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Threshold Type Responses of Indo Pacific Coral Reefs to Local Human Induced Degradation

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Abstract. Coral reef ecosystems face cumulative pressures from ocean warming, ocean acidification and diverse coastal human disturbances. As ecologically critical habitats and socio economic resources for coastal human communities, reef systems require improved understanding of how local anthropogenic activities drive degradation trajectories. Existing monitoring datasets covering the Indo Pacific region provide large scale observational evidence to disentangle reef responses against human related stressors and distinguish threshold driven shifts from gradual dose response decline. Published field observations indicate that coral cover drops sharply once measurable anthropogenic disturbance emerges, whereas further intensity elevation produces negligible additional coral loss, supporting threshold type ecological transitions rather than linear degradation gradients. Small scale artisanal and recreational fishing represents the dominant local driver of coral loss across survey level observations, while blast fishing imposes the most severe damage at individual site scales. Dive based tourism displays positive statistical correlation with coral coverage, which corresponds to preferential tourism deployment on relatively intact reef habitats instead of beneficial ecological effects. Synthesized observational evidence delivers practical reference for spatial reef conservation and targeted coastal resource management across Indo Pacific marine regions.

Keywords: Coral reef, anthropogenic impact, coral degradation

1. Introduction

Coral reef ecosystems deliver critical ecological services yet undergo widespread degradation across the Indo Pacific under combined climate and local human pressures. Thermal driven mass bleaching receives substantial research focus, whereas local scale anthropogenic stressors remain incompletely disentangled from large scale climate signals in broad scale monitoring datasets [1]. Distinguishing threshold versus gradient shaped biological responses to human pressure carries practical implications for conservation planning and reef management prioritisation.

Global research has documented declines in hard coral cover associated with coastal development, destructive fishing, pollution and recreational related damage across tropical reef regions [2]. Multiple regional scale analyses indicate fishing related pressures alter reef associated fish and invertebrate assemblages, modifying herbivory and benthic competitive dynamics [3, 4].

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Observational studies highlight that blast fishing produces persistent rubble dominated substrates that constrain coral recovery potential [5]. Nonetheless, many large scale volunteer sourced datasets remain underutilised for quantifying independent effects of individual human activities, given pervasive co occurrence among multiple stressors [6]. Regional investigations within the Indo Pacific further demonstrate that disturbance magnitude does not always correspond linearly to coral loss magnitude, raising questions regarding threshold triggered phase shift dynamics [7]. Within domestic research, coral reef investigations concentrate largely on limited national coastal transect datasets; broad scale syntheses drawing upon globally standardised citizen science monitoring across extensive Indo Pacific spatial extents remain comparatively scarce [8]. Existing syntheses also frequently fail to separate ordinal observer rated disturbance gradations into binary disturbed undisturbed contrasts for robustness evaluation.

Critical knowledge gaps persist regarding whether hard coral responses follow continuous dose response trajectories or threshold driven shifts, and which specific anthropogenic activities constitute independent predictors of coral cover loss after accounting for confounding environmental covariates. This work utilises Reef Check global standardised monitoring data to characterise benthic and faunal responses to anthropogenic disturbance, identify dominant local scale stressors, and test response form hypotheses. The analytical workflow encompasses data filtering, variable construction, non parametric group comparison, regression modelling and site averaged robustness validation.

2. Methods

2.1. Data sources

Data were obtained from the Reef Check Foundation's global coral reef monitoring database, which compiles standardized volunteer surveys worldwide. Three data tables were used per region: (i) site descriptions, recording survey metadata and observer assessed anthropogenic pressures; (ii) belt transect records of fish, invertebrates, impact indicators and rare animals; and (iii) point intercept substrate records. The study period spans 2020 to 2026. The full download includes 2265 surveys across three regional datasets: Hawaii (HI, 72 surveys), Indo Pacific (IP, 2192 surveys), and East Pacific (EP, 1 survey). Given the extreme imbalance in sample size across regions, the EP dataset was excluded owing to its single survey and insufficient representativeness, and the HI dataset was discarded because of divergent baseline environmental conditions, coral community assemblages and anthropogenic pressure backgrounds [1]. Only the IP dataset was analysed to avoid confounding effects.

2.2. Data processing and variable construction

Three tables were merged to one table using the unique survey identifier (survey_id); all 2,265 site descriptions matched belt and substrate records one-to-one. Belt transect data (four 20 m segments, s1-s4) were summed up to give organism counts per 80 m transect. Substrate coverage was estimated by the point intercept method: each survey classifies a standard 160 points (40 per segment), and the percentage coverage of each substrate category was computed relative to the actual number of valid points recorded, accommodating incomplete transects. Healthy hard coral cover (HC) was the primary response variable; bleached (HC/B) and diseased (HC/D) hard corals were retained as separate stressed coral categories. Total reef building coral cover was defined as

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HC + HC/B + HC/D; soft coral (SC) was processed as an independent benthic variable rather than incorporated within reef building coral totals [2].

Observer-rated overall anthropogenic impact (None / Low / Medium / High) (Never / Occasionally / Often / Always) served as the primary predictor. This research analyzed both four-level factor and binary contrast (impacted = any rating above None). Seventeen specific human activities were recoded as binary presences (Activities Present None). (Table 1.). For activities originally scored on intensity scales (None / Low / Medium / High), presence was defined as any rating above None. For siltation recorded on a frequency scale (Never / Occasionally / Often / Always), presence was defined as any rating above Never. Survey depth, distance from shore, approximate local population size and survey year were used as features, and country (four most-surveyed countries) was included as fixed effects where indicated. Survey sites were mapped in ArcGIS Online to verify spatial coverage prior to analysis (Figure 1 and Figure 2).

Table 1. Human activities recorded in the dataset

Human activities	Measurement
Siltation	Never / Occasionally / Often / Always)
Dynamite fishing	(None / Low / Medium / High)
Poison fishing	(None / Low / Medium / High)
Aquarium fish collection	(None / Low / Medium / High)
Harvest of inverts for food	(None / Low / Medium / High)
Harvest of inverts for curio	(None / Low / Medium / High)
Tourist diving snorkeling	(None / Low / Medium / High)
Sewage pollution	(None / Low / Medium / High)
Industrial pollution	(None / Low / Medium / High)
Commercial Fishing	(None / Low / Medium / High)
Live food fishing	(None / Low / Medium / High)
Artisanal recreational	(None / Low / Medium / High)

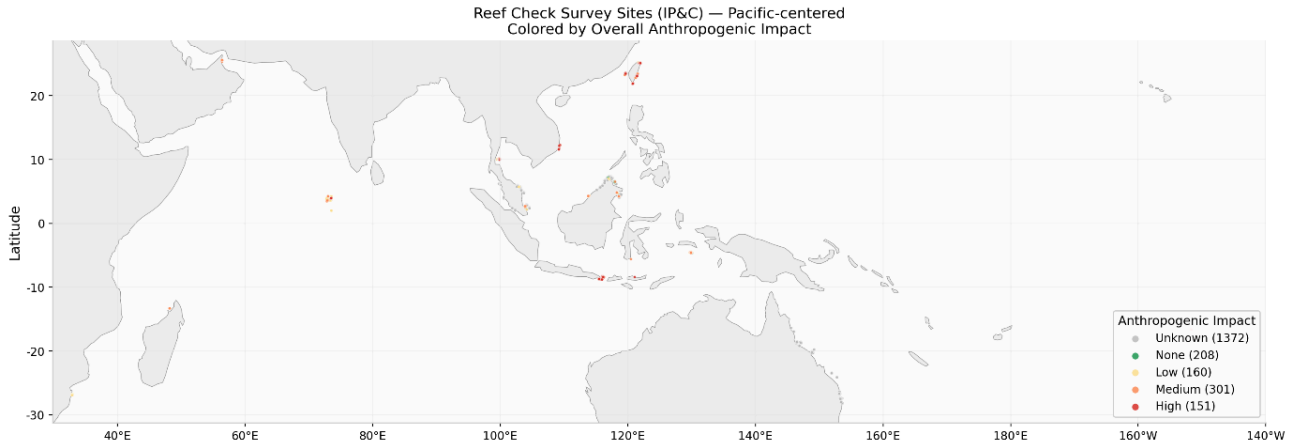

Figure 1. Survey site map for Indo-pacific colored by overall anthropogenic impact

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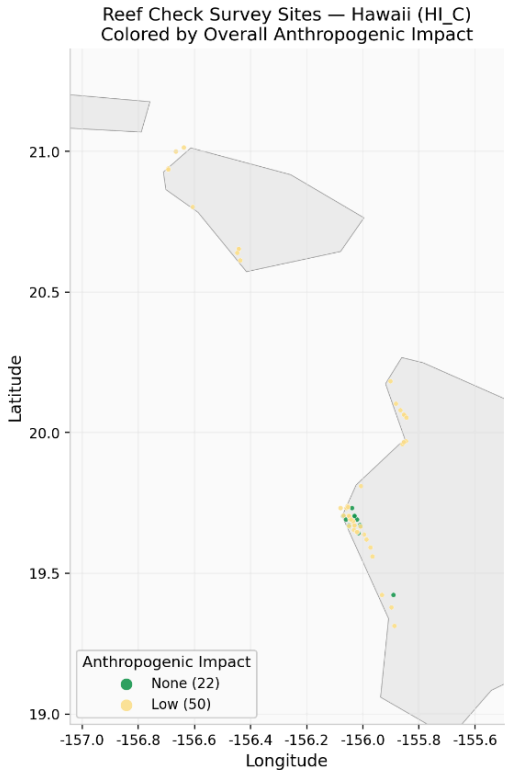

Figure 2. Survey site map for Hawaii-island colored by overall anthropogenic impact

2.3. Statistical analysis

Analyses were restricted to IP surveys excluding missing impact rating and invalid substrate data (n = 813 surveys from 250 sites; None 208, Low 160, Medium 297, High 148). Because counts and cover estimates were skewed and zero-inflated, group differences were tested non-parametrically: Kruskal-Wallis tests across the four impact categories, and pairwise Mann-Whitney U tests. The same binary contrast was applied to all biological, impact and substrate indicators with at least 20 non-missing observations per group (53 of 102 indicators); indicators with identical values across all surveys were excluded. All p-values from multiple comparisons were adjusted using the Benjamini-Hochberg false discovery rate (FDR), with significance at alpha = 0.05.

In order to control confounding, ordinary least squares (OLS) regression related hard coral cover to the binary impact indicator together with depth, distance from shore, population size and survey year (n = 754). Given that hard coral cover constitutes a percentage bounded response variable characterised by skewed and zero inflated distribution, OLS regression may violate homoscedasticity assumptions and produce predictions outside the 0–100 % range; outputs are therefore interpreted cautiously and supported via supplementary site level robustness testing [3]. Because some sites were surveyed repeatedly, all models were adjusted on site-averaged data to test robustness against pseudo-replication. Site-level values were calculated as arithmetic means across repeated surveys at each location; for categorical activity variables, a site was coded as impacted if the activity was recorded in at least one survey at that site (n = 250 sites). For the activity-level analysis, a slightly different subset of sites was used after additional filtering for complete activity covariate information (n = 274 sites); all activity indicators were entered simultaneously with depth, year and country fixed effects; spearfishing and recreational fishing were excluded after collinearity diagnostics (variance inflation factors and pairwise correlations; r up to 0.82; variables with VIF > 5

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were removed). The activity model was also adjusted on site-averaged data (n = 274 sites). Mechanistic consistency was assessed by pairing activities with their corresponding field indicators (anchoring vs. anchor damage records; sewage and industrial pollution vs. nutrient indicator algae) using Mann-Whitney U tests.

2.4. Software

Analyses were performed in Orange 3 (Bioinformatics Laboratory, University of Ljubljana) using the File, Select Columns, Select Rows, Box Plot and Python Script widgets. Custom Python code within the Python Script widget used pandas and NumPy for data manipulation and SciPy for statistical tests; OLS models were fitted by direct matrix computation (numpy.linalg.lstsq) with standard errors derived from the residual covariance. Figures were produced with matplotlib at 300 dpi. Spatial visualisation used ArcGIS Online (Esri). Code and analytical workflows are available upon reasonable request (Table 2).

Table 2. Variable roles in the analysis

Role	Variable	Notes
Response	Hard coral cover (HC, %)	Point intercept; primary endpoint
Response	Total coral cover (%)	HC + HC/B + HC/D + SC
Response	Belt indicators (counts/80 m)	Fish, invertebrates, impact records, rare animals
Primary predictor	Overall anthropogenic impact	Observer rating: None / Low / Medium / High; also binary
Predictors	17 specific activities	Binary presence (above None / Never / No)
Covariates	Depth, distance from shore, population, year	Continuous; OLS adjustment
Fixed effects	Country (top 4)	Controls regional baseline differences
Grouping	site_id	Site-level robustness aggregation

3. Results

3.1. Coral cover differs between impacted and unimpacted reefs

Hard coral cover differed significantly among the four impact categories (Kruskal-Wallis $H = 63.7$, $p < 0.001$). Unimpacted reefs (None) showed a median hard coral cover of 52.5%, compared with 35.3%, 36.9% and 34.7% at Low, Medium and High impact sites, respectively. Pairwise comparisons confirmed that unimpacted reefs had significantly higher cover than each impacted category (all FDR-adjusted $p < 0.001$); however, no significant differences were detected among the Low, Medium and High categories themselves (all adjusted $p > 0.27$), indicating a threshold-type rather than a dose-response relationship (Figure 3).

3.2. Biological and substrate indicators corroborate the impact signal

Of the 53 biological, impact and substrate indicators with sufficient sample size, 28 differed significantly between unimpacted and impacted surveys after FDR correction (Table 3). Impacted reefs were characterized by lower hard coral cover (median 29.4% vs. 50.0%), higher rubble (11.3% vs. 7.5%), sand (7.5% vs. 4.4%) and nutrient indicator algae cover (1.3% vs. 0%), and more frequent

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general trash and coral damage (Figure 5). Fish communities showed a consistent pattern: groupers of all size classes were more abundant at unimpacted reefs, whereas parrotfish were more abundant at impacted reefs (median 10 vs. 6 individuals per transect), consistent with their association with algal-dominated degraded reefs. The most striking single indicator was the long-spined sea urchin Diadema, which declined from a median of 94 individuals per transect at unimpacted reefs to 1 at impacted reefs (Figure 4). Coral bleaching indicators were the notable exception, being higher at unimpacted reefs; bleaching is driven by regional thermal stress rather than local human activity and is therefore not expected to track local impact ratings.

Table 3. Indicators differing significantly between unimpacted and impacted reefs

Indicator	Unimpacted	Impacted	Difference	adj. p
Hard coral cover (%)	50.0	29.4	+20.6	<0.001
Total coral cover (%)	52.5	36.3	+16.3	<0.001
Rubble cover (%)	7.5	11.3	-3.8	<0.001
Sand cover (%)	4.4	7.5	-3.1	0.001
Nutrient indicator algae (%)	0.0	1.3	-1.3	<0.001
Soft coral cover (%)	0.0	1.3	-1.3	<0.001
Sponge cover (%)	1.6	0.6	+0.9	0.011
Diadema urchin	94	1	+93	<0.001
Grouper total	1	0	+1	<0.001
Grouper 30-40 cm	1	0	+1	<0.001
Parrotfish	6	10	-4.0	0.003
Moray eel (dagger)	0	0	-	0.010
Lobster (dagger)	0	0	-	0.005
Giant clam total (dagger)	0	0	-	0.016
General trash	0	1	-1	<0.001
Coral damage - other (dagger)	0	0	-	0.009
Bleaching, % of colony (asterisk)	40	0	+40	<0.001

3.3. The effect persists after controlling for confounders

Multiple linear regression controlling for survey depth, distance from shore, local population size and survey year confirmed the group comparison results: the presence of anthropogenic impact was associated with a 17.6 percentage-point reduction in hard coral cover (beta = -17.58, SE = 1.64, t = -10.74, $p < 0.001$, n = 754, R-squared = 0.171). Deeper surveys (beta = -0.50 per meter, p = 0.006) and sites closer to large populations (beta = -0.03 per 1,000 residents, p = 0.022) also had significantly lower cover, whereas survey year was not significant (p = 0.249), ruling out temporal trends as an explanation for the group differences.

3.4. Robustness to site-level aggregation

To account for repeated surveys at the same sites, all variables were averaged per site (n = 250 sites, of which 180 had at least one impacted survey). The site-level regression reproduced the survey-level result almost exactly: impacted sites averaged 17.4 percentage points lower hard coral cover

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(beta = -17.36, SE = 2.51, t = -6.92, $p < 0.001$, R-squared = 0.274), confirming that the findings are not an artifact of pseudo replication.

3.5. Specific activities identify the main drivers

17 specific human activities recorded in the site descriptions, 13 showed significant univariate associations with lower hard coral cover (all FDR-adjusted $p < 0.001$). To identify independent drivers, all activities were entered simultaneously into a regression controlling for depth, survey year and country (Table 4, Table 5); spearfishing and recreational fishing were excluded owing to severe collinearity (pairwise r up to 0.82). Artisanal and recreational fishing emerged as the strongest independent driver (beta = -13.75, $p < 0.001$), followed by dynamite fishing (beta = -11.17, $p = 0.005$) and anchoring (beta = -4.62, $p = 0.008$); aquarium fish collection was marginally negative (beta = -4.84, $p = 0.065$). All four remained significant after site-level aggregation (n = 274 sites, R-squared = 0.473), with dynamite fishing showing the largest site-level effect (beta = -19.56, $p < 0.001$).

Mechanistic indicator pairings supported these estimates: sites reporting anchoring recorded anchor damage significantly more often ($p < 0.001$), and sewage and industrial pollution were each associated with elevated nutrient indicator algae cover (0.6% vs. 1.3%, $p = 0.021$; 0.6% vs. 0.9%, $p = 0.020$, respectively), although neither pollution variable independently predicted coral loss once co-occurring activities were controlled. Tourist diving and snorkeling showed a stable positive association (beta = +5.45 to +7.30 across specifications), plausibly reflecting the siting of dive tourism at healthier, often protected reefs rather than causal benefit; commercial fishing appeared positively associated in the collinear full model but was non-significant in all correctly specified models.

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Sand cover (%)	4.4	7.5	-3.1	0.001
Nutrient indicator algae (%)	0.0	1.3	-1.3	<0.001
Soft coral cover (%)	0.0	1.3	-1.3	<0.001
Sponge cover (%)	1.6	0.6	+0.9	0.011
Diadema urchin	94	1	+93	<0.001
Grouper total	1	0	+1	<0.001
Grouper 30-40 cm	1	0	+1	<0.001
Parrotfish	6	10	-4.0	0.003
Moray eel (dagger)	0	0	-	0.010
Lobster (dagger)	0	0	-	0.005
Giant clam total (dagger)	0	0	-	0.016
General trash	0	1	-1	<0.001
Coral damage - other (dagger)	0	0	-	0.009
Bleaching, % of colony (asterisk)	40	0	+40	<0.001

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Table 5. Regression coefficients (percentage points of hard coral cover) for specific human activities across three model specifications

Predictor	Survey-level	+ Country controls	Site-level
Artisanal / recreational fishing	-17.94***	-13.75***	-10.77**
Dynamite fishing	-9.69*	-11.17**	-19.56***
Anchoring	-3.02 (0.075)	-4.62**	-6.20*
Aquarium fish collection	-4.08 (0.091)	-4.84 (0.065)	-9.32**
Yachts	-6.42***	-3.62 (0.052)	-0.88 ns
Tourist diving/snorkeling	+3.52 (0.081)	+5.45**	+7.30*
Depth (per m)	-0.82***	-0.89***	-0.75*
Model R-squared	0.253	0.274	0.473

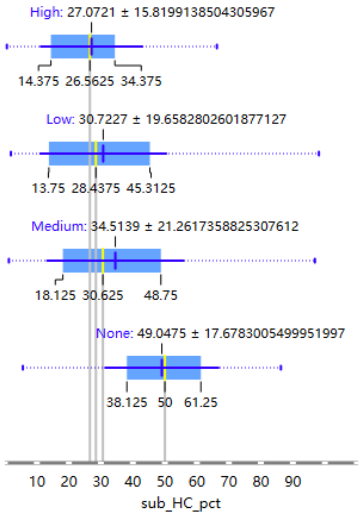

Figure 3. Hard coral cover (%) by overall anthropogenic impact category (None n = 208, Low n = 160, Medium n = 297, High n = 148; Kruskal-Wallis H = 63.7, p < 0.001)

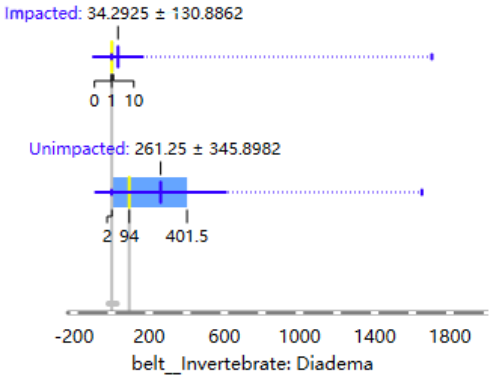

Figure 4. Abundance of the long-spined sea urchin Diadema (individuals per 80 m belt transect) at unimpacted vs. impacted reefs (median 94 vs. 1, FDR-adjusted p < 0.001)

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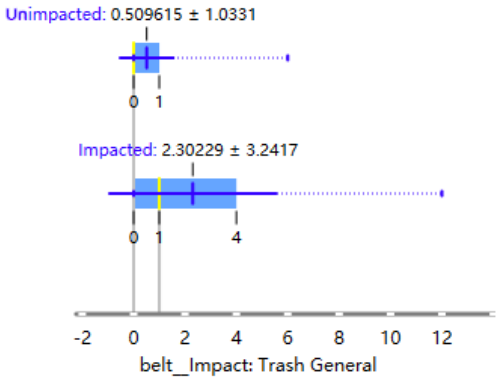

Figure 5. General trash records per transect at unimpacted vs. impacted reefs (median 0 vs. 1, FDR-adjusted $p < 0.001$), cross-validating the surveyors' impact ratings

4. Discussion

4.1. Principal findings

Across 813 Reef Check surveys in the Indo-Pacific, reefs without anthropogenic impact demonstrate substantially higher hard coral cover (None, median at 50 %) than reefs with any detectable human impact (35-37%), a difference of roughly 16 percentage points that persisted after controlling for depth, distance from shore, population size and survey year, and after site-level aggregation. Impacted reefs exhibited more rubble, sand and nutrient-indicator algae, fewer groupers and dramatically fewer Diadema urchins, but higher parrotfish abundance. At the activity level, artisanal and recreational fishing, dynamite fishing, anchoring and aquarium fish collection are the independent negative drivers of coral cover.

4.2. A threshold rather than a gradient

The most notable result is that cover did not decline further from Low to Medium to High impact ratings. Three non-exclusive explanations should be considered. First, the impact rating is assigned by volunteer observers and the distinction between Low, Medium and High may simply be less reliable than the distinction between presence and absence; the strong agreement between the ratings and objective records such as general trash supports the validity of the binary contrast. Second, the relationship may be genuinely ecological: once chronic human pressure exceeds a modest threshold, coral degradation may start, with additional pressure producing little further measurable loss in cover [4]. Third, the most sensitive reefs may already have been lost at impacted sites, leaving behind communities dominated by stress-tolerant taxa whose cover responds weakly to further disturbance [5]. Whatever the mechanism, the practical implication is the same: preventing the onset of chronic human impact appears far more valuable than attempting to limit its intensity once established.

4.3. Fishing-related activities as dominant drivers

That artisanal and recreational fishing carried the largest and most stable negative coefficient is consistent with the central role of small-scale fisheries across the Indo-Pacific, where they operate largely unselectively and with minimal regulation [6]. Dynamite fishing, though reported at only 30

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surveys, showed an effect size at the site level (-19.56 percentage points) that exceeded every other activity, underscoring the disproportionate physical destructiveness of blast fishing [7]. Anchoring damage provides a satisfying mechanistic link: sites where anchoring was recorded were significantly more likely to show anchor-specific coral damage, and anchoring remained an independent negative predictor in all model specifications - a result with an unusually direct management remedy in the form of mooring buoys [8].

4.4. Community responses and indirect pathways

The collapse of Diadema (median 94 to 1 individuals per transect) at impacted reefs runs counter to the classic expectation that urchin populations are released when their predators are overfished, indicating that habitat degradation and harvesting pressure can overwhelm trophic release effects for this easily harvested genus [9]. The increase in parrotfish at impacted reefs, by contrast, fits their well-documented association with algal-rich, structurally degraded habitats [10]. Sewage and industrial pollution were each associated with elevated nutrient indicator algae but did not independently predict coral loss once co-occurring activities were controlled; nutrient enrichment may thus act as an early, algae-visible symptom of a broader pressure cluster rather than as the proximate cause of coral decline at the spatial grain of these surveys.

4.5. The tourism paradox

Tourist diving and snorkeling were consistently associated with higher, not lower, coral cover once country baselines were controlled. This pattern reflects site self selection rather than causal improvement to reef condition: dive operators concentrate on attractive, healthy reefs, which are also disproportionately likely to fall within marine protected areas. The finding should not be explained as evidence that reef tourism is harmless; rather, it illustrates how management context can reverse the sign of an activity's raw association with reef condition. Notably, marine protected area status was not available as a covariate in the models, so this interpretation remains inferential.

4.6. Limitations

There are several limitations of this research. The analysis is correlative: although effect sizes were stable across specifications and robust to site-level aggregation, unmeasured confounders such as protection status, bleaching history, and larval connectivity remain unknown. Impact ratings and activity levels are observer-assigned and ordinal, and the subjective scale likely contributes to the absence of a dose-response gradient. Activities co-occur in clusters, and although collinearity diagnostics guided the exclusion of two variables, coefficients for correlated activities should be read as shared rather than purely independent effects. The dataset is dominated by Malaysian surveys, and site coverage within the region is uneven. Bleaching indicators were higher at unimpacted reefs; this may occur because bleaching tracks regional thermal stress rather than local human activity, because coral-rich reefs present more bleachable tissue, and because survey years were unevenly distributed across impact categories; the bleaching records here should therefore not be interpreted as a local impact signal. Finally, many biological indicators were highly zero-inflated, limiting power for rare taxa and restricting inference to occurrence rather than abundance for those groups.

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5. Conclusion

Threshold driven coral reef responses to local anthropogenic disturbance are evident across broad Indo Pacific volunteer monitoring records. Reefs experiencing any measurable human pressure exhibit substantial hard coral cover reduction together with predictable shifts in benthic substrate and reef organism assemblages, irrespective of whether disturbance ranks as low, medium or high intensity. Artisanal recreational fishing, dynamite fishing, anchoring and aquarium fish collection constitute key independent local scale stressors. Positive correlative signals for diving tourism variables stem from site selection bias and cannot be interpreted as beneficial ecological effects. Preventing the initiation of chronic local scale disturbance delivers greater conservation returns than mitigating high intensity established pressure. Correlative observational outputs emphasise the necessity of targeted local management interventions paired with continued large scale citizen science monitoring for Indo Pacific coral reef conservation.

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