Coral Reefs
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RESEARCH

Turbid coral reefs in northwestern Australia exhibit high tolerance to successive extreme heat stress events

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Abstract Suspended particulates on turbid coral reefs can mitigate thermal stress and bolster coral energy acquisition, improving resilience to climate change. Yet, questions remain regarding how corals on turbid reefs respond to successive heat stress events and whether certain coral taxa are more likely to survive under increasingly variable environmental conditions. We investigated the response of coral communities across a natural turbidity gradient in the Dampier Archipelago (Western Australia) to successive heat stress events in 2022 and 2023 (12.7 and 14.4 degree heating weeks, respectively). We then examined the influence of environmental variables, such as wave exposure, total suspended solids (TSS) and light attenuation (KD490), on coral bleaching and changes in coral cover across this turbidity gradient. Prior to heat stress, coral cover across 11 consistently surveyed reefs ranged from 17 to 68%. Approximately 30% of hard corals bleached each summer, and there was an overall 8% decline in mean cover (from 34 to 26%). Moderately turbid reefs, dominated by stress-resistant *Pavona* spp. exhibited comparatively low bleaching and maintained high coral cover throughout the study period, suggesting higher resilience to successive stress events. Conversely, *Porites* spp. showed increasing susceptibility over repeated heat stress events. Reefs dominated by plating or branching *Acropora* spp. experienced the highest bleaching prevalence and the greatest shifts in community composition. Variations in significant wave height and TSS concentration were strong, but nuanced, predictors of total hard coral bleaching and community-level bleaching susceptibility (respectively), whilst maintenance of coral cover was associated with higher KD490. Our findings highlight the capacity of corals on turbid reefs to withstand severe, repeated heat stress and bleaching, and the potential for such reefs to act as climate change refugia.

Keywords Coral bleaching · Thermal resilience · Marine heatwaves · Multiple stressors · Turbidity gradients · Hydrodynamic exposure · Local environmental variability

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Introduction

Turbid coral reefs are typically situated in shallow coastal waters and characterised by high levels of suspended particulate matter and low light. These conditions have traditionally been considered marginal or sub-optimal environments

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for coral growth due to smothering, tissue abrasion, and/or reduced rates of photosynthesis (Zweifler et al. 2021; Schoepf et al. 2023). However, a growing body of evidence demonstrates that abundant, diverse, and high-functioning coral assemblages can exist in extreme environmental conditions, including in turbid and low-light conditions (Browne et al. 2012; Morgan et al. 2016, 2017; Zweifler et al. 2021; Schoepf et al. 2023). The persistence of corals on turbid reefs, despite chronic exposure to multiple stressors, suggests that these systems may support coral assemblages that are already acclimatised or adapted to stressful conditions, potentially rendering them more resilient to elevated sea surface temperatures and subsequent bleaching than their clear-water counterparts (Cacciapaglia and Van Woesik 2016; Browne et al. 2019; Fisher et al. 2019). Indeed, nearshore turbid reefs have been identified as potential resilience hotspots and climate change refugia (e.g. along the eastern and western coasts of Australia; Cacciapaglia and Van Woesik 2016; Schoepf et al. 2023). However, responses to heat stress on turbid reefs are highly variable, highlighting important gaps in our understanding of the interacting factors shaping bleaching outcomes on these reefs.

The complex and interacting mechanisms underpinning coral thermal tolerance in turbid environments make it challenging to predict how these communities will respond under future climate scenarios. Moderate levels of turbidity may reduce heat stress and bleaching by attenuating light (Morgan et al. 2017; Fisher et al. 2019; Sully and Van Woesik 2020). Some coral species also exhibit enhanced heterotrophic feeding capabilities in turbid environments (Anthony 2000; Anthony and Fabricius 2000; Travaglione et al. 2023), which can increase in response to bleaching (Grottoli et al. 2006). However, the benefits of shading and heterotrophy may be outweighed by the costs of reduced autotrophic energy acquisition (i.e. due to lower light), increased energy demands (e.g. for active sediment rejection) and impaired reproduction/recruitment processes under high sediment loads (Riegl and Branch 1995; Jones et al. 2015; Fisher et al. 2019; Evans et al. 2020). As a result, bleaching outcomes on turbid coral reefs are likely to depend strongly on local environmental and biological context.

Beyond turbidity-associated effects on light and energy balance, a suite of other abiotic and biotic factors can interact to influence coral bleaching responses. For example, local hydrodynamics, including water residence time and flow regimes, can modulate heat stress by flushing corals with cooler waters and removing harmful metabolic radicals (Nakamura and Van Woesik 2001; West and Salm 2003; Page et al. 2019). However, the relationship between hydrodynamics and bleaching remains equivocal, as detailed information on local hydrodynamics is often unavailable when heat stress occurs. Indeed, some evidence suggests that reduced bleaching susceptibility may be more related to hydrodynamic variability rather than high water flow alone (McClanahan et al. 2005; Kenkel and Matz 2016). Similarly, repeated exposure to thermal stress can have variable and cumulative effects on coral communities, including altered bleaching susceptibility (Pratchett et al. 2013), differential survival and recovery (Schoepf et al. 2015; Babcock et al. 2021), and contrasting shifts in community composition (Pratchett et al. 2020). Despite growing recognition of interacting stressor effects on coral reefs (Ban et al. 2014; Harborne et al. 2017; Ellis et al. 2019), our understanding of how turbid reef communities respond to multiple stressors remains limited (Camp et al. 2018), and even less is known about responses to successive extreme heat stress events.

The turbid reefs of the Dampier Archipelago (Western Australia) have generally maintained moderate to high coral cover (> 30%) and diversity despite high levels of anthropogenic activity, cyclones, anomalous periods of elevated turbidity, and water temperatures regularly exceeding bleaching thresholds (Moustaka et al. 2019). Importantly, bleaching trends within the Dampier Archipelago do not always align with expected patterns based on cross-shelf turbidity gradients or accumulated heat stress, nor do they tend to coincide with El Niño–Southern Oscillation (ENSO) status as seen in other parts of Australia and the world (see Fig. S1; Table S1; Hoegh-Guldberg 1999). During the summers of 2022 and 2023, the region recorded high levels of accumulated heat stress (12.7 and 14.4 degree heating weeks [DHW], respectively, NOAA Coral Reef Watch 2025), resulting in extensive coral bleaching throughout the Archipelago. Together, these observations suggest that turbid reefs in the Dampier Archipelago may exhibit context-dependent resilience to thermal stress, warranting further investigation to better understand how interacting local factors shape bleaching responses under repeated heat stress.

Here, we assess the extent of bleaching and subsequent coral community changes across a turbidity gradient over two consecutive years of extreme heat stress in the Dampier Archipelago. We then examine how local abiotic and biotic factors influence bleaching susceptibility and subsequent mortality. Specifically, we: 1) quantify the spatial extent of bleaching and susceptibility of different hard coral taxa over successive heat stress events; 2) assess the influence of bleaching on hard coral cover and community composition; and 3) evaluate the influence of temperature, turbidity, hydrodynamics, and community composition on coral bleaching susceptibility, cover, and mortality. Our findings contribute to a growing body of evidence demonstrating that healthy and resilient reefs can occur in extreme environments and highlight the value of resilient turbid reefs for global conservation strategies.

Methods

Study location

The Dampier Archipelago comprises 42 islands situated off the coast of the Pilbara region in northwestern Australia (Fig. 1). These islands are fringed by a network of turbid reefs with moderate to high coral cover and comparable hard coral diversity to the clear waters of the World Heritage listed Ningaloo Marine Park (located ~ 300 km southwest; Hatcher 1991; Griffith 2004; Moustaka et al. 2019). Water temperature, current patterns, and turbidity vary greatly across the Archipelago due to prevailing winds, tidal movements (5 m maximum spring tidal range), aspect, and wave exposure (Semeniuk et al. 1982; Pearce et al. 2003). Extreme seasonal variation in water temperature can occur in shallow bays, ranging from 18 to 33 ℃. Annual rainfall is low (< 300 mm per year; Bureau of Meteorology 2025) and there are no riverine inputs to the system. However, periodic cyclones occur through the austral summer (December to April), which cause physical damage of reef structures and increase terrestrial runoff (Simpson 1988). Turbidity varies spatially and temporally, with more turbid conditions close to the inshore islands that are heavily influenced by tide-driven circulation patterns, fine sediment resuspension, organic particulate matter, and seasonal phytoplankton blooms (Semeniuk et al. 1982; Simpson 1988). Sediment composition also varies across the Archipelago, shifting from predominantly coarser, calcareous sediments at offshore sites to progressively finer, terrigenous silicate sediments around the inshore islands (Forde 1985). The diversity of coral communities within the Archipelago reflects these highly variable environmental conditions (Veron and Marsh 1988; Griffith 2004).

Coral reefs across the Archipelago are predominantly subtidal, with fringing reefs occurring on the seaward side of the offshore islands, and patch reefs occurring on solid substrate around the inshore and midshore islands (Jones 2004). These reefs are composed of mixed coral and algal assemblages, with key coral taxa including *Acropora*, *Porites*, *Turbinaria*, *Pavona*, *Montipora*, *Lobophyllia*, and various Merulinids (Veron and Marsh 1988). There is high spatial heterogeneity in coral cover and diversity across the Archipelago, and while the drivers of this variation are not fully understood, both peak at reefs located at intermediate distances from the mainland (Moustaka et al. 2019).

The Dampier Archipelago has some of the highest levels of coral cover in the Western Pilbara, despite experiencing repeated warm and cold water bleaching events over the past 30 years (Babcock et al. 2021). Widespread warm water bleaching was reported during the summers of 1998, 2005, 2008, 2013, 2014, and again during the recent heat stress events in 2022 and 2023 (Fig. S1; Table S1). Localised bleaching was also observed in 2020/21 (pers. obs.). While

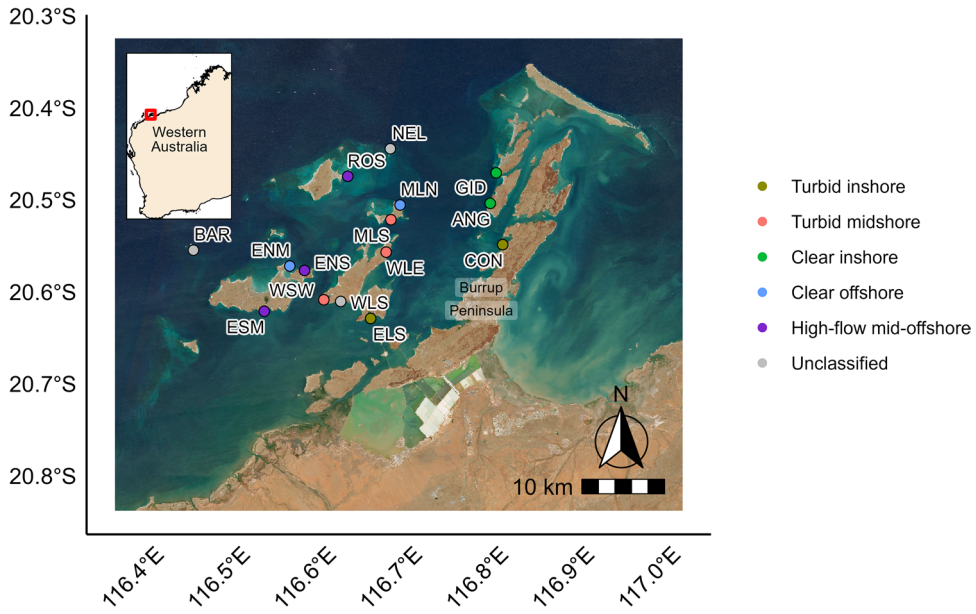

Fig. 1 Location of study sites across the Dampier Archipelago, Western Australia. Sites of the same colour have similar environmental conditions as determined via hierarchical cluster analysis (see Fig. S6 and Fig. S7). Site abbreviations: ANG = Angel Island; BAR = Bare Rock; CON = Conzinc Bay; ELS = East Lewis Island; ENM = Enderby Island (North-Medium); ENS = Enderby Island (North-Small); ESM = Enderby Island (South-Mangrove); GID = Gidley Island; MLN = Malus Island (North); MLS = Malus Island (South); NEL = Nelson Rocks; ROS = Rosemary Island; WLE = West Lewis Island (East); WLS = West Lewis Island (South); WSW = West Lewis Island (Southwest)

not all recorded bleaching events resulted in substantial coral mortality, significant reductions in coral cover were recorded following extensive bleaching in 2013 and a smaller bleaching event in 2014 (Babcock et al. 2021).

Fifteen sites spanning a natural turbidity gradient across the Archipelago were selected to provide a broad spatial assessment of bleaching and environmental conditions, with site depths ranging from 1.4 to 7.2 m (relative to mean sea level; median 3 m; Fig. 1; Table S2).

Environmental characterisation

Environmental variables were collated at multiple spatial and temporal scales to explore potential drivers of bleaching susceptibility, encompassing thermal stress (DHW), turbidity and light environment (total suspended solids [TSS], light attenuation [KD490]), hydrodynamic conditions (wave height and water velocity), and site context (depth and distance from mainland). *In situ* water temperature data were collected at 12 out of 15 sites across the Archipelago using HOBO Water Temp Pro data loggers recording every 30 min during the study. Where *in situ* water temperature data were not available (i.e. at three sites without loggers or in instances of logger failure), missing values were modelled from satellite-derived temperature (SST) data retrieved from the NOAA ERDDAP server (dataset ID jplMURSST41; Chin et al. 2017; Table S3). Daily mean *in situ* temperatures were calculated from 6 pm to 6 am data to ensure consistency with the night time only SST product and compared with corresponding SST data extracted from the closest grid cell to each logger site. Strong linear relationships were obtained at the site and Archipelago level ($R^2 = 0.94 – 0.96$, $p < 0.001$; Fig. S2; Fig. S3; Fig. S4), and these models were used to predict missing *in situ* temperature values (i.e. site-level models were used to fill in data gaps occurring due to logger failure, while the Archipelago-level model was used at sites without loggers present). Site-specific DHW values were then calculated following NOAA methodology, whereby 4–8 ℃-weeks indicates a risk of reef-wide coral bleaching, 8–12 ℃-weeks indicates risk of reef-wide bleaching and mortality of heat-sensitive corals, and > 12 ℃-weeks indicates risk of multi-species mortality (Skirving et al. 2020; NOAA Coral Reef Watch 2025). Maximum monthly means (MMM) required for these calculations were determined at the site level from historic SST data to ensure a sufficient climatology timeframe was considered (1985 – 2012) and to maintain consistency with the NOAA DHW products.

Turbidity and light environment were characterised using both TSS and the diffuse attenuation coefficient at 490 nm (KD490), which represent complementary physical and optical components of turbidity. Discrete water sampling was conducted in March, July and October/November of 2021 and 2022 at 13 out of 15 study sites (Table S3) to characterise seasonal and spatial variation in TSS across the Archipelago. Duplicate 1000 mL subsurface water samples were collected from each site (within the top 1 m of the water column) and filtered onto pre-weighed, pre-labelled 47 mm diameter 0.4 µm polycarbonate filters using a vacuum filtering manifold. These were folded and stored refrigerated at 4 ℃ in individual glass vials for later gravimetric analysis. Given high variability in turbidity over short time periods (hours to days) and small spatial scales (tens to hundreds of metres), satellite-derived KD490 was obtained to supplement the TSS data and provide an indication of characteristic turbidity levels. KD490 data at 750 m resolution was retrieved from the NOAA ERDDAP server (dataset ID noaacwNPPVIIRSSCIkd490SectorYXDaily), with the daily mean and standard deviation of values extracted from the closest cell to the survey sites (first by distance, then manually adjusted by visual inspection if most of the cell was covered by land).

To assess the spatial and temporal variability in hydrodynamic conditions, site depth (relative to mean sea level), significant wave height and water velocity were extracted from a high-resolution coupled wave circulation model previously developed and validated for the Archipelago (see Moustaka et al. 2024 and Tebbett et al. 2024 for model validation and simulation details). Mean and standard deviation values were calculated for the 12 weeks preceding each survey to coincide with the period over which DHW were calculated. All environmental metrics were calculated using the R Language for Statistical Computing (hereafter referred to as R; version 4.5.1; R Core Team 2025), and satellite data was retrieved using the rerddap package (version 1.2.1; Chamberlain 2025).

Benthic surveys

To quantify bleaching extent and subsequent changes to coral community structure, benthic imagery was collected during and post-bleaching for two consecutive years as part of this study (2022 and 2023; Table S2; Table S3). Both bleaching surveys occurred during periods of prolonged accumulated heat stress within the Dampier Archipelago (> 8 DHW; Fig. 2). The 2022 bleaching survey (April) coincided with the peak of accumulated heat stress (i.e. maximum annual DHW), whereas the 2023 bleaching survey (March) was conducted approximately six weeks prior to the maximum recorded DHW. Both post-bleaching surveys were conducted during periods of zero DHW (July 2022 and 2023). All 15 sites were surveyed at the beginning of the study. Data from the 2022 bleaching survey were excluded for one site (ENS) due to discrepancies in the placement of transects; however, initial community composition data were

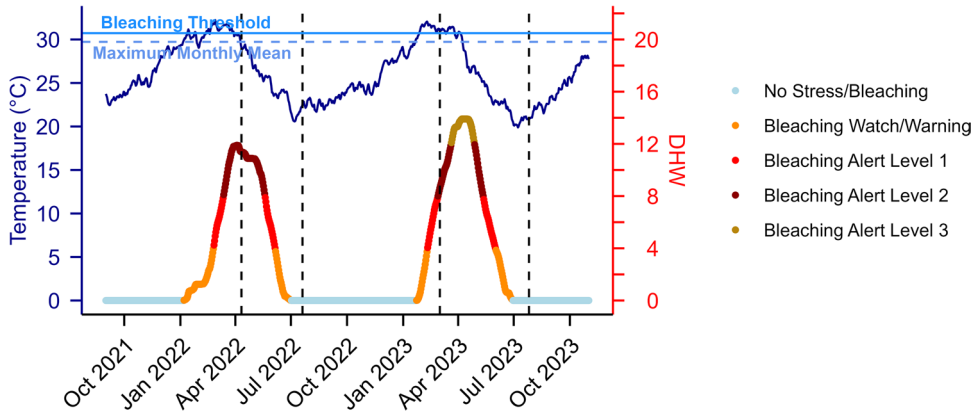

Fig. 2 Mean water temperature and degree heating weeks (DHW) across study sites in the Dampier Archipelago, Western Australia, from September 2021 to November 2023. DHW colour indicates NOAA bleaching alert level. Maximum monthly mean (MMM) calculated from historic sea surface temperature (SST; 1985–2012) and bleaching threshold (MMM + 1) are indicated with dashed and solid blue lines, respectively. Black vertical dashed lines indicate survey dates

available for this site from a scoping survey conducted one month prior (i.e. March 2022). Due to tide and swell conditions, three sites could not be re-surveyed during the second bleaching event (one turbid midshore site [WLS] and two clear offshore sites [NEL and BAR]), resulting in 11 sites that were consistently surveyed across all four timepoints (Table S3).

At each site, three 30 m transects were laid out in succession along the coral habitat, with 5 m separating each transect. Downward-facing photographs were taken every 0.5 m along the transect at a height of ~ 0.5 m above the substrate using an Olympus TG6 camera in an Olympus underwater housing (resulting in a field of view of approximately 0.35–0.4 m^2 per image, and 60 non-overlapping images or 'photo-quadrats' per transect). Benthic images were analysed using ReefCloud (https://reefcloud.ai/), with six random points overlaid on each image, consistent with other studies assessing community-level patterns in similar environments (360 points per transect; Evans et al. 2020; Ross et al. 2025). The substrate beneath each point was classified by a single observer using a modified CATAMI classification scheme (Althaus et al. 2015; Evans et al. 2020). Corals were identified to genus (when possible) and classified according to morphology and impact (binary classification of bleached vs not bleached). Percent cover and proportion bleached were calculated at the transect level for total hard coral (hereafter referred to as coral), as well as the most common taxa (i.e. *Acropora* spp., *Porites* spp., Merulinidae and *Pavona* spp.). The absolute change in total cover between surveys was also calculated for each transect, where a negative value indicates a decline in coral cover over time and a positive value indicates an increase in coral cover over time.

To account for differences in community compositions among transects and sites, a bleaching susceptibility index (BSI) was calculated for each transect. BSI was calculated following the conceptual framework of McClanahan et al. (2007) but modified to reflect the binary bleaching data collected in this study. Specifically, BSI was calculated as the sum of the relative density (percent cover standardised by total coral cover per transect) of each coral taxon multiplied by its mean percent bleaching recorded during each survey across the Archipelago, divided by the number of taxa present for that transect:

$$BSI = \frac{\sum_{i=1}^{S} \left(C_i \times B_i\right)}{S}$$

where C_i is the relative density of taxon i, B_i is the mean percent bleaching for taxon i, and S is the number of taxa present on the transect (hereafter referred to as realised BSI). Theoretical realised BSI values range from 0 to 100, with higher values indicating assemblages dominated by taxa with higher bleaching incidence. An independent BSI was also calculated using taxon-specific bleaching response indices (BRI) derived from a global dataset (Swain et al. 2016). Independent BSI was calculated using the same equation, replacing B_i with the corresponding taxon-level BRI. Taxon-BRI values represent globally standardised estimates of the mean percent coral tissue bleached and/or dead for a given coral genus or species. Independent BSI calculated in this study therefore represents the expected bleaching susceptibility of each transect based solely on its coral community composition and global susceptibility patterns, whereas realised BSI reflects locally observed bleaching patterns. As bleaching severity was not recorded in this study, realised BSI reflects patterns of bleaching incidence rather than absolute tissue-level bleaching intensity. Although derived from different response resolutions, both realised

and independent BSI represent percent-based measures of taxon-level bleaching susceptibility, allowing comparison of relative community-level patterns. Comparisons between realised and independent BSI were used to assess whether bleaching responses observed in this study reflect globally consistent taxon-level patterns or are modulated by local environmental conditions.

Data analysis

Owing to logistical constraints and the opportunistic timing of surveys, not all sites had complete environmental or benthic data. All analyses were conducted using the maximum number of sites for which the relevant data were available, and the exact number of sites included in each analysis is reported in Table S3.

Given the complex geomorphology and hydrodynamics of the Archipelago, principal components analysis (PCA) and cluster analysis were performed to group sites with similar environmental conditions. Principal components were determined via correlation matrix and PCA (see Supplementary Text; Fig. S5; Table S4), and used as the input variables for hierarchical cluster analysis based on Ward's method and K-means partitioning (Verfaillie et al. 2009). The optimal number of clusters was determined as the number of clusters with the highest Calinski–Harabasz value (Fig. S6; Verfaillie et al. 2009). Given the unique combinations of variables captured at the site level there was low replication of sites within the resulting clusters; therefore, clusters were used for discussion and visualisation purposes rather than as a factor in subsequent analyses. The PCA and cluster analysis were conducted using R and the packages factoextra (version 1.0.7; Kassambara and Mundt 2020), FactoMineR (version2.11; Lê et al. 2008) and fpc (version 2.2–13; Hennig 2024).

An analysis of variance by permutations (PERMANOVA) was used to assess temporal changes in coral community composition, using PERMANOVA + for Primer v7 (Anderson et al. 2008). Following visual inspection of the multivariate percent cover data (shade plot), a square-root transformation was applied to stabilise variance prior to calculation of a Bray–Curtis similarity matrix (Clarke and Gorley 2015). The PERMANOVA was conducted using a two-factor design of survey (fixed, n = 4) and site (random, n = 11) with replicate transects within each site and 9999 permutations were applied. Pairwise comparisons by factors with Monte Carlo correction were used to investigate significant differences. Non-metric multi-dimensional scaling (nMDS) ordinations were plotted to show differences in coral community composition between sites and surveys, and the trajectory of changes over time, using R and the vegan package (version 2.6–10; Oksanen et al. 2025).

Correlation and Bland–Altman analyses were conducted to compare realised and independent measures of BSI, grouped by survey and grouped by cluster (Bland and Altman 1986). Nonparametric Spearman's rank correlation was used for correlation analysis due to violations of normality and the presence of outliers. These statistical analyses were conducted using R and the BlandAltmanLeh (version 0.3.1; Lehnert 2015).

A combination of frequentist and Bayesian generalised additive mixed models (GAMMs) with a full-subsets approach (FSS) was utilised to assess which environmental variables were associated with total bleaching (i.e. proportion of total hard coral cover that was bleached), BSI, and change in total hard coral cover following heat stress. As TSS data were only available at 13 out of 15 sites, models were initially run in two ways: with TSS for the subset of sites, and without TSS but for all sites (Table S3). TSS was found to be an important predictor variable; therefore, only the models with TSS data included were retained. To model change in total hard coral cover following heat stress, predictor variables were taken from the previous 'during-bleaching' survey (except for the static variables of depth and distance from the mainland; Table 1). In addition, total bleaching and BSI from the previous survey were included as predictors in the total cover change models. All continuous predictor variables were plotted, assessed for normal distributions and spread of values and transformed where necessary (Table 1), and were centred and scaled prior to modelling.

For the bleaching models (total and BSI), only surveys conducted during bleaching events were included, as high accumulated heat stress (i.e. > 8 DHW) is recognised as a major driver of bleaching occurrence at broad spatial scales (Carlson et al. 2022). Total bleaching data were rescaled to account for a small number of zeros in the dataset using a Smithson–Verkuilen transformation to minimise distortion of the original distribution (Smithson and Verkuilen 2006) and were modelled with a beta distribution with a logit link. Total cover change and BSI (log-transformed) were modelled with a Gaussian distribution with an identity link. BSI was modelled on the log-transformed scale to ensure model structure remained consistent between frequentist and Bayesian models, as a tweedie distribution is not available in the rstanarm package (required for Bayesian models). Site (n = 13) and survey (n = 2 and 3 for bleaching and cover change models, respectively) were included as random effects to increase the inferential power of the model and to address potential autocorrelation (Harrison 2014). Models were limited to two explanatory metrics to avoid overfitting (Fisher et al. 2018) and models containing predictor variables with pairwise correlation coefficients exceeding 0.28 were excluded to minimise multicollinearity, following the conservative threshold recommended by Graham (2003).

Table 1 Description, justification and source of predictor variables included in full-subsets generalised additive mixed model analyses. Previous survey total bleaching and BSI were only included as predictor variables for total cover change

Variable (unit) *(transformation)*	Description	Justification	Source
Degree heating weeks (DHW; °C-weeks)	DHW represents the accumulated heat stress conditions over a 12 week period and is calculated based on local climatological conditions (where the bleaching threshold is assumed to be 1 °C above the highest climatological monthly mean; Glynn and D'Croz 1990) Range 5.87 – 15.24, standard deviation (SD) 2.30	Coral bleaching can be triggered and sustained due to prolonged heat stress (Brown 1997). When the DHW value reaches 4 °C-weeks, reef-wide coral bleaching can occur, and widespread bleaching and mortality are likely to occur when the value reaches 8 °C-weeks (Liu et al. 2003). However, DHW does not account for regional variation in coral stress response and therefore bleaching predictions based on DHW alone may be limited or inaccurate (Whitaker and DeCarlo 2024)	Calculated per site and survey from *in situ* water temperature data (this study)[a]
Distance to mainland (km)	Straight line distance to mainland Range 0.43 – 19.50, SD 5.47	Inshore reefs may be subject to light limitation due to higher turbidity and sedimentation and higher heat stress due to reduced water flushing (Dikou and Van Woesik 2006; Moustaka et al. 2019). Dominant sediment type also varies across the shelf from coarser calcareous sediments offshore to fine terrigenous silicates inshore (Forde 1985)	Calculated per site using the distance tool in QGIS (this study)
Significant wave height (m)	Mean and SD values (preceding 12 weeks) to coincide with DHW conditions Mean range 0.07 – 0.50 SD range 0.05 – 0.20	Wave energy contributes to flushing (e.g. water residence time) and therefore low significant wave height may lead to higher incidence of bleaching during thermal stress events, and vice versa (Jokiel and Brown 2004; Harrison et al. 2019)	Extracted per site and survey from a high-resolution coupled wave circulation model (resolved at 150 m or 500 m depending on grid nesting; this study)[b]
Water velocity (m s^{-1})	Mean and SD values (preceding 12 weeks) to coincide with DHW conditions Mean range 0.05 – 0.34 SD range 0.03 – 0.21	Higher water velocity can mitigate the effects of temperature stress on corals through regulation of metabolic processes and advection of water (e.g. reduced bleaching observed on macro-tidal reefs; Page et al. 2019). However, persistent high-flow environments may reduce temperature variability and tolerance of corals to thermal fluctuations, thereby increasing their bleaching susceptibility (McClanahan et al. 2005)	Extracted per site and survey from a high-resolution coupled wave circulation model (flexible mesh resolution ranging from 30 m within embayments to 500 m offshore; this study)[b]

Table 1 (continued)

Variable (unit) *(transformation)*	Description	Justification	Source
Turbidity (KD490 index, m^{-1})	KD490 is a measure of turbidity or water clarity; representing the rate at which visible blue-green light decreases with depth (i.e. light attenuation at 490 nm). Higher values indicate more attenuation of light due to increased turbidity. Mean and SD values (preceding 12 weeks) to coincide with DHW conditions Mean range 0.19 – 0.40 SD range 0.02 – 0.27	Moderate levels of turbidity shade corals from high irradiance during thermal stress events and subsequently reduce coral bleaching (Cacciapaglia and Van Woesik 2016; Morgan et al. 2017; Sully and Van Woesik 2020). However, severe turbidity/low light conditions may induce bleaching and/or result in mortality (Bessell-Browne et al. 2017a). A KD490 value > 0.13 may be considered light-limiting for typical reef flat coral communities; however, this threshold may be higher on naturally turbid reefs that vary in coral species composition (Sully and Van Woesik 2020)	750 m resolution VIIRS diffuse attenuation at 490 nm per site and survey, generated using the Wang et al. (2009) algorithm for turbid nearshore waters[c]
Total suspended solids (TSS; mg L^{-1})	TSS is a direct measure of suspended particle concentration in the water column Range 0.63 – 1.66, SD 0.31	TSS is a component of turbidity; therefore, moderate levels of TSS may reduce the effects of thermal stress on corals and reduce bleaching associated mortality. However, high sediment loads may outweigh the benefits of shading due to smothering (Fisher et al. 2019)	Gravimetric analysis of *in situ* subsurface water samples per site and representative season (this study)
Depth (m) *(sq transformed)*	Relative to mean sea level where negative values indicate subtidal areas Raw data range -1.39 – -4.75, SD 1.08	Light and temperature attenuate with depth; therefore, coral bleaching may be reduced at deeper sites (Baird et al. 2018). However, attenuation at depth combined with high turbidity may result in other adverse effects to corals on deeper reefs (Morgan et al. 2020)	Extracted per site from the high-resolution coupled wave circulation model (bathymetry derived from a compilation of data sources)[b]
Previous survey bleaching	Proportion total hard coral bleaching or realised bleaching susceptibility index (BSI) during the previous survey Total bleaching: range 0 – 0.73, SD 0.16 BSI: range 0.05 – 21.71, SD 3.05	Coral bleaching can result in partial or complete mortality of colonies, leading to both short and long-term declines in coral cover (e.g. Moore et al. 2012; Babcock et al. 2021). Responses to thermal stress vary among coral species, hence the bleaching susceptibility of a coral community will be highly influenced by the community structure (Swain et al. 2016)	Calculated at the transect level per site and survey (this study)

[a]Missing *in situ* water temperature data modelled from 1 km resolution satellite sea surface temperature (SST; dataset ID: jplMURSST41; Chin et al. 2017; see text for details). Maximum monthly means calculated from 5 km resolution NOAA CoralTemp SST (NOAA Coral Reef Watch 2025; see text for details)

[b]Model previously developed and validated for the Dampier Archipelago (see Moustaka et al. 2024 and Tebbett et al. 2024 for model validation and simulation details)

[c]Dataset ID: noaacwNPPVIIRSSCIkd490SectorYXDaily.

Following correlation filtering, a total of 29 (for both total bleaching and BSI) and 51 (for cover change) candidate models were evaluated using AICc (Akaike Information Criterion, corrected for small sample size). Models were considered to have similar explanatory power if they were within two AICc units of the model with the lowest AICc value (Akaike 1998). Variable importance was determined by summing the weight for all models containing each variable and was used to assess the relative importance across all predictor variables (Burnham and Anderson 2002). Model fit and assumptions were assessed via simulation-based model checking using the DHARMa package (version 0.4.6; Hartig 2024). The FSS GAMMs were conducted using R and the packages FSSgam (version 1.11; Fisher et al. 2018), gamm4 (version 0.2–6; Wood and Scheipl 2020) and mgcv (version; 1.9–3; Wood 2011).

Bayesian models were used to estimate the relative effect sizes of each predictor for all models with ΔAICc < 2. A separate Bayesian model was fit for each model using the stan_gamm4 function from the rstanarm package (version 2.3.2.1; Goodrich et al. 2024) with 31,000 sampling iterations completed for each model (subsequently thinned to yield a final distribution of 1000 samples). The target average proposal probability for the No-U-Turn sampler variant of Hamiltonian Monte Carlo was increased to 0.995 to reduce the number of divergent transitions during sampling. Predicted values for the response were calculated for each Bayesian model from a regular grid of all the predictors using the posterior_epred() function. The effect size for each predictor was then calculated as the difference between the maximum and minimum values obtained for that predictor, when the other predictors were averaged. This process was repeated for each of the 1000 samples in the posterior distribution. Effect sizes were standardised against the standard deviation of the response for comparability. Effect sizes were then used to select the 'best' model for each response variable to present in Fig. 6.

Results

Environmental data

Environmental conditions varied considerably across the Archipelago, from sheltered, turbid inshore sites to clear exposed and high wave energy sites around the outer islands. Five clusters were identified, representing distinct combinations of environmental conditions: 1) turbid inshore, 2) turbid midshore, 3) clear inshore, 4) clear offshore, and 5) high-flow mid-offshore (Table S5; Fig. S7). The inshore and midshore sites within the central Archipelago and mainland (Burrup Peninsula) had high mean TSS (> 1.20 mg L^{-1}), whilst midshore and offshore sites on the north and western edges of the peninsula were distinguished by low TSS (clear offshore cluster; 0.67 mg L^{-1}; Table S5). Inshore sites were distinguished from midshore sites by higher light attenuation (mean KD490 of 0.30 compared with 0.20; Table S5). The exception being site ANG (clear inshore, exposed island embayment north of the Burrup Peninsula), which was characterised by lower TSS (0.91 mg L^{-1}), high mean DHW (6.81 ℃-weeks, averaged over the four surveys) and significant wave height (0.37 m; Table S5). The remaining mid-offshore sites were characterised by high water velocity (0.21 m s^{-1}), moderate turbidity (TSS = 1.05 mg L^{-1}) and low mean DHW conditions (4.06 ℃-weeks; Table S5).

Coral cover and bleaching

Temporal and spatial patterns in coral cover and bleaching

In April 2022, regional heat stress peaked at 12.7 DHW (Bleaching Alert Level 3), with even higher accumulated heat stress recorded at most inshore and midshore sites (up to a maximum of 15.2 DHW). Coral cover across the Archipelago ranged from 17.4 to 68.1% (mean 34.2% ± 2.5 standard error [SE]), and was highest at the turbid midshore sites (> 50% at *Pavona* spp.-dominated sites, cluster mean 48.6% ± 6.4; Fig. 3). Bleaching varied among sites; from a minimum of 14.4% at one midshore turbid site to > 50% at the clear offshore sites (mean 33.9% ± 2.6). Residual heat stress conditions dissipated by mid-June (0 DHW), and in July 2022 mean coral cover had declined by 4.3% with only 1.7% of remaining corals bleached.

By early March 2023 the region had reached Bleaching Alert Level 2 (> 8 DHW). Coral cover across the Archipelago ranged from 12.4 to 62.2% (mean 26.7% ± 2.2) and was still highest at the midshore sites (mean 41.9% ± 6.0; Fig. 3). The extent of bleaching was similar to that observed in 2022 (32.8% ± 3.2) and ranged from < 1% at one clear inshore site (ANG; Merulinid-dominated) to 53.2% at an inshore turbid site 5 km away (CON). Heat stress peaked in early April 2023 at 14.4 DHW and remained above 8 DHW until mid-May. Residual heat stress dissipated by the end of June, and in July coral cover across the Archipelago ranged from 5.1 to 55.9% (mean 26.2% ± 2.4 SE) with < 1% bleaching observed. While mean coral cover declined by only 8% between the first and last surveys (23% relative decline), large declines were observed at two inshore sites (one turbid and one clear) and two clear offshore sites, including an 83.1% decline at one offshore site due to a substantial loss of *Acropora* spp. cover (Fig. S8).

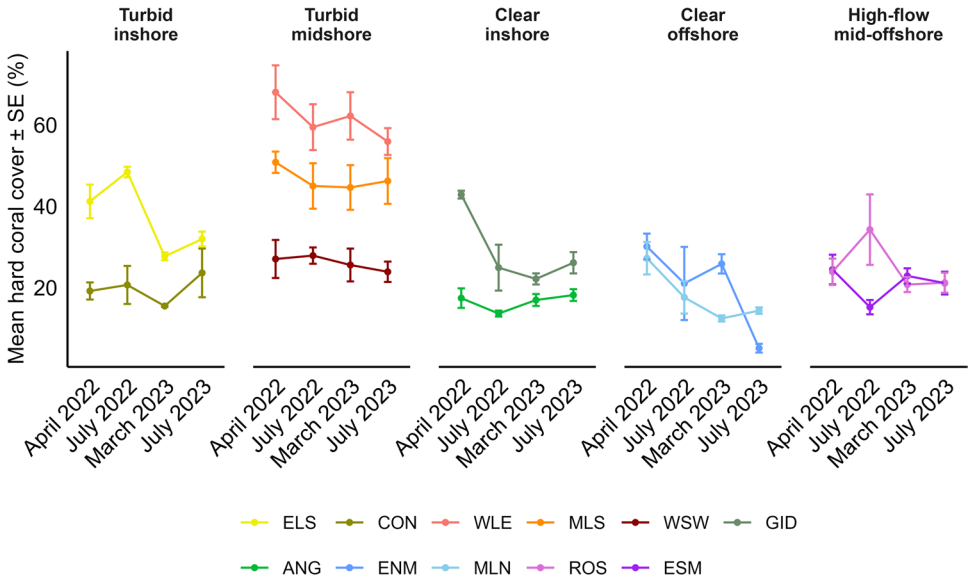

Fig. 3 Mean hard coral cover (± SE) over four surveys conducted at 11 consistently surveyed sites (grouped by cluster) across the Dampier Archipelago, Western Australia. Site abbreviations: ANG = Angel Island; CON = Conzinc Bay; ELS = East Lewis Island; ENM = Enderby Island (North-Medium); ESM = Enderby Island (South-Mangrove); GID = Gidley Island; MLN = Malus Island (North); MLS = Malus Island (South); ROS = Rosemary Island; WLE = West Lewis Island (East); WSW = West Lewis Island (Southwest)

Taxon-specific and community-level responses

Across all surveys, the most abundant taxa were *Acropora*, *Pavona*, *Porites* spp. and Merulinidae, and community composition broadly reflected the environmental clusters identified in the PCA (Fig. S7). Distinct communities occurred in the clear inshore (Merulinid dominated) and offshore sites (*Acropora* dominated; Figs. S8 and S9). In contrast, the turbid inshore sites were dominated by *Porites*, and the midshore sites tended towards *Pavona* dominated or mixed communities (Figs. S8 and S9). Communities within the high-flow midshore cluster were mixed assemblages, ranging from *Acropora* to *Porites* dominated (Figs. S8 and S9).

While mean coral bleaching across the Archipelago was similar between years, bleaching responses varied among taxa (Fig. 4). *Pavona* was the least affected by bleaching (< 15% of the cover was bleached during both surveys). *Porites* had low (11.8%) bleaching during the first survey; however, this rose to almost 50% during the second bleaching survey (Fig. 4) and was particularly high (> 70%) at three turbid sites (CON, ELS and WSW). Bleaching of *Acropora* was similar between surveys (38.9% and 46.5% in 2022 and 2023, respectively) but varied with morphology (Fig. S10). Cover of staghorn and tabulate/plating *Acropora* reduced considerably over the four surveys (92.4% and 80.4% relative declines, respectively) yet cover of corymbose *Acropora* remained relatively stable (Fig. S10). Bleaching of Merulinidae and other hard corals was considerably higher in 2022 (47.1 and 39.1%, respectively) compared with 2023 (26.0 and 28.9%, respectively, Fig. 4).

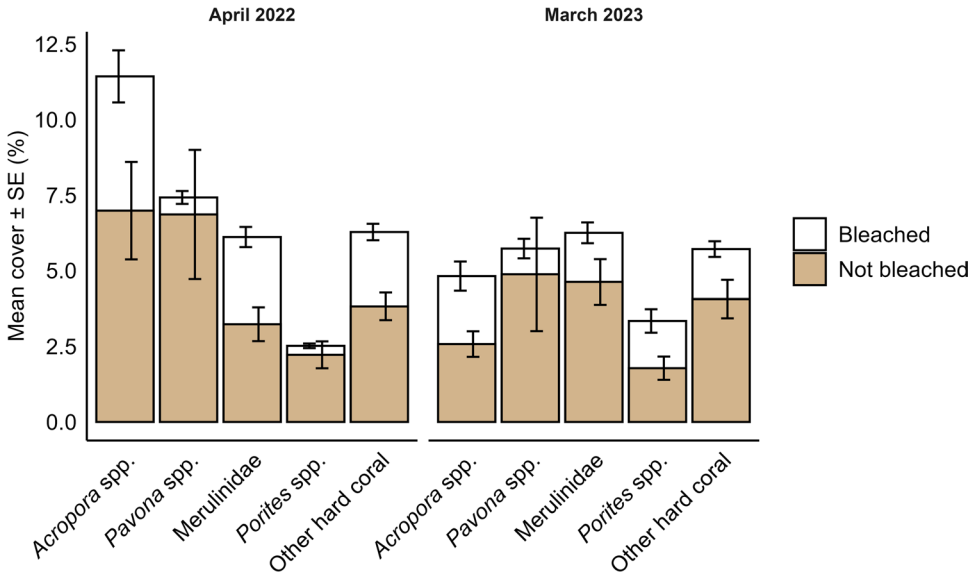

Fig. 4 Mean bleached and not-bleached per cent cover (± SE) of common hard coral taxa over two surveys at 11 consistently surveyed sites across the Dampier Archipelago, Western Australia

Patterns of coral cover change were consistent with these taxon-specific bleaching responses. *Acropora* cover was highest at clear offshore and high-flow midshore sites but declined over the study period, including a major loss at one clear offshore site (ENM) that drove a pronounced shift in community composition (Figs. S8 and S9; Tables S6 and S7). *Pavona* cover remained low across most of the Archipelago but was consistently high, and increased further, at two turbid midshore sites (WLE and MLS), contributing to increasingly *Pavona*-dominated communities (Figs. S8 and S9). *Porites* cover was highest and most stable at the turbid inshore sites (Figs. S8 and S9). In contrast, Merulinidae cover was greatest at clear inshore sites but declined at several locations (ELS, MLS, ENM), with one clear inshore site (ANG) showing increased Merulinidae cover and modest *Acropora* recovery (Figs. S8 and S9). Overall, community composition changed significantly through time at a subset of sites, with the largest shifts occurring where substantial *Acropora* loss or *Pavona* increases were recorded (e.g. ENM, MLS, WSW; Figs. S8 and S9; Tables S6 and S7). In contrast, several turbid sites with low *Acropora* cover (ELS, WLE) showed highly stable community structure across surveys (Figs. S8 and S9; Tables S6 and S7).

Realised vs independent BSI

Spearman correlation and Bland–Altman analysis indicated broad agreement between realised and independent measures of BSI at the Archipelago level (Spearman's $\rho = 0.63$, $p < 0.001$, mean difference −0.12; Table S8; Fig. S11). Grouping by survey revealed similar associations that were consistent between bleaching surveys (Table S8). Across environmental clusters, the direction and magnitude of differences between measures of BSI varied notably. Strong and significant correlations were observed for clear offshore (Spearman's $\rho = 0.99$, $p < 0.001$), high-flow mid-offshore (Spearman's $\rho = 0.91$, $p < 0.001$) and turbid inshore (Spearman's $\rho = 0.92$, $p < 0.001$; Table S8) clusters, indicating close alignment between realised and independent BSI in these environments. In contrast, no significant correlations were observed for clear inshore and turbid midshore clusters ($p = 0.169$ and 0.666, respectively, Table S8). Agreement between measures of BSI was highest for the high-flow mid-offshore cluster (mean difference = 0.17; 95% limits of agreement [LoA]: −0.28 to 0.63) and lowest for the turbid midshore cluster (mean difference = –1.01; LoA: −2.98 to 0.96; Table S8), indicating variability in how well the two metrics aligned across environmental clusters. A negative mean difference was observed for the turbid midshore cluster (−1.01), indicating that realised BSI was lower than expected based on the independent BSI, whereas the clear offshore cluster exhibited a positive mean difference (0.56; Table S8; Fig. S11).

Environmental drivers of bleaching and changes in coral cover

Variation in bleaching among sites was most strongly associated with hydrodynamic conditions (significant wave height, water velocity) and turbidity (TSS, KD490). The variation (i.e. standard deviation) in significant wave height featured in all candidate models (ΔAICc < 2), and had the greatest effect size and variable importance score (Table 2; Figs. 5 and S12), indicating that it was the strongest and most consistent predictor of bleaching. Fewer corals bleached under both low (< 0.08 m) and high (> 0.18 m) variability in wave height, suggesting a nonlinear relationship (Fig. 6). In addition, bleaching gradually increased with mean water velocity, yet the effect size was notably smaller than that of the standard deviation of wave height (Table 2; Figs. 5 and 6). Other predictors present in the lower-ranked candidate models (standard deviation of water velocity, distance from the mainland, and mean KD490) were

Table 2 Best generalised additive mixed models (GAMMs) for predicting total bleaching, Bleaching Susceptibility Index (BSI) and total hard coral cover change in the Dampier Archipelago, Western Australia. Reported R^2 values are conditional. All models with < 2 ΔAICc (Akaike information criterion, corrected for small sample size) are presented, with italics indicating the top model (presented in Fig. 6). edf = estimated degrees of freedom

Response variable	R^2	ΔAICc	wAICc	edf	Model
Total bleaching	0.56	0.00	0.35	12.15	*Significant wave height (SD) + Water velocity (mean)*
	0.58	1.61	0.16	12.61	Significant wave height (SD) + Water velocity (SD)
	0.58	1.72	0.15	12.25	Distance from mainland + Significant wave height (SD)
	0.59	1.90	0.14	13.00	Significant wave height (SD) + KD490 (mean)
BSI	0.75	0.00	0.18	9.96	*Total suspended solids (mean)*
	0.78	0.69	0.13	13.75	KD490 (mean)
	0.74	1.53	0.08	9.53	(sq) Depth + Total suspended solids (mean)
Total cover change	0.50	0.00	0.34	11.16	*KD490 (mean) (prev.) + Bleaching (mean) (prev.)*
	0.49	1.60	0.15	12.05	Bleaching (mean) (prev.)

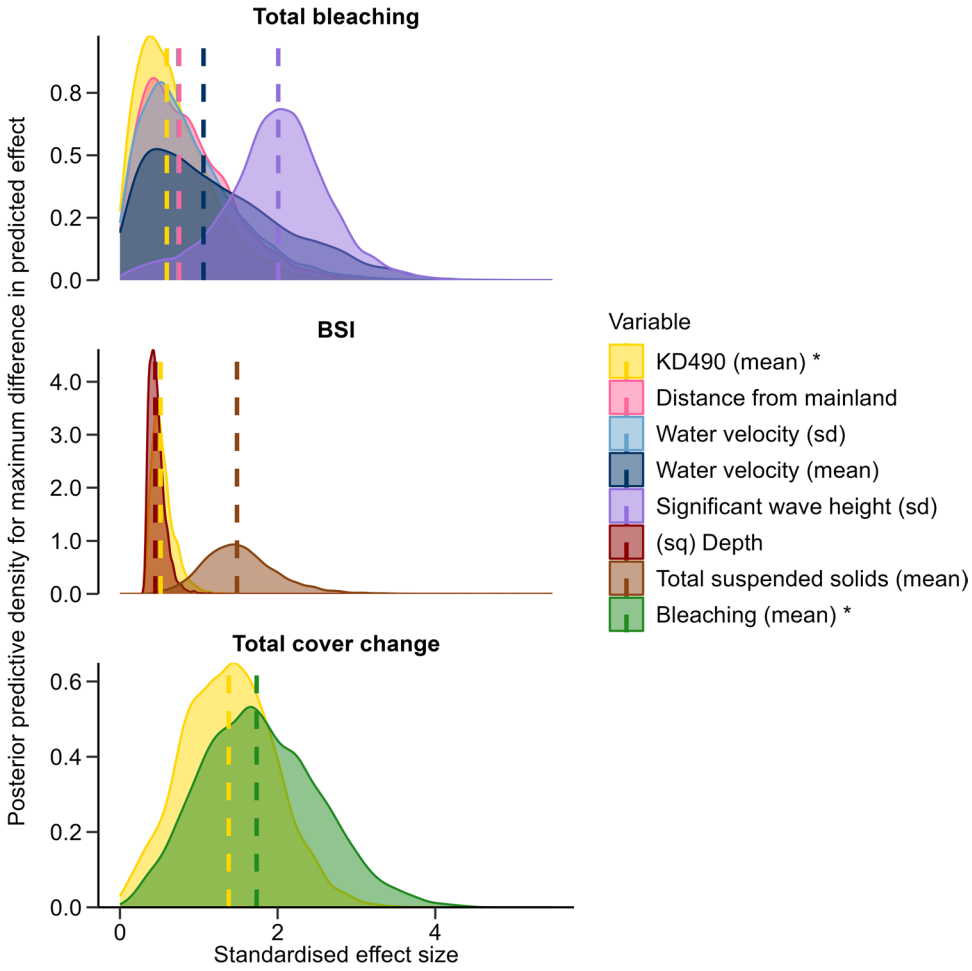

Fig. 5 Bayesian estimates of standardised effect of predictor variables on Bleaching Susceptibility Index (BSI), total hard coral bleaching and total hard coral cover change. Shown are posterior probability density estimates representing the maximum predicted difference for each predictor variable across all models with ΔAICc (Akaike information criterion, corrected for small sample size) < 2. Vertical dashed lines indicate the median effect size on the x-axis. Values positioned to the right indicate stronger effects of the predictors. Asterisks (*) denote predictor variables for which values from the previous survey were used (for total hard coral cover change models only)

correlated with mean water velocity, but had smaller effect sizes (Table 2; Figs. 5 and S13).

BSI was best predicted by TSS and mean KD490 (Table 2; Fig. 6). BSI was highest at low TSS concentrations (~0.6 mg L^{-1}) and decreased sharply up to ~1 mg L^{-1}, after which the influence of TSS was negligible (Fig. 6). BSI also declined as KD490 increased; however, the effect of KD490 was weaker than for TSS (Fig. 5). Although depth was included in one of the candidate models, its effect size was small and no strong directional relationship with BSI was apparent (Table 2; Fig. 5).

Change in total coral cover was best explained by a model that included mean KD490 and total bleaching from the previous survey (Table 2; Fig. 6). Cover declined most where bleaching was high (> ~60%), while higher KD490 (> ~0.30) promoted the maintenance (stability) of cover (Fig. 6).

Discussion

Environmental factors can moderate the extent of bleaching within coral assemblages, altering community composition and creating areas of resilience to heat stress within turbid inshore reef systems. In the Dampier Archipelago, moderate bleaching (~30%) over two consecutive years of extreme heat stress (> 12 DHW) was associated with a 23% relative decline in coral cover, although this varied considerably among sites and remains within the long-term average (26%) for the region (Moustaka et al. 2019; Babcock et al. 2021). In contrast, reefs in the Exmouth Gulf, south of the Dampier Archipelago, experienced similar levels of heat stress (14.2 DHW) but 95% bleaching and an 84% relative decline in coral cover following the 2010–2011 marine heatwave (Moore et al. 2012). This spatial heterogeneity in responses between and within regions is likely related to complex long-term patterns in hydrodynamics and turbidity that, combined with previous heat exposure, have resulted in variable coral community structures.

Turbidity as a buffer against bleaching

Turbidity appears to offer a degree of protection against bleaching and mortality (Van Woesik et al. 2012; Carlson

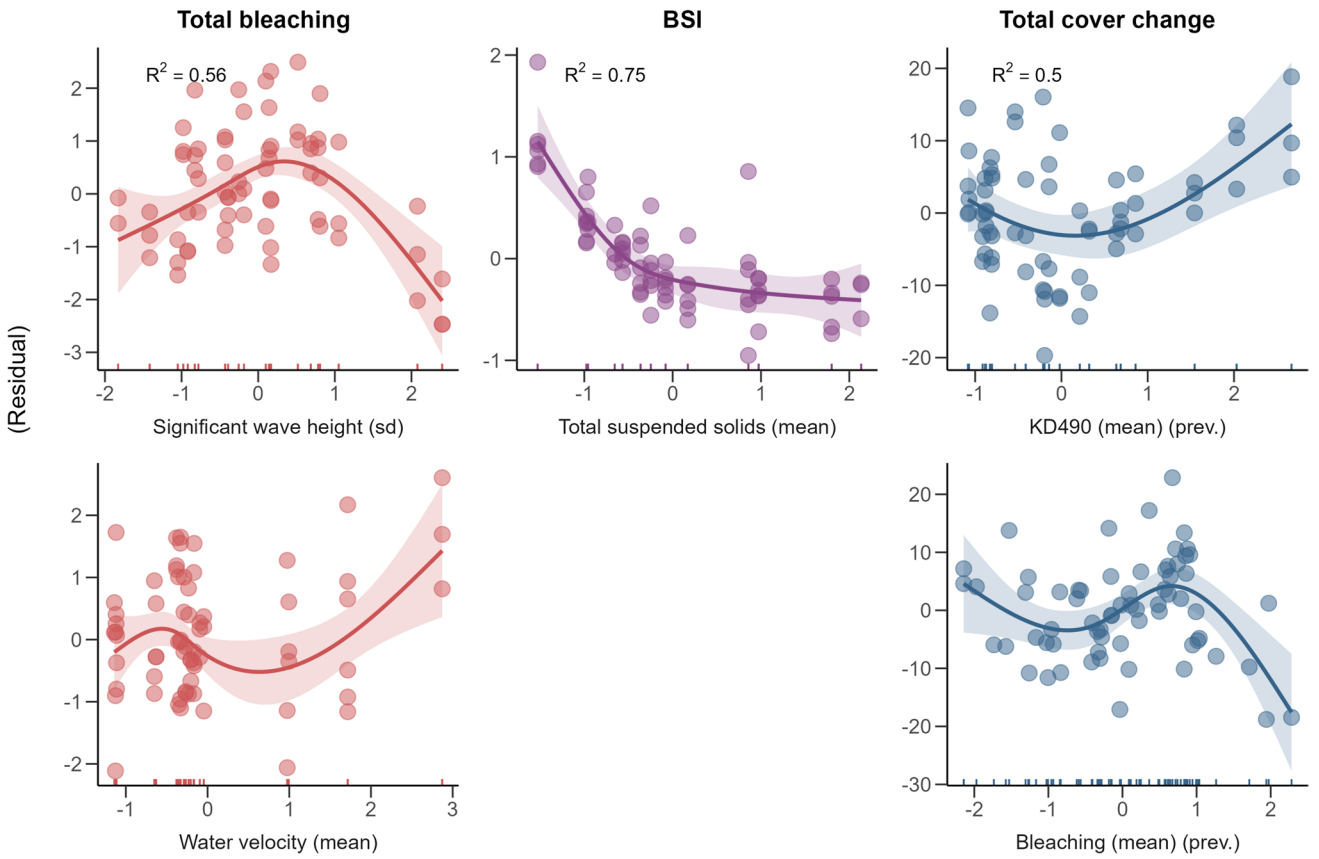

Fig. 6 Best generalised additive mixed model partial effects plots showing patterns of bleaching and cover residuals for total hard coral bleaching (left panel), Bleaching Susceptibility Index (BSI; middle panel) and total hard coral cover change (right panel) in the Dampier Archipelago, Western Australia

et al. 2022; Zweifler et al. 2024b). Naturally turbid reefs are often characterised by resilient coral taxa; however, moderate levels of turbidity can also shade corals and enhance heterotrophic feeding, thereby reducing the impact of heat stress on coral survival (Morgan et al. 2017; Rosedy et al. 2023). Our findings were largely consistent with this concept; high coral cover was generally maintained at turbid sites and those dominated by bleaching-tolerant taxa compared to those in clearer water. While a significant decline in cover was observed at one turbid inshore site, community composition remained consistent over time. This may reflect a combination of site-specific coral community structure (lower proportion of vulnerable *Acropora* and resistant *Pavona* than at other turbid sites) and site-level differences in environmental conditions, such as differing nutrient levels or sediment loads (Tebbett et al. 2024; Bassett et al. in review). In contrast, offshore reefs characterised by lower turbidity and high cover of *Acropora* exhibited high levels of bleaching, large declines in coral cover, and larger shifts in community composition. Our models also showed reduced BSI associated with higher TSS, and greater stability in coral cover at sites with higher mean KD490. We acknowledge that these models did not capture the full inshore–offshore turbidity gradient, and that modest sample sizes can increase uncertainty in predictor importance and model rankings. However, consistency observed across frequentist and Bayesian modelling frameworks provides complementary evidence, increasing confidence that the identified effect directions and magnitudes reflect ecologically meaningful gradients rather than artefacts of sampling coverage and/or small sample size. Other lines of evidence further support these findings. For example, when comparing realised and independent measures of BSI, we observed strong agreement at exposed offshore sites, characterised by heat-susceptible taxa, but weak agreement at the turbid midshore sites. Divergence between realised and independent BSI likely reflects differences in how bleaching is expressed locally, including variation in bleaching severity, acclimatisation, and historical exposure. The lower-than-expected realised BSI at these midshore sites provides further evidence that turbidity can alleviate the effects of heat stress on corals.

Interactions between heat stress, hydrodynamics, and turbidity

While our models predicted low bleaching at sites with highly variable wave height, we propose that this response was influenced by complex interactions between heat stress, hydrodynamics, and turbidity. Reduced bleaching susceptibility under variable flow regimes has been observed in tidally influenced systems, potentially due to regulation of metabolic processes, advection-driven cooling, or acclimation to thermal fluctuations (Page et al. 2019). Conversely, low-flow conditions can promote high water residency times, which reduce flushing of nutrients, waste products and warmer water, and in extreme cases can lead to severe bleaching and localised mass mortality (e.g. Richards et al. 2024). In a turbid environment, strong water flow can also disperse suspended particulates that might otherwise reduce light stress through shading (Larcombe and Woolfe 1999; Van Woesik et al. 2012; Rosedy et al. 2023). As the Dampier Archipelago is macrotidal, it is likely that all our study sites receive some benefits from tidal flushing, yet this may be offset by lower turbidity at high-energy sites, where low TSS is associated with greater wave heights. We note that our models do not capture reductions in bleaching susceptibility that may occur at greater depths or under true offshore/exposed conditions, as our study sites were shallow (1.4–4.8 m) and wave heights were relatively low (mean range 0.07–0.50 m) compared with open coastlines (e.g. Ningaloo; range 1–4 m; Zhang et al. 2013) and offshore atolls (e.g. Mermaid Reef; range 0.3–3.2 m; Grimaldi et al. 2023). However, historical reports of severe bleaching and mortality at shallow, exposed sites within the Dampier Archipelago suggest that past disturbances filtered out vulnerable taxa, which may have influenced the observed relationship between wave energy and bleaching severity (pers. obs.; Moustaka et al. 2019). Importantly, as TSS emerged as a key predictor of realised BSI and coral cover was maintained at turbid sites that experience the highest TSS and DHW, our findings suggest that turbidity can offset thermal stress, underscoring the importance of local environmental conditions in predicting bleaching responses.

Taxa-specific responses to environmental gradients

While environmental conditions underpin resilience at the community level, responses to environmental conditions vary greatly by taxa and morphology. We observed higher cover of *Porites* spp. at sites characterised by lower wave energy, higher TSS, and moderate variation in light attenuation (KD490). Conversely, *Acropora* cover was generally high at sites further from the mainland, with high wave energy, and low TSS concentrations. These contrasting responses to environmental conditions may reflect differences in trophic strategies. *Porites*, *Pavona* and Merulinids (e.g. *Platygyra* and *Favites* spp.) are characterised as mixotrophic to heterotrophic with moderate trophic plasticity (Conti-Jerpe et al. 2020; Price et al. 2021; Travaglione et al. 2023). In contrast *Acropora* spp. are typically more autotrophic to mixotrophic, but with potential for high trophic plasticity in turbid settings (Conti-Jerpe et al. 2020; Travaglione et al. 2023; Zweifler et al. 2024a). Heterotrophic plasticity may allow bleached corals to persist when autotrophic energy is reduced (Grottoli et al. 2006; Hughes and Grottoli 2013). Yet heterotrophic compensation is not a universal response, and is dependent on sediment load, particulate composition, and nutrient content (Nahon et al. 2013; Zweifler et al. 2024a). Further, the cumulative effects of turbidity and thermal stress may differ among taxa, and the potential benefits of turbidity may be outweighed by shading or smothering at high turbidity levels (Fisher et al. 2019; Evans et al. 2020). These findings highlight that site-specific environmental conditions and taxa-specific trophic strategies can lead to markedly divergent bleaching outcomes.

Variation in bleaching susceptibility within taxa

There is a growing body of evidence to suggest that taxa-specific bleaching susceptibility varies considerably between turbid and clearwater reefs. For example, reduced bleaching susceptibility of *Acropora* compared with other taxa has been observed in turbid waters of the Exmouth Gulf (Zweifler et al. 2024b), Great Barrier Reef (Morgan et al. 2017), Malaysia (Guest et al. 2012; Szereday et al. 2024), and Singapore (Guest et al. 2016), although these appear to be context-dependent cases. In contrast, we observed moderate to high bleaching of *Acropora* during both heat stress events, resulting in a significant decline in cover over the study period. These findings generally align with 'traditional' views of bleaching vulnerability and mortality for corals in this genus (Loya et al. 2001), yet we also observed high variability in bleaching response among *Acropora* morphotypes.

For a turbid reef system, the Dampier Archipelago has uniquely high cover and morphological diversity within the genus *Acropora*, with 'vulnerable' staghorn and plating/tabulate morphologies present even at turbid inshore sites. While cover of staghorn and tabulate/plating *Acropora* was reduced considerably following heat stress, cover of corymbose *Acropora* was comparatively unaffected over the study period. The apparent resilience of corymbose corals may be attributed to their slower growth and metabolic rates, resulting in reduced oxidative stress during bleaching (Baird and Marshall 2002; Hoogenboom et al. 2017). Further, corymbose *Acropora* within the Dampier Archipelago

have demonstrated high trophic plasticity with the capacity to increase heterotrophy in highly turbid waters (Travaglione et al. 2023), which may allow bleached corals to compensate longer when autotrophic energy inputs are reduced (Grottoli et al. 2006; Hughes and Grottoli 2013). Accordingly, communities may become increasingly characterised by corymbose, rather than branching or plating morphologies. Given the differences in spatial coverage, calcification rates, and structural complexity of different *Acropora* growth forms, such a shift towards more compact/corymbose morphotypes could have implications for reef function and ecosystem stability (Graham and Nash 2013; Wilson et al. 2019; Priest et al. 2024).

Potential vulnerabilities of 'resilient' taxa under cumulative and recurrent stressors

Coral taxa traditionally considered more resilient to bleaching may face heightened vulnerability under recurrent heat stress and with multiple stressors (e.g. low-light/high turbidity). For example, *Porites* have historically been considered a heat-stress-tolerant coral (e.g. Loya et al. 2001) and more tolerant of sedimentation (Fabricius 2005). However, we observed a fourfold increase in bleaching of *Porites* in 2023 (> 70% bleaching observed at three turbid inshore sites) compared with 2022, despite lower heat stress at the time of sampling. This is likely a conservative estimate of the true increase in bleaching severity between years, as the 2023 bleaching survey was conducted approximately six weeks prior to peak heat stress. Increased bleaching susceptibility of massive corals (including *Porites*) has also been observed at turbid sites in the Exmouth Gulf (Zweifler et al. 2024b). Collectively, these results suggest that turbidity-associated benefits may diminish under recurrent heat stress, reflecting a cumulative physiological limit beyond which previously 'resilient' taxa become more susceptible to bleaching. The vulnerability of massive corals to synergistic impacts of thermal stress and turbidity has been found to increase under low-light (and high sedimentation) conditions (Fisher et al. 2019), likely due to reduced energy status and capacity to clear deposited sediment (Bessell-Browne et al. 2017b). Compared with other taxa, *Porites* also have a delayed response to heat stress, a high incidence of partial mortality (Baird and Marshall 2002), and reduced recovery potential (Browne et al. 2019). There is also evidence of increased susceptibility of massive *Porites* during recurrent or extreme reef-scale bleaching events (Guest et al. 2012; Grottoli et al. 2014; Burn et al. 2023; Szereday et al. 2024; Zweifler et al. 2024b). Consequently, the full extent of heat stress impacts on Dampier's reefs may not yet be realised. As key reef framework builders on turbid reefs, the susceptibility of *Porites* to severe recurrent and cumulative stressors could significantly undermine reef complexity and habitat availability, with consequences for turbid reef ecosystems under global climate change (Pratchett et al. 2020).

Transition towards resilient reef communities

Previous exposure to repeated heat stress, combined with highly variable local environmental conditions, has likely contributed to the development of heterogeneous coral communities in the Dampier Archipelago that exhibit high, yet variable, resistance to cumulative and recurrent stress events. In particular, localised bleaching may have 'filtered' the community composition at some shallow exposed sites, removing more vulnerable taxa and genotypes and contributing to a transition towards more stress-tolerant communities. Here we observed significant declines in coral cover at some sites following the 2022 bleaching event, attributed to high bleaching and mortality of *Acropora*. Lower coral mortality was observed following the 2023 event, despite higher accumulated heat stress. Collectively these findings suggest that the Dampier Archipelago's reefs are shifting towards more resilient coral communities, as observed on other reefs exposed to repeat heatwave events (e.g. Graham et al. 2024). The maintenance of high coral cover at the Archipelago scale is largely supported by communities of resilient corals in midshore moderately turbid reefs. Although these reefs have demonstrated resilience to successive heat stress events, ongoing cumulative pressures, along with the increased frequency and severity of disturbances, are likely to result in detrimental impacts in the future (Fisher et al. 2019; Pratchett et al. 2020). Although the Dampier Archipelago has previously been identified as a priority area for conservation (CALM 1994), these reefs are subject to increasing anthropogenic impacts. Limiting anthropogenic pressures could reduce the potential for synergistic effects of high turbidity and temperature stress (Donovan et al. 2021). However, further research is required to tease apart the nuanced interactions between environmental and ecological factors contributing to resilience at the reef scale. This will be particularly important for maintenance of reproductive and adaptive capacity of these reefs which have a high degree of self-seeding and low (but unique) genetic diversity for key reef-building species (Underwood 2009; Feng et al. 2016; Thomson et al. 2021).

This study contributes to a growing body of evidence demonstrating that resilient coral reef systems can and do occur in extreme environments, highlighting the importance of identifying and safeguarding reefs across a diverse range of environmental settings (Colton et al. 2022). The composition and function of resilient turbid reefs are inherently different to their clearwater counterparts, and these differences require consideration when developing effective conservation and management strategies.

Limiting additional local stressors and focussing conservation and restoration efforts on resilient taxa and reefs will be important to ensure the long-term preservation of turbid coral reefs. As the occurrence of turbid reefs increases with climate change and coastal inundation, these complex systems will play an important role in maintaining the resilience and function of coral reefs globally.

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Author contributions TJB, NKB, MM, SKW and RDE contributed to the conceptualisation of the study. TJB, MM, SKW and RDE contributed to the methodology, TJB, MM, RKG and RDE carried out the investigation, with software and validation conducted by MVWC. Data curation was carried out by TJB, MM, MVWC, RKG, with formal analysis undertaken by TJB, MM and MVWC. TJB prepared the original draft, with visualisations prepared by TJB and MM. All authors contributed to the review and editing of the manuscript. Resources were provided by MVWC and RKG, and funding was acquired by RDE. Project administration was managed by TJB, MM and RDE, and supervision was provided by NKB, SKW and RDE.

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Data availability The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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