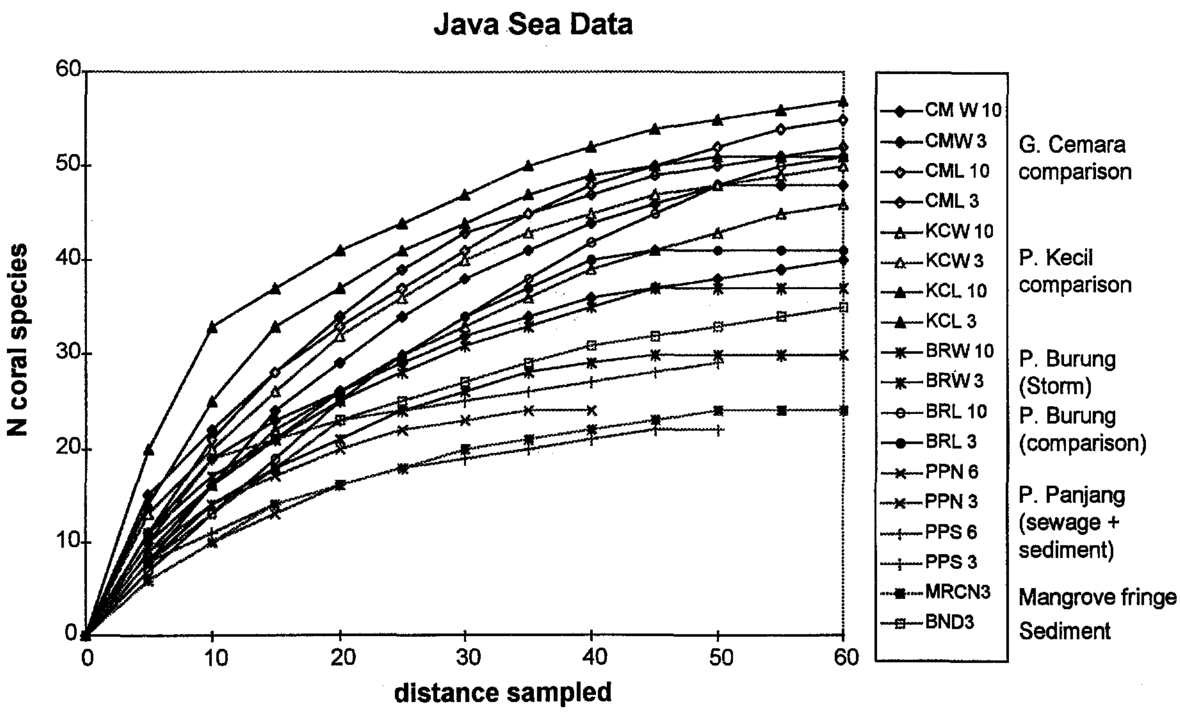

Fig. 4 Java Sea species-area curves. Site codes follow Tables 1 and 3; stresses listed at margin. Within-habitat diversity is significantly less at affected sites (Pulau Panjang, Bondo, Lagun Marican) than at comparison sites in Karimunjawa.

subjected to various forms of degradation (Ambon, Fig. 2; Sulawesi, Fig. 3; Central Java, Fig. 4). Figures 5–7 show the effects of different kinds of reef degradation, pooled among the various regions.

3.2. Comparison/comparison reefs

The comparison reefs in Ambon (Tanjung Setan 3 and 10 m) and Sulawesi (Kapoposan 10 m) all show approximately equivalent diversity (Fig. 5). The most diverse comparison Central Java reefs at P. Kecil and G. Cemara, Karimunjawa are *ca* 20% less diverse than their Eastern Indonesian counterparts. The differences between Eastern Indonesian diversity and Java Sea diversity probably reflect both biogeographic differences (Cornell and Karlson, 1996; Fraser and Currie, 1996; Wallace, 1997) and more intense overfishing in

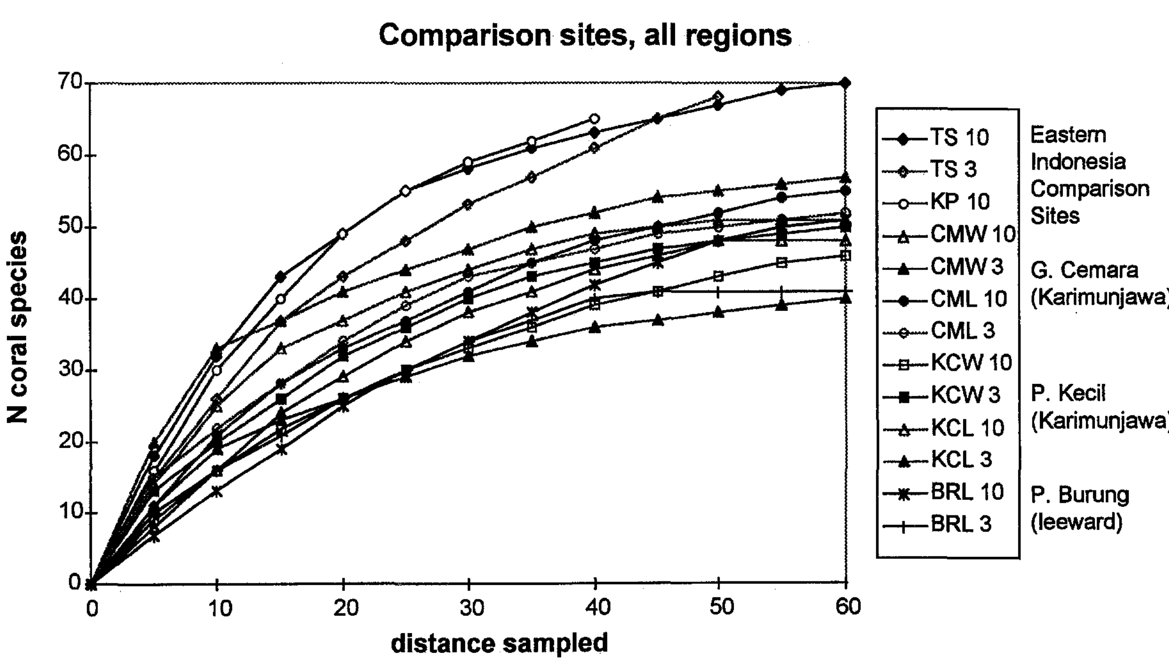

Fig. 5 Species-area curves: comparison sites and overfishing. Site codes follow Tables 1 and 3. Within-habitat coral species diversity on the Java Sea comparison sites is ca 20% less than on eastern Indonesian comparison sites.

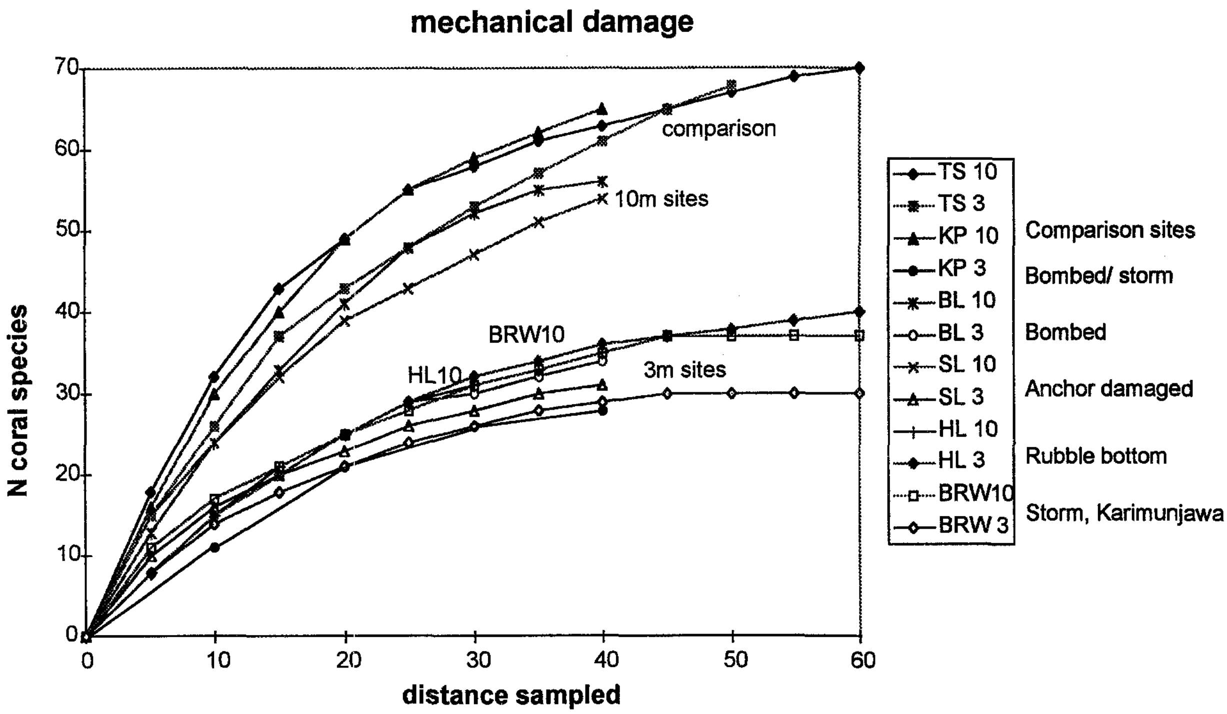

Fig. 6 Species-area curves: mechanical damage. Site codes follow Tables 1 and 3. Nearly exact coincidence between curves for HL3, HL10, and BRW 10, at the top of the 3 m sites group, makes the three curves difficult to separate on the graph.

the Java Sea (Roberts, 1995); this question is addressed elsewhere (Edinger, 1998).

Coral cover and species diversity are approximately equivalent at P. Kecil, G. Cemara and P. Burung (leeward side), and the coral faunas at P. Kecil and G. Cemara are > 77% similar [Jaccard similarity index, $S = 63.5$; Edinger (1998)]. The leeward sides of these reefs are generally 15–20% more diverse than the windward sides (Table 3).

3.3. Mechanical damage

Two reefs subject to anthropogenic mechanical damage, such as anchor damage (Samalona) or bombing (Barang Lompo), show dramatically reduced

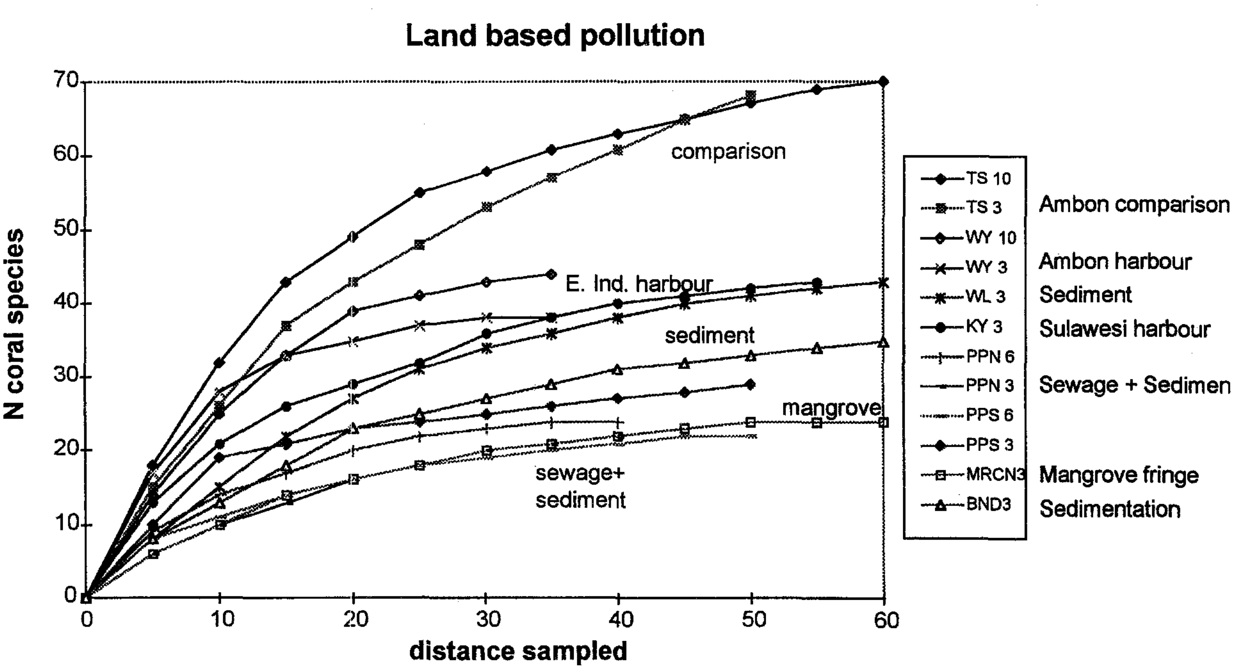

Fig. 7 Species-area curves: land-based pollution. Site codes follow Tables 1 and 3.

diversity at 3 m, *ca* 50% of diversity on comparison reefs in the region. Diversity at 10 m on these reefs is only slightly reduced below the level on comparison reefs (Fig. 6). By contrast, a reef damaged by storms (P. Burung, Karimunjawa, windward side) had 30% reduced diversity at 3 m, and 15% reduced diversity at 10 m, relative to the windward sides of P. Kecil and G. Cemara averaged. The reef at Hila, growing on a rubble bottom, and affected by bombing, construction damage, and villagers overturning corals in shallow water, had 50% reduced diversity at both 3 and 10 m depth.

3.4. Eutrophication stresses

Five reefs subject to various forms of land-based pollution were sampled (Fig. 7). In most cases, these reefs suffered from a combination of stresses, and it is difficult to separate clearly the effects of sewage, agricultural and aquacultural runoff, sedimentation and industrial effluent. Reefs subject to these stresses had approximately equivalent reductions in coral diversity, *ca* 30–60%, with diversity reductions at 10 m greater than or equal to those at 3 m, except at Wayame (Ambon). Sites subjected to sedimentation and agricultural runoff (e.g. Bondo) had greater diversity than those subjected to combined sewage and sedimentation (e.g. P. Panjang). The lowest diversity sites in Jepara had equivalent diversity to fringing reefs bordering intact mangroves in Karimunjawa (L. Marican).

3.5. Statistical comparisons

The slopes of the $\log_{10}$-transformed species–area curves were used for calculating statistical analyses of diversity. Fig. 8(A) shows the mean diversity ±95% confidence limits of reefs sampled in each degradation type and depth, summed over all three regions. Although variance is particularly high for mechanical damage at 10 m depth, where two sites (anchor damage and bombing) had much higher diversity than the other two (construction/rubble bottom and storm damage), and for the harbour sites (Wayame, Kayangan), average slopes are significantly different among the various groups (ANOVA, $F = 6.98$, $P < 0.0002$, $\mathrm{df} = 36$). There is a biogeographic bias to these groupings, however, where Eastern Indonesian sites of all degradation types appear to be more diverse than Java Sea counterparts of the same degradation types. Biogeographic differences in diversity are discussed in Edinger (1998).

Analysis of the slopes of the log-transformed species-area curves showed that relative diversity among the degradation types studied may be ranked as follows:

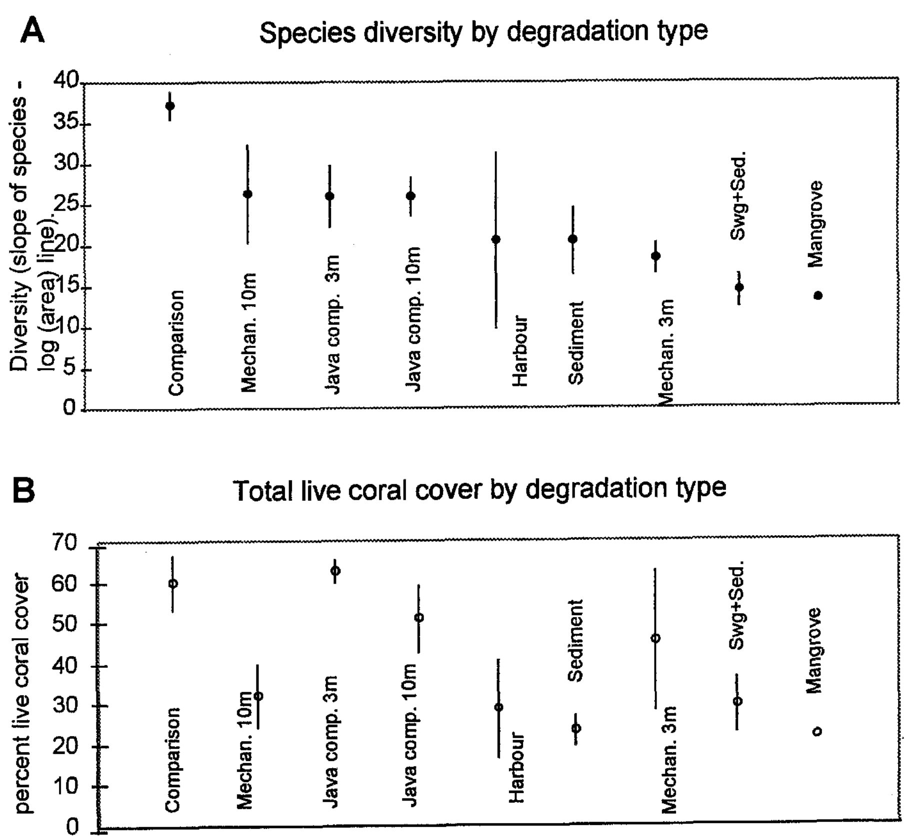

Fig. 8 (A) Coral species diversity, measured as slope of log-transformed species area curve, mean ±95% confidence limits, by degradation type. (B) Total live coral cover by degradation type, mean ±95% confidence limits, by degradation type.

1. Eastern Indonesian comparison reefs;
2. Java Sea comparison reefs;
3. mechanically damaged reefs at 10 m depth;
4. Eastern Indonesian polluted reefs;
5. mechanically damaged reefs at 3 m depth; and

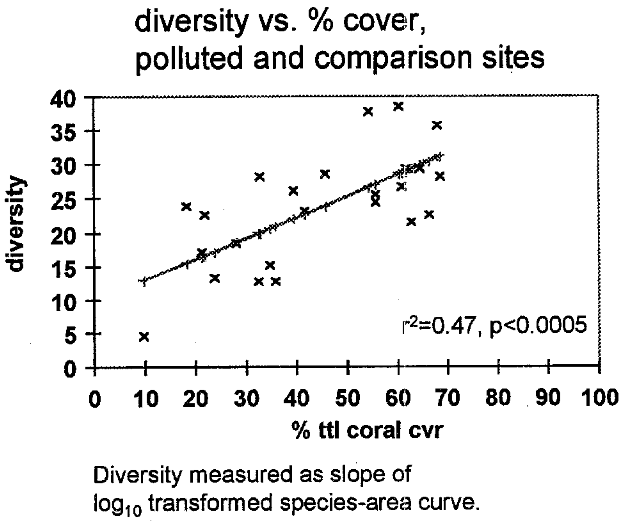

Fig. 9 Diversity vs. cover, pollution-affected reefs and comparison reefs. Diversity measured as slope of log-transformed species-area curve.

6. Java Sea polluted reefs.

These differences are high significant (ANOVA, $F = 23.96$, $P < 0.0001$, df = 29). Further analysis by *post-hoc* Tukey test (Table 4) shows the same ranking.

Additionally, the site data may be grouped into six major categories: the three site types (comparison, mechanical damage and land-based pollution) times 3 and 10 m depths, which have very highly significant differences in diversity (one-way ANOVA, $F = 9.26$, $P < 0.0001$).

3.6. Live coral cover

Total percent live coral cover was highest on the Eastern Indonesian comparison reefs, but was not significantly different among the Eastern Indonesian comparison sites and the Karimunjawa comparison reefs. Total live coral cover was intermediate on reefs subject to mechanical damage, and lowest on reefs subject to eutrophication stresses, such as sedimentation, or combined sewage and sedimentation [Fig. 8(B); one-way ANOVA, $F = 10.28$, $P < 0.0001$]. Table 3 shows the diversity and major cover class data for all the sites. Mortality index was higher on reefs subject to land-based pollution ($\bar{x} = 0.44$) than on comparison

TABLE 3
Diversity and cover summaries for all reefs.

Reef	Stress	Site	Depth	S/40 m	Slope	Acropora (%)	% Non-Acropora	% Live coral	% Dead coral	% Algae	% Other fauna	% Abiotic	Mortality index
Wailiha	Sediment	WL 3	3	38	22.66	5.98	15.75	21.73	22.31	4.44	21.10	30.41	0.51
Wayame	Harbour	WM 10	10	44	28.25	10.51	22.18	32.69	20.59	3.44	16.54	26.76	0.39
		WM 3	3	38	28.25	14.95	24.36	39.31	25.94	1.22	17.15	16.39	0.40
Hila	Rubble	HL 10	10	35	21.83	0.71	22.25	22.96	30.33	0.02	9.32	37.37	0.57
		HL 3	3	36	21.47	4.11	27.26	31.37	26.46	0.94	9.78	31.45	0.46
Tjg. Setan	Control	TJS 10	10	63	38.58	21.56	38.80	60.36	19.41	0.87	11.42	7.96	0.24
		TJS 3	3	61	35.81	23.82	44.19	68.01	16.19	1.78	10.81	3.23	0.19
Kayangan	Harbour	KY 10	10	6	4.55	0.00	9.83	9.83	11.23	1.99	15.71	61.08	0.59
		KY 3	3	40	23.90	3.52	14.67	18.18	25.67	12.63	9.13	33.16	0.59
Samalona	Offshore	SM 10	10	54	30.59	4.91	36.64	41.55	16.85	0.05	14.57	26.98	0.29
	Anchor	SM 3	3	31	18.32	14.18	32.86	47.04	14.66	0.55	5.35	32.30	0.24
B. Lompo	Local sewage	BL 10	10	56	32.51	6.92	33.34	40.26	18.81	2.01	6.41	32.51	0.30
	Bombed	BL 3	3	34	19.44	24.15	30.01	54.16	16.85	1.29	7.07	20.64	0.23
Kapoposan	Control	KP 10	10	65	37.79	7.47	47.02	54.49	6.80	7.28	22.42	3.42	0.18
	Bom/strm	KP 3	3	28	16.10	28.80	45.59	74.39	13.67	1.33	8.24	2.25	0.14
Cemara	Control/	CMW 10	10	44	25.59	18.15	37.65	55.80	24.35	0.00	0.75	16.85	0.30
	overfish	CMW 3	3	36	21.61	47.35	15.58	62.93	16.69	6.01	3.95	7.81	0.21
		CML 10	10	48	28.51	8.57	36.98	45.55	20.27	0.17	4.57	29.28	0.31
		CML 3	3	47	28.26	41.32	27.18	68.50	19.83	1.02	9.09	1.55	0.22
Kecil	Control/	KCW 10	10	39	23.24	6.72	34.70	41.42	24.54	4.92	5.35	17.80	0.37
	overfish	KCW 3	3	45	26.81	27.37	33.53	60.90	20.70	4.47	5.32	6.75	0.25
		KCL 10	10	49	29.22	2.40	62.10	64.50	25.88	5.53	0.33	3.61	0.29
		KCL 3	3	52	29.22	25.84	35.90	61.74	13.61	5.85	4.23	14.58	0.18
Burung	Storm	BRW 10	10	35	20.74	8.82	23.67	32.48	12.17	7.50	13.10	34.75	0.27
	Storm	BRW 3	3	29	17.12	10.32	17.90	28.22	4.40	46.97	6.33	14.08	0.13
	Control/	BRL 10	10	42	24.53	22.23	33.58	55.82	9.80	13.47	11.05	9.87	0.15
	overfish	BRL 3	3	40	22.65	37.57	28.82	66.38	8.00	6.62	12.50	6.50	0.11
Marican	Mangrove	MRCN 3	3	22	13.24	1.85	21.92	23.77	5.38	37.10	17.10	16.65	0.18
Jepara	sewg+sed	PPN 6	6	24	15.13	0.00	34.75	34.75	18.63	0.00	7.88	38.75	0.35
		PPN 3	3	22	12.65	0.63	31.89	32.51	15.35	3.24	26.39	22.51	0.32
		PPS 6	6	21	12.73	0.00	35.77	35.77	37.47	0.00	3.55	22.32	0.51
		PPS 3	3	27	17.13	0.50	20.68	21.18	58.93	0.00	0.80	18.63	0.74
Bondo	Sediment	Bondo	3	31	18.43	0.55	27.48	28.03	21.22	3.85	10.10	36.80	0.43

W, L, 3 or 10 at ends of codes indicate aspect (windward/leeward) and depth. Slope refers to the slope of the log-transformed species-area curve.

TABLE 4

Results of Tukey HSD *post-hoc* test on coral species diversity, measured as the slope of log-transformed species-area curves.

Site type	N sites	Subset 1	Subset 2	Subset
Java Sea eutrophic	4	14.35		
High sedimentation	3	18.11	18.11	
Eastern Indonesia mechanical, 3 m	5	18.49	18.49	
Java Sea mechanical damage	2		26.21	
Eastern Indonesian eutrophic	4		26.28	
Java Sea unaffected (overfishing)	8		26.42	
Eastern Indonesian mechanical 10 m	3		27.21	27.24
Eastern Indonesian unaffected	3			37.39

Means listed in a given column are statistically equivalent ($P < 0.05$).

reefs ($\bar{x} = 0.22$) or mechanically damaged reefs ($\bar{x} = 0.31$; ANOVA, $F = 10.13$, $P < 0.0005$, df $= 32$).

3.7. *Relationships between diversity, live coral cover and environmental variables*

Coral species richness and live coral cover are positively correlated in coral communities that are undersaturated, that is, where diversity is not limited by interspecific competition (Aronson and Precht, 1995; Cornell and Karlson, 1996).

The positive correlation between cover and diversity (log-transformed slope) is good for reefs affected by land-based pollution and comparison sites (Fig. 9; $r^2 = 0.47$, $n = 24$, $P < 0.001$), but not for reefs subject to mechanical damage ($r^2 = 0.14$, $n = 11$, $P > 0.25$; three comparison sites included in regression). Coral species diversity on polluted and comparison sites is negatively correlated with chorophyll A concentration ($r^2 = 0.73$, $P < 0.0001$, $n = 24$) and SPM ($r^2 = 0.58$, $P < 0.0001$, $n = 24$), both of which are indicative of land-based pollution. On mechanically damaged sites, diversity is not significantly correlated with any environmental variables.

Diversity and total live coral cover are positively correlated among all the sites ($r^2 = 0.18$, $n = 32$, $P < 0.015$), but there is considerable scatter to the data. This relation appears to be driven primarily by the non-*Acropora* corals ($r^2 = 0.17$, $n = 32$, $P < 0.02$). Most of the eutrophied or high sediment sites have little or no *Acropora* cover, particularly in the Java Sea (Table 3). Average *Acropora* cover on reefs subject to land-based pollution was 3.5%; compared to 8.8% on mechanically damaged reefs, and 22.8% on comparison reefs.

3.8. *Change in diversity over time*

There are very few regional-scale quantitative studies of coral species diversity in Indonesia. Most records consist of species-lists, but do not record how much area was searched (e.g. Randall and Elldredge, 1983), and cannot readily be compared to examine within-habitat diversity changes resulting from reef degradation. It is extremely difficult to perform comparisons with previous reef studies. Not only does the taxonomic

TABLE 5

Number of coral genera on two Sulawesi reefs, 1980 and 1995.

Reef	N genera	N genera	Change (%)
Year	1980	1995	
Samalona	37	28	−25
Barang Lompo	39	29	−26

expertize of the two sets of researchers have to be equivalent, and the methodologies comparable, but site locations must be precisely specified in both studies.

The best known previous work quantifying coral species diversity in the areas sampled is the Ph.D. research by Moll (1983) conducted mainly during 1980 across the Spermonde archipelago of S. Sulawesi, using similar methods and sampling intensity as in this study: repeated line intercept transects at 3 and 10 m depths. These estimates of within-habitat species diversity from species–area curves yielded results comparable to ours (Moll, 1983).

Moll also listed the genera occurring on each of the eight reefs he sampled. Two of the same reefs were resampled in 1995: Samalona and Barang Lompo, and *ca* 25% fewer genera on each reef were recorded (Table 5).

4. Discussion

4.1. *Effects of reef degradation types on coral biodiversity*

This study compares land-based pollution stress versus mechanical damage, or chronic vs acute stress, in terms of their effects on coral biodiversity. At this time it is not possible to separate statistically the effects of different kinds of land-based pollution, such as sedimentation, sewage pollution and industrial pollution on Indonesian coral biodiversity. Land-based pollution is associated with greater reductions in diversity at all depths than is mechanical damage.

On reefs subject to anthropogenic mechanical damage (Samalona, Barang Lompo, Kapoposan 3 m), coral species diversity is reduced by 50% at shallow depths (3 m), but not at 10 m (reef slope). This contrasts with the reef damaged by storms (P. Burung), where diversity is reduced by 30% at 3 m and 15% at 10 m. The pattern of diversity and cover reduction at P. Burung is typical of storm impacted reefs (Karlson and Hurd, 1993; Rogers, 1993). Reefs affected by mechanical damage can recover from that damage, if two conditions are met:

1. they are protected from further damage; and
2. some reefs in the area are undamaged (Pearson, 1981; Done, 1995).

On reefs subject to land-based pollution stress, coral species diversity is reduced 40–60% at shallow depths, and an equal or greater amount at 10 m. Those reefs subject to the greatest combined sediment and nutrient loads often have little (Kayangan) or no (Wailiha, P.

Panjang, Bondo) coral growth at 10 m depth. Coral species diversity at 6 m at Pulau Panjang, subject to sewage, sedimentation and effluent from shrimp ponds, is reduced by *ca* 50–60% relative to comparison reefs in Karimunjawa. Diversity on reefs subject to high sediment and nutrient loads (P. Panjang) is similar to coral diversity on fringing reefs adjacent to healthy mangroves (Lagun Marican). The highly significant correlation between species richness and coral cover among pollution-affected reefs indicates that local species diversity has not reached saturation on these reefs, and that extrinsic factors (i.e. pollution) restrict species diversity on these sites, rather than intrinsic factors like spatial competition (Aronson and Precht, 1995; Cornell and Karlson, 1996).

Land-based pollution stresses, such as sewage, sedimentation and industrial pollution, alter the physical and biological environment on a long term basis (Pastorok and Bilyard, 1985; Tomascik and Sander, 1987; Rogers, 1990; Montagioni *et al.*, 1993). It is extremely difficult for reefs to recover from such chronic stresses (Pearson, 1981; Pastorok and Bilyard, 1985; Grigg, 1995). As chronic stresses on reefs, pollution effects endure until the source of the pollution is shut off; recovery from eutrophication damage to reefs appears to require at least 10 years (Maragos *et al.*, 1985; Grigg, 1995). Pathogenic bacteria in untreated sewage attack and can kill corals (Mitchell and Chet, 1975). Bioerosion increases with nutrient availability (Rose and Risk, 1985; Risk *et al.*, 1995), reducing accretion of carbonate material into the reef system (Hallock and Schlager, 1986).

4.2. Regional patterns

There are no accurate estimates available for the amount of reef area throughout Indonesia subject to the various forms of reef degradation outlined. All national-scale reef surveys published to date in Indonesia have focused on coral cover only (e.g. Moosa and Suharsono, 1996; Chou, 1997), not including coral species diversity, and have quantified condition based on a linear scale of live coral cover only (Gomez and Yap, 1988). More important, they do not quantitatively classify the types of degradation occurring.

In general, chronic pollution stresses are localized along heavily populated shorelines (e.g. the north coast of Java, coast of S. Sulawesi), or near major cities [e.g. Jakarta, Surabaya, Ujung Pandang Willoughby (1986) and Tomascik *et al.* (1993)], and are a more serious threat to reefs in western Indonesia than in the relatively underpopulated east (Chou, 1997). Blast fishing and cyanide fishing appear to be most prevalent in Eastern Indonesia (Erdmann and Pet-Soede, 1996), although the west coast of Sumatra has also suffered considerable bomb and cyanide damage in the last 5–10 years (A. Kunzmann, personal communication, 1996; Molis, 1997). Blast and cyanide fishing appear to be a greater threat to Indonesia reefs that are far from major population centres.

4.3. Land-based sources of pollution and threats to reef coral biodiversity

Land-based pollution on Indonesian reefs comes from three primary sources: agricultural runoff (including increased sedimentation from deforestation and aquacultural runoff), untreated human sewage and industrial effluent (Brown, 1986; McManus, 1988; Yap, 1992; BAPPENAS, 1993). The aquaculture industry, particularly the shallow brackish water shrimp ponds (tambaks) prevalent in much of Indonesia, are a considerable source of nutrient and sediment effluent into coastal waters, including reefs (Chua *et al.*, 1989; Tomascik *et al.*, 1993). Widespread clearing of mangroves for shrimp ponds further exacerbates their effects (Yap, 1996).

4.3.1. Sewage

There is no sewage treatment system in place for any major coastal city in Indonesia. $\delta^{15}N$ data suggest that sewage pollution from the city of Ujung Pandang reaches many of the nearshore reefs of the Spermonde archipelago (Jompa, 1996). The decline and death of the remaining reefs in Jakarta Bay, and in the southern islands of the Pulau Seribu attest to the long distance effects of urban effluent on Indonesian reefs (Tomascik *et al.*, 1993; Willoughby *et al.*, 1997).

4.3.2. Industrial effluent

Industrial effluent was a factor in three of the sites studied. Wailiha (Ambon) reef is *ca* 200 m from a new plywood factory, and corals there have elevated lignin concentrations in their skeletons (Limmon, 1996). Wayame reef (Ambon Bay) is adjacent to the oil delivery terminal for Ambon City, and oil slicks have been observed in Ambon Bay (Evans *et al.*, 1995). Kayangan reef (Sulawesi) is in the mouth of Ujung Pandang harbour, and receives oil from shipping activities and other industrial wastes dumped into the Ujung Pandang harbour, in addition to intense sewage pollution. The leeward side of Kayangan reef is entirely dead (Jompa, 1996).

The reefs of Jakarta Bay, however, show the clearest effects of combined industrial waste and sewage on reefs. These reefs are now entirely dead (Tomascik *et al.*, 1993), and many of the Jakarta Bay islands are now submerged (Uneputty and Evans, 1997). While most kinds of strand-line litter and chemical pollution decrease away from the shoreline (Willoughby *et al.*, 1997), fishing gear debris and oil pollution in the Jakarta Bay–Thousand Islands region increases offshore; most of this oil apparently comes from South China Sea oilfields (Uneputty and Evans, 1997).

Surveys in 1985 in the Pulau Seribu islands north of Jakarta showed that the amount of plastic garbage per linear metre of strand line was the best single measure of pollution from Jakarta, and the best single correlate of reef health, in 38 islands in the chain (Willoughby,

1986). Repeat surveys in 1994 (Uneputty and Evans, 1997) and 1995 (Willoughby *et al.*, 1997) showed that the amount of garbage per length of strand line had doubled, that the relationships with reef health still applied, and that many of the reefs in Jakarta Bay that were in serious decline in 1985 are now entirely dead, and the islands are now submerged (Uneputty and Evans, 1997).

4.4. Reduction in diversity over time

Following time trends in diversity on coral reefs can be done by comparing present studies with ones done in the past, but in fact it is extraordinarily difficult to relocate and replicate previous coral reef surveys. Locations of the original surveys must be given with a precision that allows re-occupying the same site, with an error of only a few metres. In addition, the original reference must give sufficient details of the methodology that similar techniques may be employed in the re-survey. This is rarely the case in coral reef science. Even when sample sites are 'permanenty' marked, by stakes, nails, etc., there needs to be regular checking of the site. In work in the Maldives, for example, it was found that one-third of the markers (large nails in corals or hardground, pieces of pipe driven into the sediment, etc.) disappeared each year, either through vandalism or coral head dislodgement. There are very few coral reef surveys more than a decade old that are published with enough detail to allow proper resurvey. In the area studied, the only published survey results it was felt were sufficiently precise for the present purposes came from Moll's PhD research (Moll, 1983).

Comparing sites that were sampled by Moll and the authors, it is shown that there has been a 25% decrease in coral generic diversity over the past 15 years. A 20–25% reduction in local generic diversity over 15 years is shocking; a similar level of extinction in the fossil record would be considered a minor mass extinction (Sepkoski, 1997). Nonetheless, the authors hasten to point out that they have established only two reefs from the Spermonde Archipelago where this decrease has been demonstrated, and while it is strongly suspected that this decrease is anthropogenic, it cannot be proved that this is so. It is not clear whether similar decreases have occurred on reefs throughout Indonesia, especially as the baseline coral diversity in Indonesia is very poorly known.

On the other hand, both the reefs surveyed by Moll (1983) and ourselves are well offshore Ujung Pandang. They are subjected to the same sorts of stresses that affect most, if not all, Indonesian reefs. The comparison between Moll's results and ours, therefore, may well serve as a general guide to the situation in the entire country.

4.5. Implications for coral reef fisheries in Indonesia

Coral reef fisheries depend heavily on the quality and quantity of coral reef habitat. Fish diversity and abundance on coral reefs is positively correlated with live coral cover (Bell and Galzin, 1984; Jennings *et al.*, 1996), and with habitat complexity (Risk, 1972; Luckhurst and Luckhurst, 1978; Roberts and Ormond, 1987; Dulvy *et al.*, 1995; Jennings *et al.*, 1996). The loss of *Acropora* on polluted nearshore habitats as documented in this study causes a dramatic reduction in habitat complexity (Done, 1996; Edinger, 1998). Thus, coral cover in the Pulau Seribu islands is positively correlated with distance from Jakarta, and fish diversity is positively correlated with live coral cover ($r^2 = 0.67$), resulting in the loss of most reef fish species on nearshore reefs of the Pulau Seribu (Harger, 1992). Likewise, fisheries yields on bombed Philippine reefs were approximately five times lower than on reefs in good to excellent condition (McAllister, 1988; Rubec, 1988).

Cesar (1996) has modelled the economic effects of reef degradation in Indonesia, and estimates losses to the Indonesian fishery sector resulting from reef degradation and overfishing at $410 000 km^{-2}, assuming a 10% discount rate, summed over 25 years. Assuming that these economic models are correct, and assuming that the figures are representative of the overall situation of Indonesian reefs, then Indonesia has already lost 40% of its reef fisheries resources. Given *ca* 75 000 km^2 total reef area in Indonesia, this yields an estimated $30 billion loss to the Indonesian economy over 25 years.

4.6. Limitations to this study

There are several important limitations to this study:

1. There are no pristine coral reefs in the data set. There may be none in Indonesia – Jackson (1997) argues that any discussion of pristine coral reefs worldwide is ludicrous, given the intensity of reef resource exploitation. Even the Tanjung Setan reefs in Ambon, the closest the authors could find to reefs protected from anthropogenic impacts, are subject to artisanal fishing.
2. Many of the impacted sites are subject to more than one type of anthropogenic stressor. For example, Barang Lompo, which has been bombed along with many of the reefs of the Spermonde archipelago, also suffers impacts from locally generated sewage pollution (Jompa, 1996), and may be affected by oil and other chemical pollution from Ujung Pandang (Erdmann and Caldwell, 1997).
3. Anthropogenic effects are not completely separated from the effects of substrate type (Hila, Wailiha), successional stage (possibly some shallow sites in the Spermonde shelf) and biogeographic effects (Java Sea vs Eastern Indonesia).

Nonetheless, the consistent and highly significant inverse correlations between coral species diversity and environmental variables indicative of land-based pollution on the polluted and comparison reefs provide

sufficient evidence that pollution reduces coral biodiversity to make environmental policy decisions (cf Sindemann, 1997).

5. Conclusions

1. Stresses from land-based sources of pollution are associated with 40–70% reductions in coral species diversity at all depths, with greater impact at 10 m depth than at 3 m depth.
2. Mechanical damage to coral reefs is generally associated with up to 50% reduced coral species diversity in shallow water (3 m), with relatively minor effects at 10 m depth. The reduced diversity in 3 m is approximately equivalent to the reductions associated with natural mechanical damage such as storms or growth on an unstable bottom, but these natural forms of mechanical damage also reduce diversity at 10 m depth.
3. Coral species diversity and live coral cover are positively correlated. Diversity and cover are both reduced most on reefs subject to combined sewage and siltation, while reefs subject to mechanical damage show more variation.
4. Efforts at coral reef and marine biodiversity conservation that do not include controlling land-based pollution sources will fail to address the major threats to Indonesian coral reefs.

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