Coral Reefs
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RESEARCH

Patterns of coral community composition along Suva, a Pacific Island urban reef system

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Abstract Hard corals (Order Scleractinia) form complex, heterogeneous communities that underpin reef ecosystem functions but are increasingly threatened by anthropogenic stressors, particularly in urbanised coastal settings. This study characterised coral community composition and juvenile coral distribution within the urban reef systems adjacent to Fiji's capital, Suva. We recorded 27 coral genera, with *Acropora* and *Porites* together contributing over 56% of total coral cover. Coral cover varied among reef zones, peaking at reef crests (mean coverage ± SE; 44.11 ± 2.41%), and declining on reef flats (23.58 ± 2.06%) and back reefs (17.27 ± 1.90%). Juvenile analyses focused on the four most common genera: *Acropora*, *Porites*, *Goniopora*, and *Pocillopora*. *Acropora* juveniles were the most abundant and broadly distributed, while *Porites* exhibited highly clustered spatial patterns. Juvenile *Goniopora* distribution was restricted to back reefs, and *Pocillopora* displayed a dispersed, sporadic distribution. These patterns indicate strong habitat-driven zonation and genus-specific sensitivities, with *Acropora* more abundant in high-quality, stable environmental conditions and *Porites* and *Goniopora* tolerating more nutrient-rich, turbid conditions. Although all surveyed reefs fall within the broader urbanised area, differences among zones and reef systems were noted, reflecting varying exposure to local stressors (e.g., turbidity, nutrient loading, and sedimentation) rather than a strict urban/non-urban contrast. Thus, our findings describe ecological variability within an urban reef system rather than comparing urban and non-urban reefs. Conservation and restoration of Suva's reefs should therefore prioritise improving local water quality through strengthened wastewater management and reduced land-based runoff and implementing targeted, habitat-specific interventions informed by environmental sensitivities. Collectively, these results underscore both the resilience and vulnerabilities of urban reef systems and highlight the need for adaptive, habitat-based management strategies in Fiji and comparable Pacific settings.

Keywords Urban coral reefs · Juvenile coral · Reef zonation · Anthropogenic stressors · Scleractinia · Fiji

Introduction

Hard corals of the order Scleractinia are primary reef builders, forming the basis of tropical coral reefs and laying the foundation for complex community assemblages. This complexity and habitat provision facilitates the critical ecosystem functions offered by reef systems. However, hard coral communities also exhibit considerable heterogeneity, with multiple pressures shaping their diversity, distribution, and assemblage complexity. This is especially the case in coastal tropical systems where environmental conditions are highly variable. For example, fluxes in nutrient availability, physicochemical conditions, and turbidity act as drivers that shape coral community composition (De'ath and Fabricius 2010; Fabricius et al. 2012).

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Hard corals thrive under stable oligotrophic nutrient conditions that regulate their symbiotic relationships with zooxanthellae and support overall coral growth and development (Buckingham et al. 2022; Jung et al. 2025). In contrast, chronic exposure to excess nutrients, in particular dissolved inorganic nitrogen (ammonia, nitrate, and nitrite) and/or phosphorus (DIP), can impair skeletal development, reduce tissue biomass, and increase susceptibility to bleaching and disease (Bruno et al. 2003; Fabricius 2005; Vega Thurber et al. 2014; Zaneveld et al. 2016; Donovan et al. 2020). Notably, imbalances between nitrogen and phosphate (specifically high nitrogen coupled with low phosphate availability, causing phosphate starvation) have been found to influence coral physiology and bleaching responses more than elevations of both nutrients (Wiedenmann et al. 2013). At the same time, responses among hard coral species to nutrient enrichment are not uniform, with some species displaying high resistance and adaptive capacity (Fox et al. 2021), further highlighting the species-specific and context-dependent nature of nutrient impacts on coral health and community composition. At a larger scale, elevated nutrient levels prompt hard corals to compete with copiotrophic species, such as algae or cyanobacterial mats (Ford et al. 2018; Silbiger et al. 2018; Lesser 2021).

Beyond nutrients, physiochemical conditions further regulate the composition, distribution and survival of hard corals (Dias et al. 2019; Jones et al. 2020; Samperiz et al. 2025). Thermal stress for example, is the primary driver for mass bleaching events in corals within tropical reefs, while salinity fluctuations beyond the typically optimal 30–35 PSU can not only inhibit growth and recruitment but also induce bleaching under prolonged low-salinity exposure (Kerswell and Jones 2003; Zuo et al. 2015; Dias et al. 2019; Jones et al. 2020). Chronic exposure to low oxygen levels can further compound these conditions by inducing metabolic stress (Haas et al. 2014). Again, there is some variation in hard coral responses to temperature and oxygen, with some species exhibiting physiological plasticity under a highly stressful environment, albeit with metabolic trade-offs (e.g., reduced photosynthesis-to-respiration ratios (Solomon et al. 2025)). Turbid environments can pose additional challenges in terms of reduced growth rates, restricted larval settlement and development, as well as diminished efficiency of photosynthesis (by symbiotic zooxanthellae) (Fabricius 2005; Browne 2012; Bessell-Browne et al. 2017; Zweifler et al. 2021). Furthermore, the composition and stability of benthic substrates also play a role in mediating hard coral distribution, which play a pivotal role in regulating regime shifts between hard coral–dominated and alternative non-calcifying organisms (Norström et al. 2009; Medina-Valmaseda et al. 2020; Lalas et al. 2023).

These environmental processes not only regulate overall hard coral assemblages but are essential in shaping the structure of future coral communities by regulating recruitment processes including juvenile distribution, growth and survivorship (Pedersen et al. 2019; Couch et al. 2023; Edmunds 2023). For example, settlement distribution of coral larvae is highly selective, whereby studies show that larvae prefer to settle on substrate composed of crustose coralline algae (Tebben et al. 2015), which itself can be negatively affected by declining water quality (Fabricius and De'ath 2001). The survival, growth rate and calcification of juvenile corals have also been shown to be enhanced under stable temperature and oxygen levels, and low turbidity and nutrients (Edmunds 2007; Evans et al. 2020). Beyond these environmental factors, adult coral populations play a key role in shaping juvenile distribution; they can facilitate juvenile presence by providing suitable habitat, but may also limit distribution when space becomes saturated. Studies in the Caribbean (Mumby 1999) and in the Pacific, such as French Polynesia (Penin et al. 2007), provide examples of this pattern, highlighting the general ecological principle that adult coral density influences juvenile distribution.

Consequently, as a result of a complex and multifaceted array of environmental variables that regulate metabolic, physical, and ecological processes in hard corals, their distribution and recruitment patterns follow varying and naturally occurring tolerance thresholds. These follow natural environmental gradients shaped by long-term coastal processes, and include characteristic observable patterns, such as zonation across reef zones (e.g., reef crest, reef flat and back reef) (Medina-Valmaseda et al. 2020; Oakley-Cogan et al. 2020). Subsequent shifts in environmental conditions result in corals with narrower tolerance limits to become extirpated or rare, while those with wider tolerance thresholds become more dominant (Hughes et al. 2017; Camp et al. 2018). Anthropogenic activity, particularly along coastal zones where stressors such as coastal development, urbanisation, terrestrial runoff and pollution are prevalent, leads to unnatural changes in environmental parameters (Morrison et al. 2013; Hughes et al. 2017). However, the strength and direction of inshore–offshore environmental gradients in urban reef systems can vary considerably at fine spatial scales, influenced by localised inputs and hydrodynamic variability. Contrasting responses among coral taxa are especially relevant in urban reef systems, where nutrient inputs are often elevated and variable, making it difficult to predict ecosystem-level outcomes (Browne et al. 2012; Goberdhan and Kininmonth 2021; Samperiz et al. 2025). Understanding how anthropogenic stressors influence coral community composition and juvenile distribution dynamics is essential for understanding ecosystem functioning and potential shifts in resilience, subsequently allowing for responsive and effective conservation and management strategies (Anthony et al. 2015).

Within Pacific Island Countries and Territories (PICTs), where approximately 99% of the population live within 50 km of a reef (excluding Papua New Guinea where ~ 53% live within 50 km) (Sing Wong et al. 2022), coastal reef systems provide essential ecological, physical, economic and social services. In Fiji, for example, coral reef systems contribute approximately 10% (7610 km^2) to the regional reef area (Lyons et al. 2024), host 342 scleractinian coral species (72 genera) and 12 non-scleractinian coral species (5 genera) (Lovell and McLardy 2008), and provide a basis for food security, livelihood and traditional practices (Kitolelei and Sato 2016; Kitolelei et al. 2021), in addition to contributing significantly to the national GDP (Gonzalez et al. 2015). While Fiji's reef systems include potential climate refugia (Beyer et al. 2018), many of Fiji's reefs are under considerable threat from localised anthropogenic pressures, particularly with regards to sediment and nutrient runoff from widescale land-use change to foster Fiji's agriculture and tourism sectors (Dadhich and Nadaoka 2012; Brown et al. 2017b, 2017a). Urban centres, such as the Greater Suva Urban Area (GSUA), further compound human-induced stressors, exemplifying anthropogenic challenges faced by reef systems in PICTs (Lal et al. 2018; Goberdhan and Kininmonth 2021; Dehm et al. 2024). These include untreated and inadequately treated wastewater discharges, urban stormwater runoff, and sedimentation from watershed activities, all of which adversely impact water quality (Morrison et al. 2005; Pratap et al. 2020; Lal et al. 2021; Dehm et al. 2025).

This study aims to (i) characterise hard coral community composition along the urban reef system adjacent to the GSUA, (ii) to infer recent recruitment and early survival and growth of dominant coral genera, and (iii) to assess the influence of environmental variables and substrate characteristics in mediating juvenile abundance patterns of dominant coral genera. These findings will contribute valuable knowledge to inform adaptive management approaches for sustaining urban reef ecosystems in Fiji and the broader Pacific region amidst escalating anthropogenic pressures.

Methods

Site description and survey method

This study is centered along the GSUA, located on the southeastern coastline of Viti Levu, Fiji (Fig. 1A; ~ 18.14° S, 178.45° E). The GSUA has undergone considerable population growth from 160,000 in the 1980 s (Fiji Bureau of Statistics 1882) to an estimated 268,432 by 2017 (Fiji Bureau of Statistics 2018); driven by rural-to-urban migration, industrialisation, and modernisation. This influx, coupled with inadequate infrastructure (particularly with regards to wastewater and urban runoff), has resulted in increased anthropogenic pressure on the adjacent coastal marine environment quality (Morrison et al. 2005; Pratap et al. 2020; Lal et al. 2021; Dehm et al. 2025). Fluvial input from the Rewa River and other smaller tributaries transports sediment loads and terrestrial contaminants, such as nutrients and chemical pollutants, into the coastal waters (Thammadi and Pisini 2022; Glaus et al. 2023).

Reef surveys were conducted across 51 sites (Fig. 1B) across three zones (reef crest, reef flat, and back reef) and four reef systems (Namuka, Suva, Laucala and Nasoata) between May and July 2022. Surveys were conducted using photo transect methods adopted from (Hill and Wilkinson 2004; Roelfsema and Phinn 2008; Roth et al. 2018). Within each site, three 50 transects were laid parallel to the reef flat at a depth ~ 1.5 m (depth range of 0–3 m). Triplicates were spaced approximately 50 m apart to ensure spatial independence. Within each transect line, photos (Olympus TG4 and TG6) covering 1 m^2 substrate were taken every 2 m, resulting in 25 photographs per transect (75 per site, 3825 in total).

Coral identification and image analysis

All photographs were analysed using Coral Point Count with Excel Extensions (CPCe, v.4.1; Kohler and Gill 2006), with 50 randomly generated points classified per image into eight substrate categories including hard corals, consolidated substrate, crustose coralline algae, fleshy algae, seagrass, soft coral, unconsolidated substrate and other biotic substrate (Dehm et al. 2025). The use of 50 random points per image was selected to balance precision with processing efficiency and is consistent with recent large-scale benthic survey approaches (Heres et al. 2021; Williams 2022; Government of the Republic of Fiji & Blue Prosperity Fiji 2025). Live hard coral points were categorised further to genus level. For each site, the percent cover of each coral genus was calculated as the proportion of points relative to the total number of live hard coral points across all photographs from that site. Additionally, colony size was measured using image J v.1.52a (Schneider et al. 2012) as the maximum diameter (cm) of discrete coral colonies visible in scaled photographs. Colonies were defined as visually distinct coral entities separated from neighbouring colonies. All hard corals were classified as either adult or juvenile, whereby a coral was considered an adult if it had a maximum diameter > 5 cm, and as a juvenile if it had a maximum diameter of ≤ 5 cm (based on definitions discussed in Edmunds 2023). When points fell on small areas of tissue that visibly belonged to a larger colony with partial mortality, it was not considered as a juvenile.

To ensure accuracy in coral identification, classification to genus level was supported by the *Coral Finder 2022*

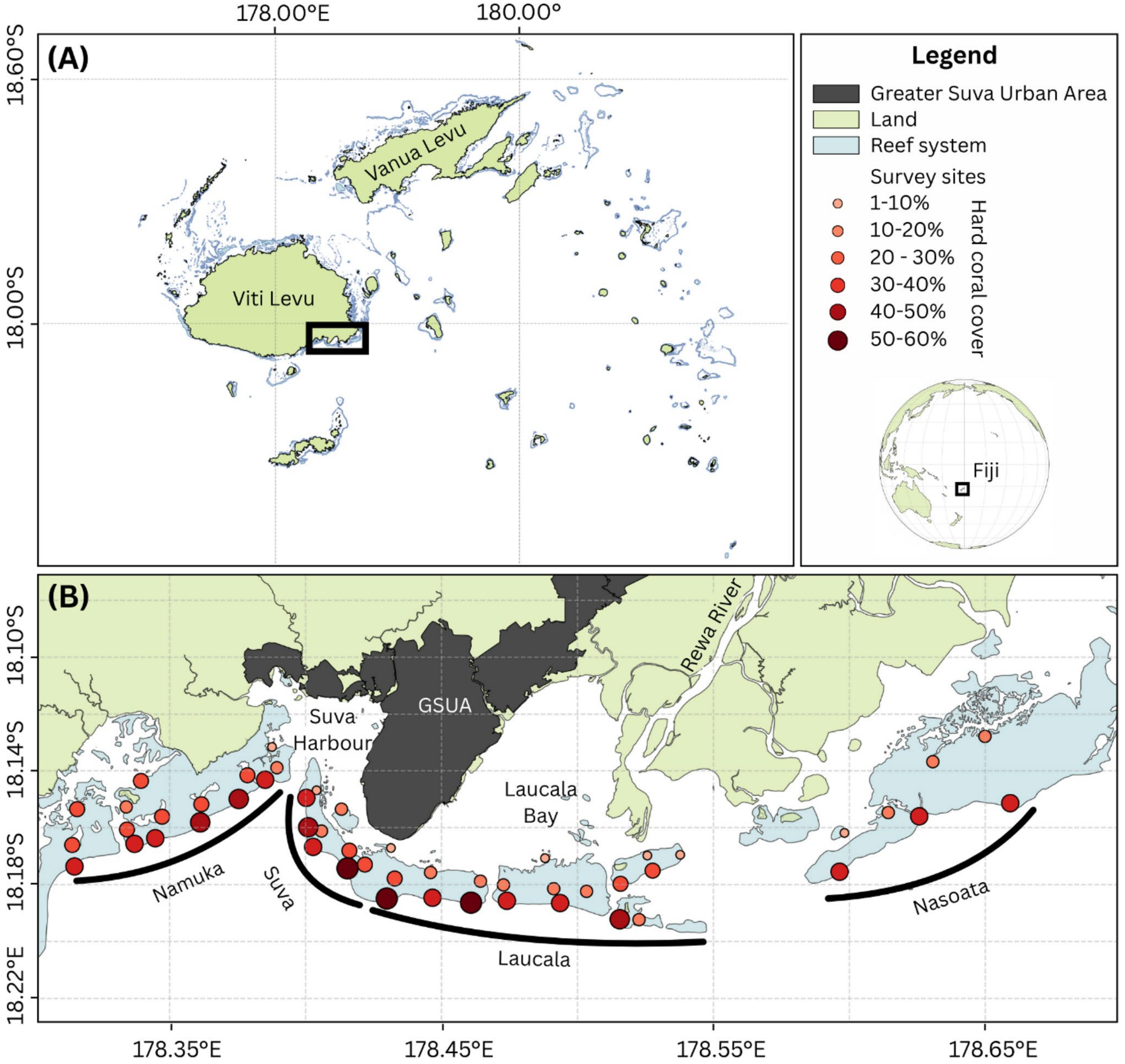


Fig. 1 (**A**) The study region along the southeastern coastline of Viti Levu Fiji, adjacent to the Greater Suva Urban Area (GSUA; shown in grey). (**B**) A total of 51 sites distributed across the reefs around the GSUA were surveyed. Survey sites are grouped by the four reef systems (Namuka, Suva, Laucala, Nasoata). The colour and size of survey site markers reflect coral cover (%), with larger, darker markers indicating higher coverage. Open-source country shapefiles were obtained from www.naturalearthdata.com, while shapefiles for rivers, reefs and urban centres were obtained with prior approval from the Department of Lands, Ministry of Lands and Mineral Resources, Fiji

(Kelley 2022), which aligns with the World Register of Marine Species (WoRMS) taxonomy. Additionally, 120 images from the photo transects were randomly selected and overlaid with distributed points for review by six experienced reef ecologists. These expert validations confirmed consistent identification across observers, with no discrepancies observed in genus-level classification.

Environmental parameters

In our analysis, we used water quality parameters from Dehm et al. (2025), which provide fine-scale nutrient, physicochemical and sediment data collected at multiple time points over a 12-month period (October 2021, November 2021, January 2022, March 2022, June 2022, August 2022), to account for wet and dry season conditions, and at a broader spatial extent than our study region. Our reef surveys were conducted within the temporal range and the geographic coverage of the Dehm et al. (2025) dataset, making it a relevant and representative source for our study. In summary, the previous study analysed water samples for nutrient concentrations, specifically ammonia (NH_3), nitrate (NO_3^-), nitrite (NO_2^-), dissolved inorganic phosphorus (DIP), and chemical oxygen demand (COD) using a Thermo Scientific Orion™ AQUAfast™ colorimeter (AQ3700). Additional physicochemical parameters, including temperature, salinity, dissolved oxygen, and turbidity, were recorded in situ using calibrated sensors, including the Sea-Bird Scientific SBE19 CTD, SBE 43 dissolved oxygen probe, and Campbell Scientific OBS-3 + turbidity sensor. Finally, as an additional measure of turbidity, total suspended solids (TSS) concentrations were determined by filtering site water through pre-weighed 0.45 µm Whatman® filters. After filtration, filters were rinsed with ammonium formate to remove salts, dried at 60 °C for 24 h, and weighed to calculate TSS based on weight difference relative to filtered volume.

Statistical analysis

All spatial and ecological analyses (Supplementary Material 1) were conducted in Python (v3.9) using a variety of libraries suitable for ecological statistics, spatial analysis and data visualisation. Data handling was conducted using *pandas* (v 2.2 (McKinney 2010)) and *NumPy* (Harris et al. 2020), while visualisation, including maps, was created using the *GeoPandas* (Jordahl 2014), *Matplotlib* (Hunter 2007) and *seaborn* (Waskom 2021) suites.

To evaluate differences in total coral cover (i.e. percent cover) and richness (i.e. number of genera) across reef zones, across reef systems, and among zones between systems, Kruskal–Wallis (*scipy.stats.kruskal,* Virtanen et al. 2020*)* rank sum tests were applied to nonparametric data. Where significant differences were detected ($\alpha = 0.05$), Dunn's post hoc pairwise with Bonferroni correction were used using *scikit-posthocs* (Terpilovskii 2024). Spatial intensity maps were generated to illustrate the distribution and relative abundance of the dominant coral genera across the study area. For each genus, the percent cover relative to total hard coral cover was calculated at each site and map symbology (point size and colour) was scaled to these categories using *GeoPandas* and *Matplotlib.*

Multivariate differences in whole coral community composition were assessed using Bray–Curtis dissimilarities calculated from square-root transformed whole coral genus abundance data using *scipy.spatial.distance.pdist* and *squareform.* To test for compositional differences, Analysis of Similarities (ANOSIM) was performed using skbio.stats.distance.anosim, with 999 permutations. To identify key taxa driving these differences, a SIMPER-like approach (as no native SIMPER package exists for Python 3; Garcia Navarro et al. 2024) was applied for each pairwise group comparison. Genera were ranked by the absolute difference in mean abundance between groups, and the top five contributors to dissimilarity were retained. This method was designed to follow the core logic of the traditional SIMPER approach from PRIMER software, using the *pandas*, *NumPy*, and *scipy.spatial.distance.pdist* packages. This approach offers a practical alternative for estimating taxon-level drivers of dissimilarity; however, it does not incorporate within-group variance as in standard SIMPER analyses. To further visualise coral community structure, individual genus distribution plots were mapped, with cover intensity depicted by size and colour-scaled points over reef, island and urban base GIS layers.

To assess the juvenile coral distribution of the four most abundant genera (*Acropora, Goniopora, Pocillopora,* and *Porites)*, summary statistics were calculated for both life stages, including juvenile to adult ratios of percent cover, site-level prevalence, and proportional contributions. Because juvenile and adult coral data were derived from point-intercept classifications rather than direct colony counts, results are expressed as percent cover rather than density (colonies m^{-2}). For each genus assessed, a Wilcoxon signed-rank test (*scipy.stats.wilcoxon*), due to the nonparametric distribution of data, was conducted to statistically compare adult and juvenile percent coverage. Similarly, to evaluate the significance of juvenile distribution across reef systems and among reef zones, Kruskal–Wallis tests were conducted, followed by Dunn's post hoc comparison with Bonferroni correction using *scikit-posthocs*. Spatial trends in juvenile coral composition were visualised using geospatial maps and overlaid with ecological data. Principal component analysis (PCA) was applied to z-score normalised percent cover data using scikit-learn (*sklearn.preprocessing.StandardScaler*, *sklearn.decomposition.PCA*) to reduce dimensionality and identify dominant spatial patterns. Spatial autocorrelation was assessed using Moran's I to evaluate clustering patterns in juvenile coral distributions, utilising *esda* from the *PySAL* library (Rey and Anselin 2010).

To assess the relationships between juvenile coral abundance, environmental drivers and substrate types were assessed using a two-step approach adapted from Pederson (2019). Firstly, pairwise Spearman's rank correlation (*scipy.stats.spearmanr*) was used to identify monotonic associations between juvenile assemblages relative to environmental parameters and substrate types. Correlations with an absolute value of $|\rho| \geq \pm 0.3$ were retained for further analysis to reduce dimensionality. Secondly, generalised linear models (GLMs), using *statsmodels.api.GLM,* with Poisson distribution and log-link function, were fitted using only environmental parameters and substrate types with Spearman's correlations meeting the inclusion threshold. For each of the assessed coral genera, all combinations of one to three strongly correlated environmental parameters and substrate types were tested as predictor variables. Models were ranked by computing the Akaike Information Criterion (AIC) to identify the best-fitting models using *itertools* (Python Software Foundation v 3.13, 2024), following logic adapted from the R *MuMIn* (Bartoń 2010) package. Model performance was evaluated using adjusted pseudo-R^2 and dispersion, with the latter used to assess over or under dispersion relative to Poisson assumptions. This two-step procedure reduced model complexity and the potential for overfitting by limiting predictor combinations (maximum of three variables) and using AIC-based selection to identify parsimonious, ecologically supported models.

Results

Overall, total hard coral cover varied substantially, ranging from 6.32 to 60.40%, with a mean cover of 30.68 ± 1.27% (Fig. 1B, Supplementary Material 2). A total of 27 genera were observed, including 26 scleractinian genera and one hydrocoral (*Millepora*) (Fig. 2). Of these, *Acropora*, *Millepora*, *Pocillopora* and *Porites* were observed at all sites. A further eight genera (*Goniastrea* [62.7%], *Merulina* [58.8%], *Stylophora* [56.9%], *Fungia* [52.9%], *Diploastrea* [52.9%], *Psammocora* [51%], *Goniopora* [51%] and *Isopora* [51%]) were recorded at over 50% of sites. Five genera: *Acropora* (29.23 ± 1.80%), *Porites* (27.18 ± 1.70%), *Pocillopora* (10.83 ± 1.22%), *Goniopora* (8.69 ± 1.77%) and *Millepora* (6.75 ± 0.83%) contributed to over 75% of the total hard coral cover. Twenty-two genera contributed on average less than 5% (between 0.06 ± 0.04% to 2.18 ± 0.38%) to overall hard coral cover across the sites surveyed.

Hard coral coverage varied significantly across reef zones ($H = 2.12$, $p < 0.05$), with the highest cover observed at the reef crest zone (44.11 ± 2.41%); double that of the reef flat (23.58 ± 2.06%) and the back reef (17.27 ± 1.90%). In contrast, no significant differences in coral cover were detected between reef systems ($H = 1.29$, $p = 0.73$) or in pairwise zone-system comparisons (all $p > 0.05$; Supplementary Material 3).

Coral genera richness varied but did not differ significantly across sites, zones, or reef systems ($p > 0.05$, Supplementary Material 3). Across zones, the reef flat exhibited the highest mean richness (19.38 ± 1.39), followed by the back reef (16.08 ± 1.68), and the reef crest with the lowest richness (7.74 ± 0.52). At the reef system level, mean coral

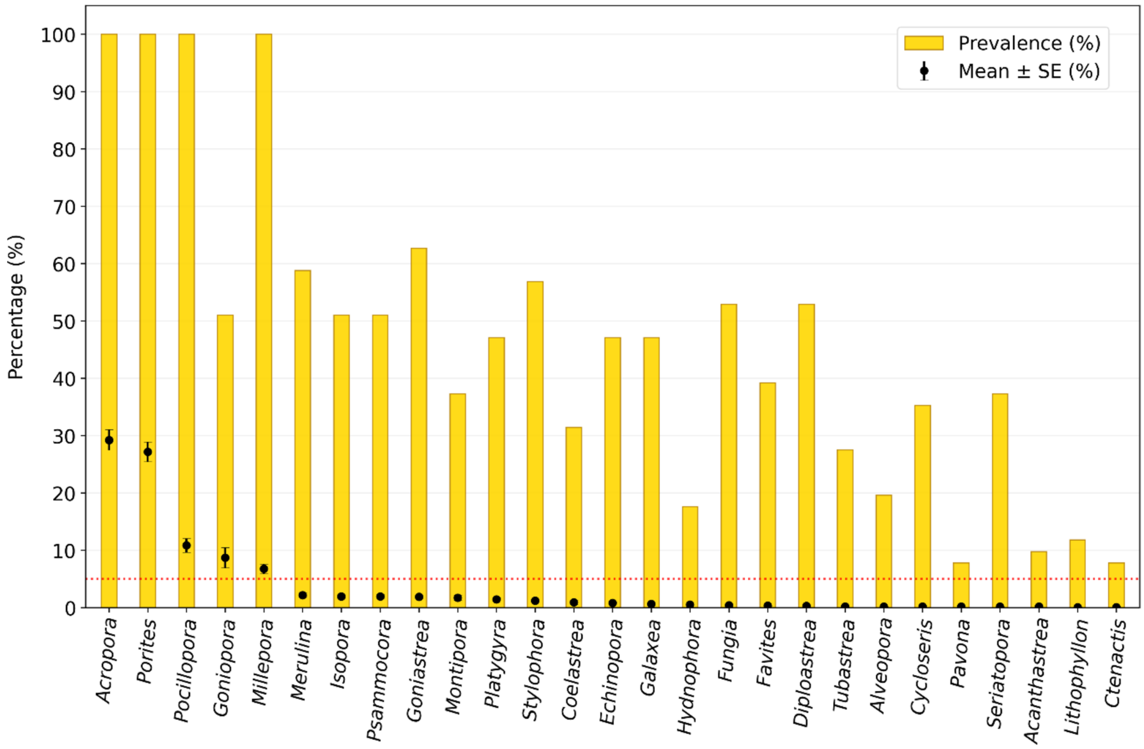


Fig. 2 Prevalence (%) across sites (bars) and mean (points ± SE) coral cover of observed hard coral genera across survey sites. The dashed red line indicates 5% threshold below which mean contribution to hard coral cover is assumed to be minimal

genera richness ranged from 15.00 ± 2.02 in the Namuka System to 11.38 ± 2.45 in the Suva System. The Laucala and Nasoata Systems recorded intermediate values (12.00 ± 1.17 and 12.57 ± 2.64, respectively). When comparing individual reef zones between each system, mean richness patterns were consistent with coverage, i.e. reef flats possessed the highest richness, followed by back reefs, and then reef crests, however these differences were not statistically significant.

Coral community composition between reef zones and reef systems

Within each of the four reef systems (Namuka, Suva, Laucala and Nasoata), coral community composition differed across reef zones, with variation most pronounced in the Suva (R = 0.96, $p = 0.005$) and Nasoata fringing reefs (R = 0.86, $p = 0.05$) (Supplementary Material 4). In

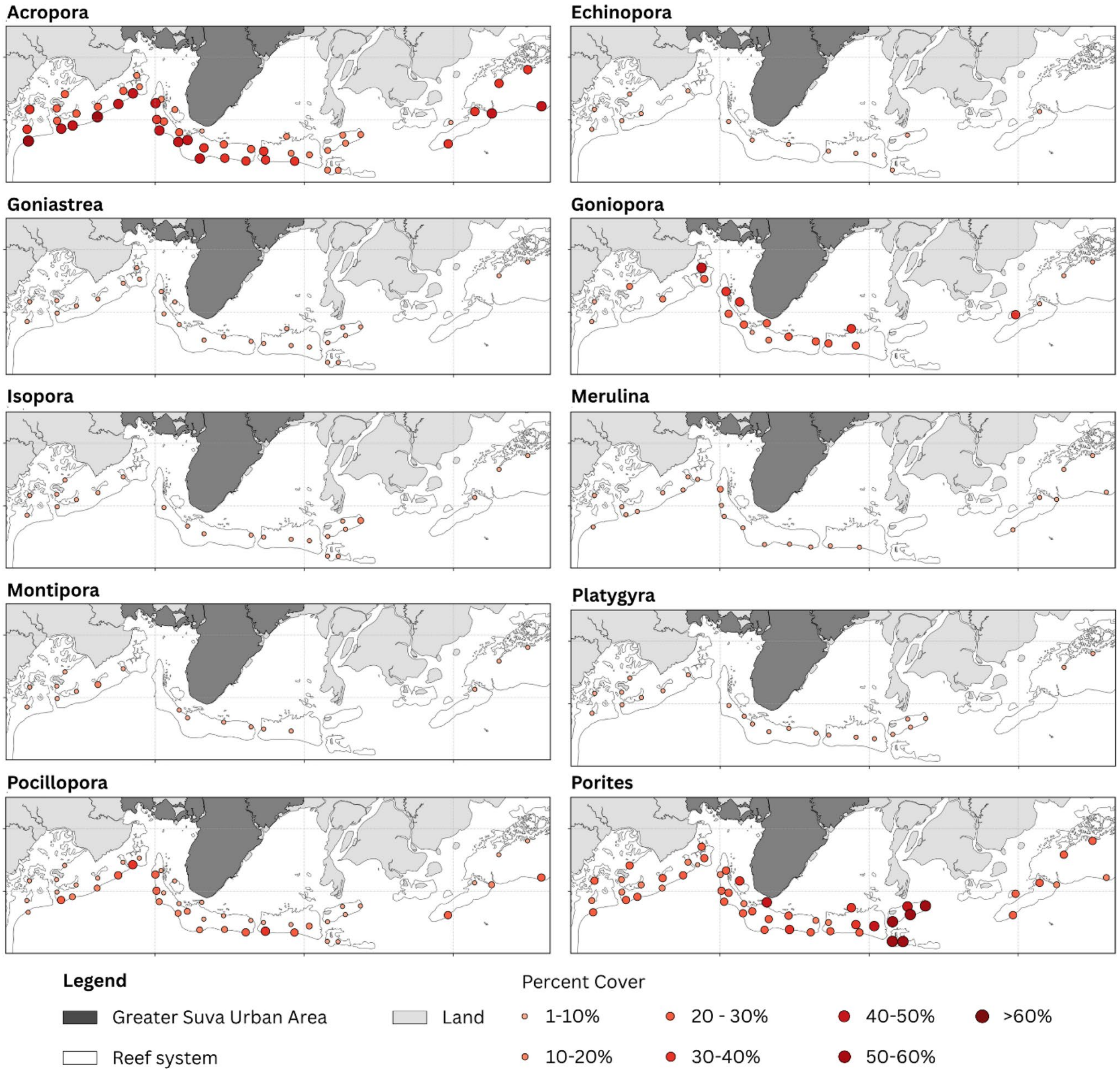


Fig. 3 Coral genera distribution plots depicting contribution to coral community composition across the GSUA region. Each map shows the percent cover of the respective genus relative to total hard coral cover at each survey site. Symbol colour and size indicate binned percent cover categories. The ten genera displayed correspond to those contributing most strongly to within- and between-zone dissimilarities (Supplementary Material 4 and 5). Remaining genera are presented in Supplementary Material 6

Suva, this difference was primarily driven by *Goniopora*, *Merulina*, *Pocillopora*, *Acropora* and *Goniastrea* (Fig. 3), while within Nasoata, the genera *Montipora*, *Isopora*, *Pocillopora*, *Goniopora*, and *Echinopora* were the drivers of the dissimilarity. Community composition also differed considerably between the reef crest and reef flat in both systems (average dissimilarity: 0.41 for both), whereas reef flat and back reef communities were more similar (average dissimilarity: 0.22 [Suva]; 0.17 [Nasoata]). Moderately significant differences in coral community patterns were evident at Namuka (R = 0.63, $p = 0.002$), with the greatest dissimilarity between the reef crest and the reef flat (average dissimilarity: 0.52) was driven by *Montipora*, *Pocillopora*, *Coelastrea*, *Goniastrea* and *Acropora*. Progressively smaller differences between the reef crest and back reef (average dissimilarity: 0.48), and the reef flat and back reef (0.33) were evident in this reef system. Coral communities within the Laucala system displayed marginal differences across reef zones (R = 0.216, $p = 0.055$), with the most prevalent dissimilarities between the reef crest and back reef systems (average dissimilarity: 0.39), reef crest vs. reef flat (average dissimilarity: 0.37), attributed to *Goniopora*, *Montipora*, *Porites*, *Platygyra*, *Merulina* and *Echinopora*.

In contrast to the strong zonation patterns observed within reef systems across reef zones, comparisons of coral community composition within zones across reef systems were similar (Supplementary Material 5). Among reef crest zones, marginally significant differences (R = 0.22, $p = 0.043$) in community composition were driven by *Acropora*, *Hydnophora*, *Porites*, *Stylophora* and *Isopora*. While among reef flat and back reef zones, coral community assemblages did not differ significantly (R = 0.08, $p = 0.29$, R = − 0.04, $p = 0.488$, respectively).

Patterns in juvenile coral distribution

Four genera (*Acropora*, *Porites*, *Goniopora*, and *Pocillopora*) of hard corals were analysed for juvenile distribution based on their total prevalence (> 50%) across sites and substantial coral coverage (> 5%). For each genus, the proportion of adult colonies was significantly higher than that of juveniles, ($p < 0.05$, Supplementary Material 7), although the spatial distribution of juveniles varied among genera. Juvenile *Acropora* accounted for 23.8% of the total *Acropora* population and were present at all sites. Juveniles exhibited lower variability across cover (IQR = 6.4) compared to adults (IQR = 16.4), which showed a bimodal distribution (Fig. 4). *Goniopora* juveniles represented 15.1% of the total population, with 30 sites showing no juvenile presence. Juvenile cover had a low IQR of 0.6, compared to adults (IQR = 6.1), indicative of a narrow distribution concentrated within a few high-abundance sites. Juvenile *Pocillopora* contributed 12.5% of the total population and showed low variability (IQR = 1.4), whereas adults had a broader and more normal distribution (IQR = 8.9). *Porites* juveniles comprised 18.8% of the total *Porites* population and were ubiquitous across Suva sites. Juvenile cover showed a relatively constrained spread (IQR = 2.6), while adults had a wider but consistent distribution (IQR = 7.5).

Across reef zones, juveniles of *Acropora*, *Goniopora* and *Pocillopora* showed statistically significant zonation, while juvenile *Porites* showed no statistically detectable zonation (Fig. 5A&B, Supplementary Material 8). *Acropora* exhibited the highest juvenile abundance on reef crests (9.53 ± 0.85%),

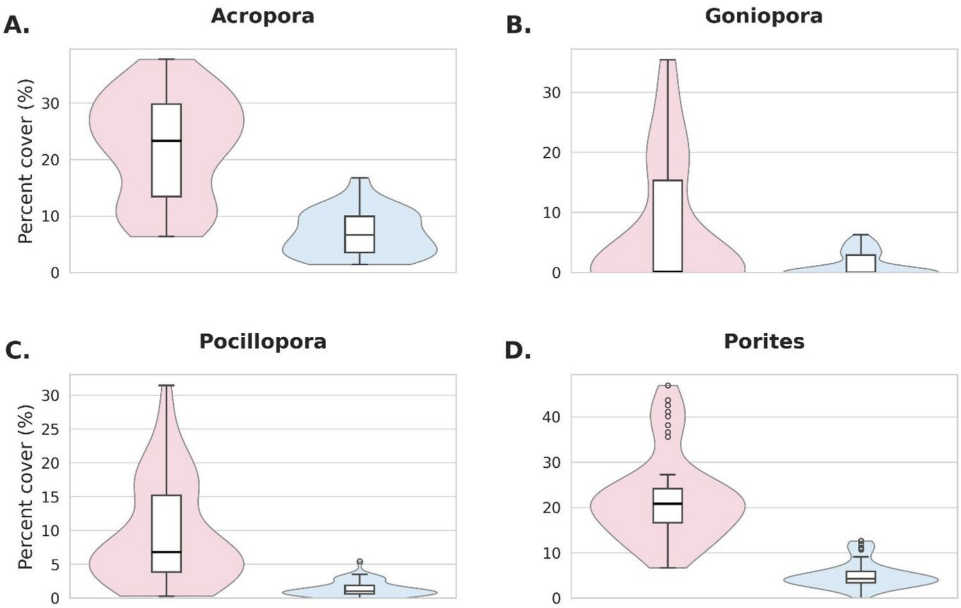


Fig. 4 Box and violin plot depicting juvenile coral distribution relative for adult coral distribution for each of the four genera, A. *Acropora*, B *Goniopora*, C. *Pocillopora*, D. *Porites*. Peach coloured plots represent adult coral, while blue plots represent juvenile coral

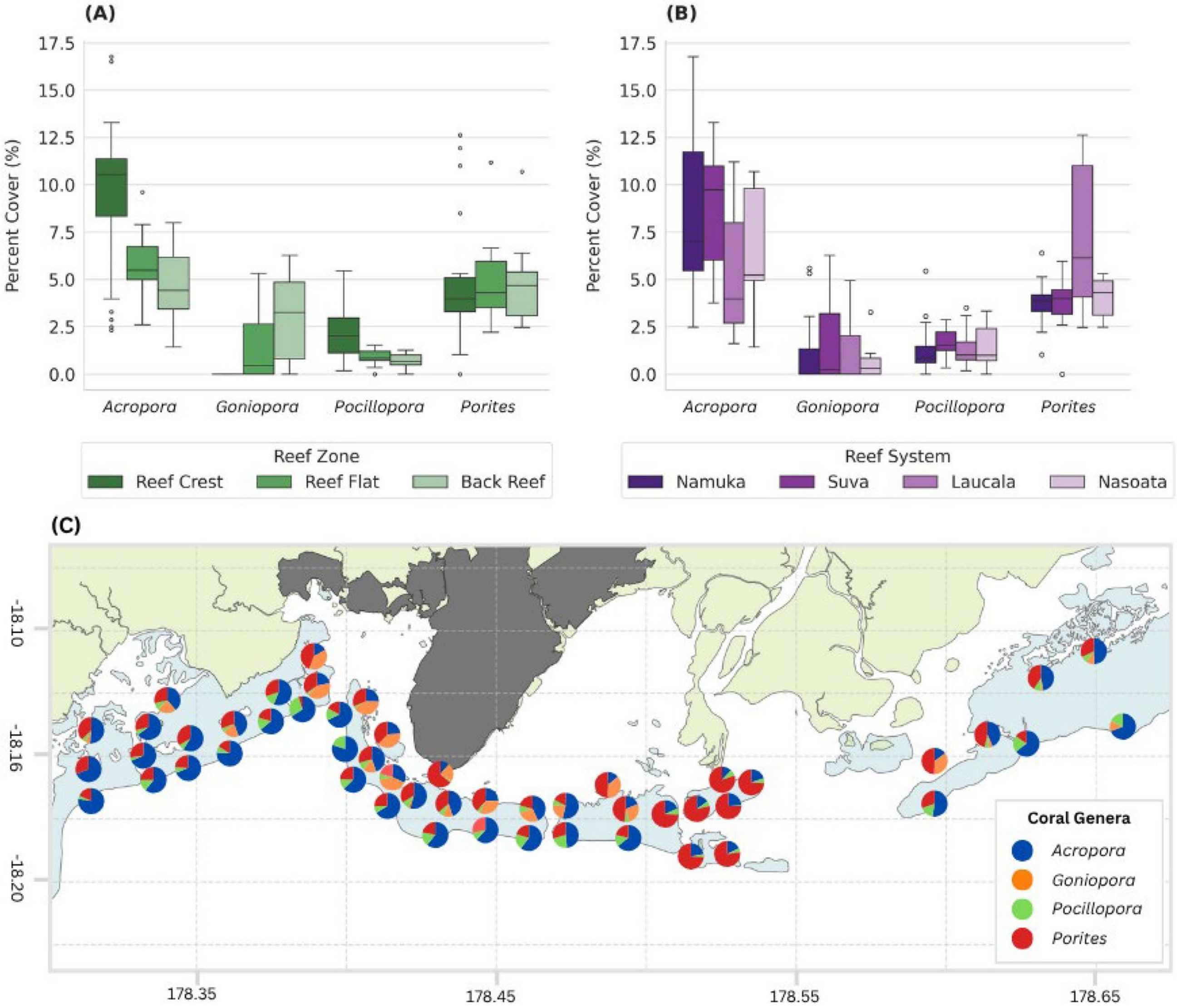


Fig. 5 Juvenile coral percent cover across reef zones (**A**) and across reef systems (**B**). Relative spatial distribution of juvenile *Acropora*, *Goniopora*, *Pocillopora*, and *Porites* are shown as proportional pie charts (**C**)

with significantly lower values on reef flats and back reefs (H = 14.8, $p < 0.001$). *Goniopora* showed the strongest zonation pattern (H = 27.0, $p < 0.00001$), with juveniles restricted to back reefs (3.02 ± 0.64%), absent on reef crests, and present at lower abundance on reef flats. *Pocillopora* juveniles also varied significantly across zones (H = 17.0, $p < 0.001$), being most abundant on reef crests (2.14 ± 0.26%), with reduced presence on reef flats and minimal coverage in back reef areas. In contrast, *Porites* juveniles were evenly distributed across reef zones (4.8–5.2%), with no significant differences detected (H = 0.17, $p = 0.97$).

Juvenile abundance for *Acropora* (H = 5.8, $p = 0.119$), *Goniopora* (H = 2.4, $p = 0.493$), and *Pocillopora* (H = 1.5, $p = 0.671$) did not differ significantly across reef systems (Supplementary Material 9), with relatively consistent cover observed across Suva, Namuka, Laucala, and Nasoata. Conversely, *Porites* exhibited significant system-level variation (H = 8.8, $p = 0.033$), with the highest juvenile cover in Laucala (7.20 ± 0.91%), nearly double that of other systems, and significantly greater than Namuka ($p = 0.042$).

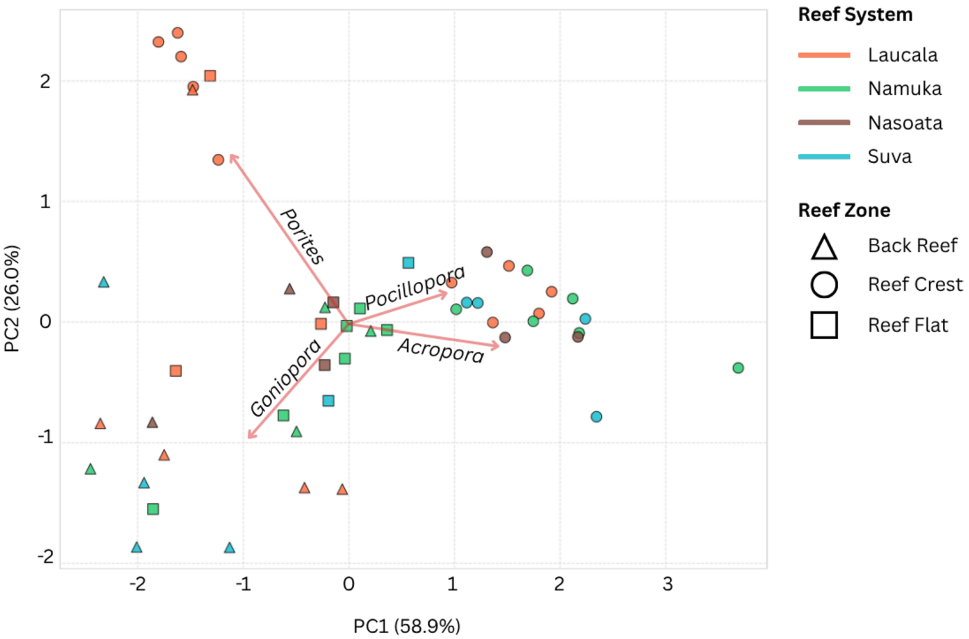
In terms of overall spatial distribution, *Acropora* juveniles were the most widespread and frequently dominant genus across multiple reef zones and systems (Fig. 5C). High abundances were observed throughout the back reef, reef flat, and reef crest zones at Namuka, as well as along the reef crests of the Suva Barrier Reef and western Laucala Barrier Reef. Similarly, *Acropora* dominated across reef zones at Nasoata Reef but was comparatively less abundant on the back reefs of the Suva and Laucala Barrier reefs. *Goniopora* juveniles exhibited a more restricted distribution, being predominantly dominant along the back reef zones of the Suva and Laucala Barrier reefs. *Goniopora* was notably lower or nearly absent in reef crest and reef flat zones, particularly within the Namuka reef system. *Porites* juveniles were strongly clustered, with peak dominance across all reef zones in the eastern Laucala Barrier Reef system. Furthermore, *Porites* were notably prevalent along back reefs and reef flats of Namuka, Suva and Nasoata, though less abundant than *Acropora* juveniles. *Pocillopora* juveniles showed a broad distribution pattern with no significant clustering. They were moderately abundant in certain areas, particularly along the reef crests of Suva, Laucala and Nasoata, but overall, their spatial presence was more sporadic compared to the other genera. Principal components analysis (PC1 = 58.9% variance; PC2 = 26.0% variance, Fig. 6) supported these patterns, identifying two dominant compositional gradients separating *Acropora*–*Pocillopora* dominated sites from those dominated by *Porites* and *Goniopora*. Spatial autocorrelation results further indicated random distributions for *Acropora* (Moran's I = 0.16), *Goniopora* (0.12), and *Pocillopora* (–0.03), while *Porites* exhibited strong clustering (0.69).

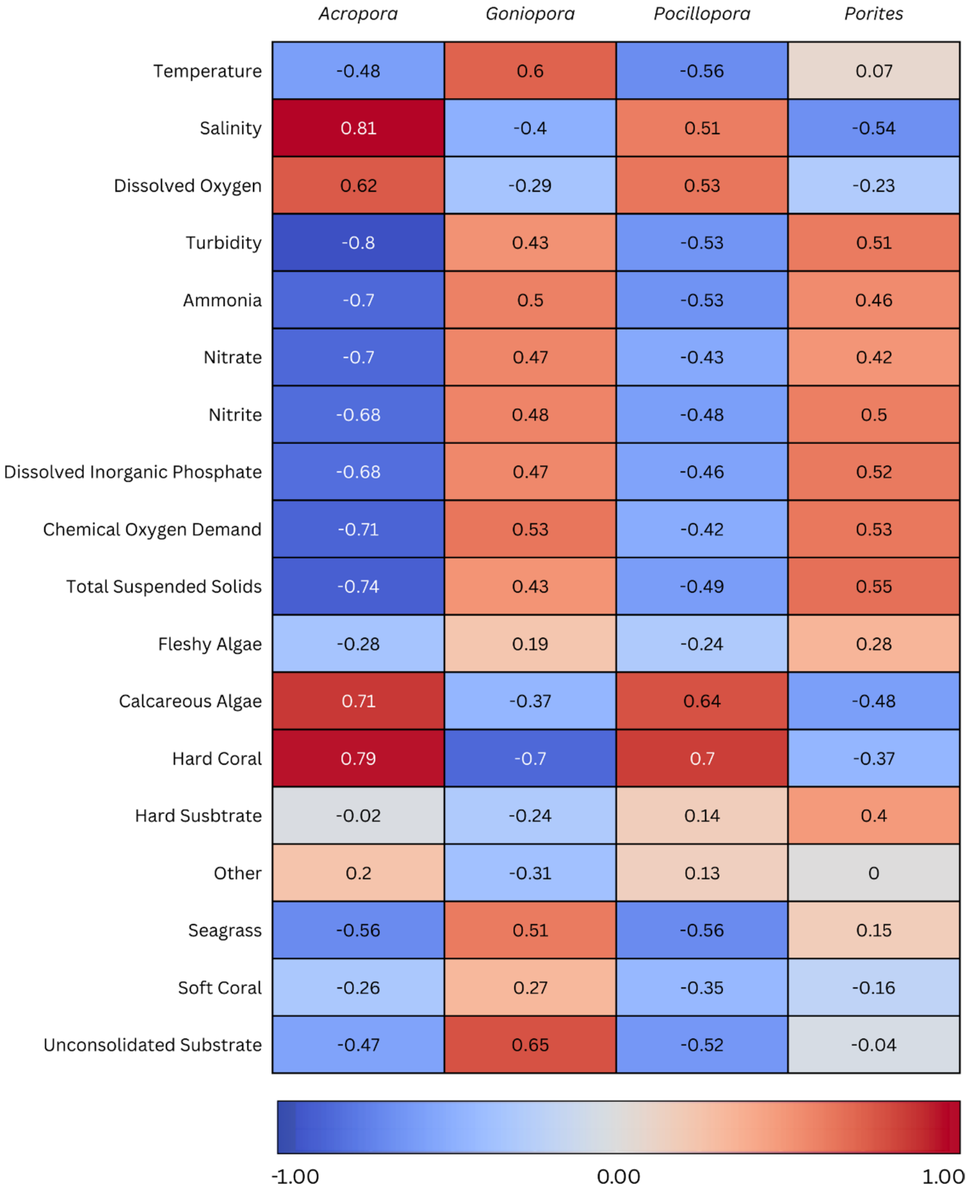
Drivers of juvenile coral distribution

Spearman rank correlation analysis identified respective significant associations ($\rho \geq \pm 0.3$) between juvenile coral abundances and environmental variables (Fig. 7). *Acropora* juveniles showed the greatest number and strength of correlations, including strong positive correlations with salinity ($\rho = 0.81$), dissolved oxygen ($\rho = 0.62$), and hard coral cover ($\rho = 0.79$), as well as strong negative correlations with turbidity ($\rho = -0.80$), total suspended solids ($\rho = -0.74$), and ammonia ($\rho = -0.70$). *Goniopora* juveniles were positively correlated with temperature ($\rho = 0.60$), ammonia ($\rho = 0.50$), and unconsolidated substrate ($\rho = 0.65$), and negatively correlated with hard coral cover ($\rho = -0.70$) and salinity ($\rho = -0.40$). *Pocillopora* juveniles were positively associated with hard coral cover ($\rho = 0.70$) and dissolved oxygen ($\rho = 0.53$) and negatively associated with turbidity (NTU) ($\rho = -0.53$) and ammonia ($\rho = -0.53$). *Porites* juveniles exhibited moderate positive correlations with TSS ($\rho = 0.55$), chemical oxygen demand ($\rho = 0.53$), and dissolved inorganic phosphate ($\rho = 0.52$), and a moderate negative correlation with salinity ($\rho = -0.54$).

GLMs identified distinct contributions of environmental drivers on juvenile coral distribution, with the best-supported variables varying by genus (Table 1). For *Acropora*, the best-supported model included salinity, dissolved oxygen, and hard coral cover (AIC = 222.17, adjusted $R^2 = 0.75$, dispersion = 0.62). The second and third ranked models included salinity + hard coral and dissolved oxygen + turbidity (NTU) + hard coral, respectively. For *Goniopora*, the top model included temperature, ammonia, and hard coral cover (AIC = 109.70, adjusted $R^2 = 0.70$, dispersion = 0.90). The next best-fitting models included combinations of ammonia, chemical oxygen demand, and nitrite. *Pocillopora* models consistently included hard coral cover, either alone or with dissolved oxygen and turbidity, with the top model having an AIC of 127.80 and adjusted R^2

Fig. 6 Principal components analysis (PCA) of juvenile coral distribution across study sites. Each point represents a survey site, with colours indicating reef systems (Laucala = orange, Namuka = green, Nasoata = brown, Suva = blue) and shapes representing reef zones (triangles = back reef, circles = reef crest, squares = reef flat)





	Acropora	*Goniopora*	*Pocillopora*	*Porites*
Temperature	-0.48	0.6	-0.56	0.07
Salinity	0.81	-0.4	0.51	-0.54
Dissolved Oxygen	0.62	-0.29	0.53	-0.23
Turbidity	-0.8	0.43	-0.53	0.51
Ammonia	-0.7	0.5	-0.53	0.46
Nitrate	-0.7	0.47	-0.43	0.42
Nitrite	-0.68	0.48	-0.48	0.5
Dissolved Inorganic Phosphate	-0.68	0.47	-0.46	0.52
Chemical Oxygen Demand	-0.71	0.53	-0.42	0.53
Total Suspended Solids	-0.74	0.43	-0.49	0.55
Fleshy Algae	-0.28	0.19	-0.24	0.28
Calcareous Algae	0.71	-0.37	0.64	-0.48
Hard Coral	0.79	-0.7	0.7	-0.37
Hard Susbtrate	-0.02	-0.24	0.14	0.4
Other	0.2	-0.31	0.13	0
Seagrass	-0.56	0.51	-0.56	0.15
Soft Coral	-0.26	0.27	-0.35	-0.16
Unconsolidated Substrate	-0.47	0.65	-0.52	-0.04

Fig. 7 Spearman correlation between juvenile coral abundance relative to environmental parameter and substrate. Complete table is depicted in Supplementary Material 10

Table 1 Top predictive models of juvenile coral distribution. Models ranked by Akaike Information Criterion (AIC) with explanatory power (Adj R^2) shown

Genus	Rank	Predictors	AIC	Adj R^2
Acropora	1	Salinity + Dissolved Oxygen + Hard Coral	222.17	0.75
	2	Salinity + Hard Coral	223.26	0.72
	3	Dissolved Oxygen + Turbidity (NTU) + Hard Coral	223.94	0.73
Goniopora	1	Temperature + Ammonia + Hard Coral	109.7	0.7
	2	Ammonia + Chemical Oxygen Demand + Hard Coral	112.86	0.68
	3	Temperature + Nitrite + Hard Coral	116.57	0.66
Pocillopora	1	Dissolved Oxygen + Hard Coral	127.8	0.53
	2	Hard Coral	128.2	0.48
	3	Turbidity (NTU) + Hard Coral	129.27	0.5
Porites	1	Total Suspended Solids	224.46	0.35
	2	Nitrite + Dissolved Inorganic Phosphate + Total Suspended Solids	224.87	0.39
	3	Nitrate + Dissolved Inorganic Phosphate + Total Suspended Solids	224.88	0.39

of 0.53. For *Porites*, the top-ranked model was based on TSS alone (AIC = 224.46, adjusted $R^2 = 0.35$), followed closely by models that also included dissolved inorganic phosphate, nitrite, and nitrate.

Discussion

This study aimed to characterise hard coral community composition across reef zones at four reef systems that comprise the urban reef adjacent to Suva, Fiji, and to understand the role of environmental variables and substrate characteristics in mediating juvenile distribution of dominant coral genera. In doing so, the results presented here offer valuable insights into the spatial and ecological structure of coral communities along Suva's urban reef system. Four major themes emerged in the data: 1. dominance and low evenness in coral assemblages, 2. zonal differentiation drives coral community structure, 3. genus-specific juvenile distribution strategies and constraints, 4. environmental drivers of juvenile coral distribution. Each of these themes is explored in further detail hereafter.

Dominance and low evenness in coral assemblages

Coral communities within the reefs adjacent to Suva were characterised by dominance of a small subset of genera, with *Acropora* and *Porites* together contributing over 56% of mean coral cover and notable but smaller contributions of *Pocillopora*, *Goniopora* and *Millepora*. This pattern of dominance is consistent with other inshore, turbid Indo-Pacific reefs, where *Acropora*, *Goniopora*, and *Porites* can dominate due to genus-specific traits such as rapid growth (*Acropora*) or sediment tolerance (*Porites* and *Goniopora*) (Browne et al. 2012). In contrast, findings from some urbanised Caribbean reefs indicate that branching taxa like *Acropora* are often uncommon under heavy urban influence, and modelling studies highlight shifts in assemblages affecting calcification rates (Alvarez-Filip et al. 2013; Heery et al. 2018). Together, these studies illustrate that while a few tolerant, fast-growing or sediment-resistant taxa dominate many disturbed reef systems, the specific composition may vary between Indo-Pacific and Caribbean settings, reflecting local environmental gradients and disturbance histories. The scarcity and low cover of many other genera, such as *Acanthastrea*, *Ctenactis*, and *Pvona*, highlights low community evenness, suggesting reduced functional diversity which may reduce ecosystem resilience (Darling et al. 2012; Bellwood et al. 2019). Notably, *Acropora* spp. tend to have fast growth rates with the potential to recover quickly from disturbances (i.e. competitive life history), *Porites* spp. (the other dominant taxa) have slow growth but with higher resistance to stress (i.e. stress-tolerant life history) (Darling et al. 2012). The high variability and patchy distributions observed in genera such as *Goniopora* and *Merulina* suggest that localised environmental conditions strongly shape adult and juvenile community heterogeneity, consistent with niche specialisation reported in other coral assemblages (Mumby and Steneck 2008; Hughes et al. 2010; Pratchett et al. 2020). These patterns could suggest vulnerability of Suva's reefs, where structural complexity and diversity are often focussed on a limited number of taxa resulting in reduced response diversity (Nyström 2006; Gowan et al. 2014; Yoshioka et al. 2016). However, Pratchett et al. (2020) demonstrated through empirical models that *Acropora* can continue to dominate assemblages so long as intervals between disturbances are > 2 years, whereas *Porites* are favoured under bi-annual moderate impacts, and both genera are removed only under more frequent (< 2 years) severe disturbances, suggesting that the dominance of these two genera may infer system resilience. Furthermore, Côté and Darling (2010) present a hypothesis that communities shaped by local stressors may in fact exhibit higher resilience in the face of climate change, if we can assume co-tolerance to multiple stressor types.

Zonal differentiation drives community structure

Our findings demonstrate that reef zonal differences, specifically the distinct gradients across reef crest, reef flat and back reef, are a stronger determining factor of coral community composition than the reef system identity and thus proximity to the urban centre at the scale of this study. Significant differences in community composition were observed between zones, with genera such as *Acropora*, *Goniopora*, and *Pocillopora* driving zonal dissimilarities. Between zones of different systems (e.g., crest 1 vs. crest 2 vs. crest 3 vs. crest 4), differences were weak, suggesting that local environmental conditions across zones within systems exert a greater influence than geographic separation or urban proximity. Although we did not test environmental parameters across zones within this study, previous work in the same region (Dehm et al. 2025) identified clear spatial water quality gradients consistent with the observed zonal differentiation in coral assemblages. Notably, some reefs such as those in eastern Laucala exhibited deviations from this general pattern, with higher percent cover and different juvenile composition; these exceptions highlight local variability but do not alter the overarching trend of zonal dominance. These results align with recent findings showing that zonal factors such as depth, exposure, and microhabitat heterogeneity are primary drivers of coral assemblages, often outweighing the influence of urbanisation or reef system boundaries (Afiq-Rosli et al. 2021; Ng et al. 2021; Cook et al. 2022). While urban proximity introduces stressors such as turbidity and nutrient loading (Heery et al.

2018; Dehm et al. 2024), its influence appears secondary to habitat-driven zonal variation. Coral and fish assemblages shift predictably along these environmental gradients, with urban impacts compressing but not eliminating underlying zonal patterns (Gowan et al. 2014; Cook et al. 2022; Tsai and Connolly 2025).

Genus-specific juvenile distribution strategies and constraints

Juvenile coral distributions revealed distinct distribution patterns across genera, with consistently lower juvenile abundance compared to adults. *Acropora* showed widespread juvenile presence but was particularly dominant on reef fronts, indicating environmental thresholds may limit juvenile distribution and survival even in areas with healthy adult populations. *Goniopora*, by contrast, showed sparse and highly localised juvenile prevalence, suggesting this genus is dependent on specific habitat conditions for successful settlement and survivorship in early stages. *Porites* exhibited reliable but environmentally-filtered juvenile assemblages, while *Pocillopora* demonstrated stable adult populations but limited juvenile representation. These genus-specific distribution patterns reflect documented reproductive strategies: *Acropora* often shows positive adult–juvenile relationships but is constrained by environmental thresholds and fragmentation reliance, while *Pocillopora* exhibit high juveniles densities in disturbed habitats (Bramanti and Edmunds 2016; Tuhumena et al. 2019). In contrast, *Porites*, a genus common across reefs, can often dominate in marginal or degraded environments, indicating resilience under suboptimal conditions (Cabral-Tena et al. 2018; Deng et al. 2024; Tortolero-Langarica et al. 2024). These patterns suggest that juvenile distribution and survival constrain coral regeneration in urban reefs (Bramanti and Edmunds 2016; Doropoulos et al. 2022; Loke et al. 2024). The abundances of juveniles may be further mediated by larval supply, substrate stability and microhabitat complexity, which may influence settlement success, early survival or growth via trade-offs between predation and competition (Doropoulos et al. 2015; Edmunds 2023).

Environmental drivers of juvenile coral distribution

Environmental parameters strongly influence juvenile coral abundance in a genus-specific manner, emphasising the critical role of local habitat quality in driving juvenile patterns and survivorship, highlighting the challenges of projecting future populations or community composition. *Acropora* juveniles showed strong positive associations with salinity, dissolved oxygen, and existing hard coral cover, and negative correlations with turbidity, suspended solids, and nutrient levels. This pattern underscores their sensitivity to water quality and reliance on stable, oxygenated habitats, consistent with previous findings that *Acropora* recruits favour clean water and low competition environments (Bramanti and Edmunds 2016; Ricardo et al. 2021; Drake et al. 2025). In contrast, *Goniopora* juveniles were positively associated with higher temperatures, ammonia concentrations, and unconsolidated substrates, but negatively linked to salinity and hard coral cover, potentially indicating greater tolerance for more variable or disturbed conditions; a niche specialisation reflected in their patchy adult distributions. This genus has previously been reported to recruit successfully in turbid inshore reefs on the Great Barrier Reef (Jonker et al. 2019). Juvenile *Pocillopora* distribution correlated moderately with hard coral cover and oxygen, reflecting benefits from structurally complex and well-oxygenated reefs. On the other hand, *Porites* juveniles were associated with elevated suspended solids and nutrient concentrations but reduced salinity, indicating a tolerance for turbid, nutrient-enriched conditions and an ability to recruit closer to freshwater inputs (Manzello and Lirman 2003; Padilla-Gamiño et al. 2012). Across most genera, hard coral cover was positively associated with juvenile abundances, highlighting the importance of existing reef structure in facilitating settlement and survival. The absence of spatial autocorrelation suggests that distribution patterns are primarily driven by localised environmental filters rather than spatial clustering. These patterns correspond with broader literature linking reproductive modes, microhabitat preferences, and water quality to genus-specific distribution outcomes (Doropoulos et al. 2015; Gouezo et al. 2020).

What this means for reefs of the GSUA

Taken together, our findings suggest that while urban stressors such as turbidity and nutrient enrichment undoubtedly influence coral assemblages around Suva, reef community composition is shaped more strongly by habitat-driven zonal differentiation and genus-specific ecological traits (Duprey et al. 2016; Lawson et al. 2021; Tsai and Connolly 2025). However, this does not preclude urbanisation from having substantial impacts. It is possible that its effects operate at spatial or temporal scales beyond the resolution of this study, or manifest through subtle shifts in environmental quality that interact with zonal gradients. Testing for interactions between zone and distance from the city in future analyses may reveal whether urbanisation intensifies or modifies zonal differences.

The dominance of a few fast-growing, disturbance-tolerant genera (*Acropora, Porites, Pocillopora*, and *Millepora*) reflects patterns seen in other degraded or urbanised systems (Duprey et al. 2016; Lal et al. 2018; Mayer-Pinto et al. 2018; Januchowski-Hartley et al. 2020), raising concerns about reduced functional redundancy and resilience.

Uneven juvenile distribution across all major genera, driven by environmental thresholds, narrow habitat specialisations, and microhabitat quality, further limits the capacity for natural recovery, with local environmental filters playing a stronger role than spatial proximity to urban centres (Fiebig and Vuki 1997; Navarrete et al. 2005; Lal et al. 2018; Goberdhan and Kininmonth 2021). These results indicate that conservation and restoration in Suva's reefs should prioritise maintaining habitat diversity across reef zones, protecting existing structural complexity to support settlement, and tailoring interventions to habitat-specific environmental sensitivities. Given the challenges posed by differing environmental requirements among coral genera, future work should also emphasise resolving the mechanisms that underpin genus-specific resilience and recovery, enabling more informed and adaptive restoration strategies under increasingly variable conditions. Such strategies may help buffer against urban impacts, sustain biodiversity, and improve the adaptive capacity of these ecologically and socially valuable reef systems.

Implications and limitations for Urban Reef Management

Our findings emphasise the ecological specialisation and vulnerability of some coral genera within Suva's reefs. The dominance of a limited number of structurally important taxa, coupled with taxon-specific juvenile distribution constraints, suggests that reef regeneration may be limited by both environmental quality and ecological bottlenecks. Conservation and restoration strategies should prioritise the protection of high diversity areas, especially with prevalent juvenile abundance, and consider genus-level sensitivities to water quality in future planning. A targeted approach that supports both dominant and functionally diverse coral taxa will be critical for maintaining resilience in rapidly changing coastal environments.

Although our analyses treated zone and reef system as independent factors, observed patterns suggest potential interactions between urbanisation and habitat zonation. Future models incorporating interaction terms could clarify whether urban impacts are zone-specific, such as disproportionately affecting sheltered or sediment-prone back reefs. Furthermore, unmeasured factors (e.g. disease, predation) may further influence outcomes. Future work should integrate experimental approaches, long-term monitoring, and expanded ecological variables to refine urban reef management strategies. In addition, future studies could incorporate multivariate ordination methods, such as separate nMDS or Redundancy Analysis (RDA), to directly relate coral community composition to environmental gradients and improve visualisation of dissimilarity patterns across reef zones and systems. As our juvenile data were derived from point-based classifications, values represent relative percent cover rather than colony density. Incorporating direct counts of juvenile colonies (colonies m^{-2}) in future monitoring would complement percent cover analyses and enhance comparability.

Conclusion

The coral reefs around Suva exhibit a community dominated by a few resilient genera, notably *Acropora* and *Porites*, and exhibit distinct patterns in juvenile assemblages. While the relatively low evenness indicates that functional diversity may be limited, these reefs have maintained coral cover over time, suggesting a degree of resilience to current levels of disturbance. Consistent with Pratchett et al. (2020), our findings imply that unless disturbances become more frequent than approximately every two years, dominant genera such as *Acropora* and *Porites* are likely to sustain their prevalence. While urban pressures such as increased turbidity and nutrient enrichment undoubtedly influence water quality, our findings indicate that environmental gradients linked to reef zonation, such as depth, exposure, and habitat complexity currently play a more decisive role in structuring adult and juvenile coral assemblages than proximity to the urban centre alone. Data reported highlight environmental correlations which require further investigation, for example, *Acropora* were associated with high water quality and stable substrates, whereas others, such as *Goniopora* and *Porites*, were linked to more disturbed or nutrient-rich environments. These nuanced responses suggest that urban impacts modify but do not override fundamental habitat-driven patterns. To align our conclusions with the management context of Suva's urban coastline, we highlight several targeted priorities. First, improving sewage and wastewater treatment infrastructure, including reducing untreated overflows during heavy rainfall events and strengthening regulation of industrial and commercial discharges, would directly address the nutrient enrichment and pollutant loads affecting Laucala Bay. Second, reducing sediment and contaminant runoff through watershed-scale interventions is critical. Priority actions include restoring mangroves and riparian vegetation, re-naturalising creek edges, and reducing impermeable surfaces within the GSUA to slow stormwater delivery and sediment transport. Third, limiting chemical inputs such as fertilisers and pesticides within the urban and peri-urban catchment would help mitigate nutrient-driven shifts that disproportionately affect sensitive taxa such as *Acropora*. Finally, implementing routine ecological and water-quality monitoring together with improved regulatory enforcement would enable early detection of stressors and allow managers to more effectively evaluate restoration success. Collectively, these actions provide specific, actionable pathways for supporting habitat quality and enhancing the recovery potential of dominant and functionally important coral taxa within Suva's urban reef environment.

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Author contributions J.D. and A.S. conceptualised the study. J.D. conducted the fieldwork, data collection, data preparation data analysis, and drafted the initial manuscript. A.S. supervised the work and contributed to manuscript review and editing. A.F. and M.L. reviewed the results analysis and critically reviewed and edited the manuscript. L.M. contributed to data collection, visualisations, and review and editing of the manuscript. All authors contributed to the finalisation of the manuscript.

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Data availability All data supporting the findings of this study are included in the manuscript and its supplementary information files. Additional datasets, including raw data, are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare that they have no competing financial interests. Non-financial interests: This research forms part of the doctoral work of J.D., supervised by A.S.

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