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RESEARCH

Assessing protective shading and lowering of coral nurseries during a mass bleaching event on the great barrier reef

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Abstract Tropical coral reefs are increasingly threatened by more frequent and severe global stressors induced by Anthropogenic climate change. Restoration-based interventions, such as in situ coral propagation and out-planting, are increasingly being adopted to enhance natural recovery. However, these interventions face the same global stressors affecting natural reefs, and hence also need protection. Shading or relocating corals can reduce the severity of coral bleaching, but how such protective interventions are best suited to coral nurseries on the Great Barrier Reef (GBR) remains untested. We therefore conducted a manipulative field experiment factorially crossing two treatments, adding shade structures and lowering of nurseries, to test the efficacy of decreasing solar irradiance during an ocean heatwave to improve coral-bleaching outcomes at two sites on Opal Reef, GBR in 2024. Metrics of coral health (paling and mortality) were monitored for 138 days. The nursery-lowering treatment (from 4 to 7 m) statistically improved bleaching outcomes (less paling and higher survival) at one site, but not the other. Overall, shading nurseries did not reduce coral paling or mortality, suggesting that irradiance may not have been a primary regulator of bleaching severity, or that thermal stress was not severe enough wherein shading would mitigate bleaching. Our results suggest practitioners should first consider lowering coral nurseries where possible ahead of predicted bleaching conditions as this may provide a low-cost low-effort benefit. Consideration of nursery stock importance, practitioner context, and irradiance projections will further help assess the risk/reward of additional shading. We recommend further research could evaluate different shading regimes (e.g., time and length of shading and percentage shade) on nursery corals under higher irradiance conditions.

Keywords Shade · Coral nursery · Propagation · Bleaching · Restoration

Introduction

Anthropogenic-driven climate change remains the primary global threat to the persistence of tropical coral reefs beyond this epoch (Hughes, et al., 2017a, b; Hughes et al. 2018). Increasing severity and frequency of disturbance events over the past three decades has occurred in all tropical coral reef regions driving multiple global coral bleaching events (Hughes et al. 2018; Reimer et al. 2024). As such, windows of respite required for natural recovery (10–15 years, Kayanne et al. 2002; Gilmour et al. 2013; Mc Clanahan 2014; Glynn et al. 2015) are continuously eroding. The importance of applying nature-based solutions to expedite natural recovery and "buy time" for coral reefs while global stressors are mitigated is widely recognised (Knowlton et al. 2021; Voolstra et al. 2021; Peixoto et al. 2024). Reef restoration practitioners are intervening to expedite natural recovery with a toolbox approach, that includes a variety of techniques

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from coral gardening to assisted migration, and other more extreme interventions like assisted evolution and geoengineering (Suggett and Van Oppen 2022), with a common goal to increase overall coral biomass (Boström-Einarsson et al. 2020; Suggett et al. 2024; Edwards et al. 2024). Practitioners are refining and tailoring such approaches to maintain or increase resilience relevant to their reef sites (e.g., (Morikawa and Palumbi 2019)) through robust scientific evaluations (Suggett et al. 2024; Peixoto et al. 2024).

One approach to resilience-based management of coral reefs involves harnessing asexual coral reproduction via in situ coral propagation and out-planting to maintain or increase biodiversity at degraded or high value reef sites (Mcleod et al. 2019; Rinkevich 2021; Suggett et al. 2024). Such reef rehabilitation (sensu Edwards et al. 2024) steps often use intermediary coral nursery phases to increase coral biomass of high value parent stock prior to out-planting onto the reef (Boström-Einarsson et al. 2020; Edwards et al. 2024). Selection of this high value stock may be from thermal tolerance (e.g. survival through a previous bleaching event (Morikawa and Palumbi 2019)), rare genotypes (e.g. certain colour morphs or low abundance species with historical importance (Chamberland et al. 2015; Herlan and Lirman 2008)) or to maximise diversity (and hence adaptive potential of a population (Baums et al. 2022; Madin et al. 2023)). While targeted coral stock selection to build living gene banks is now a priority for many restoration initiatives (Camp 2022) these corals are typically grown close to the natural reef (Boström-Einarsson et al. 2020) and are subject to many of the same stressors as the natural reef; for example, elevated temperatures during marine heatwaves (Muller et al. 2018; Shaish et al. 2010). Given the projected increase in the frequency and magnitude of future mass coral bleaching events (Eakin et al. 2022; Hoegh-Guldberg et al. 2023; Hughes, et al. 2017b; Reimer et al. 2024), there is a pressing need to explore interventions that could protect corals within restoration initiatives from adverse environmental conditions.

Current predictions indicate that > 95% of coral reefs will face environmental conditions beyond critical thresholds by 2030 (Hoegh-Guldberg et al. 2019; Voolstra et al. 2021). Of most concern is repeated thermal stress events, which disrupt coral-algae symbioses to result in coral bleaching and eventually mortality unless stressors subside or corals acquire resilience, e.g. altered feeding regimes or shuffling to more resilient algal symbionts (Suggett and Smith 2020). Coral bleaching is most commonly associated with elevated temperatures (Hughes, et al., 2017a, b; Hughes et al. 2018), but also high light intensities and ultra violet (UV) exposure (Jokiel and Coles 1977; Fit and Warner 1995; Warner et al. 1999; Courtial et al. 2017) amongst other factors that exacerbate heat stress (Suggett and Smith 2020). Larger-scale strategies such as shading (via marine cloud brightening, (Latham et al. 2013)) and cooling (via artificial upwelling, (Feng et al. 2020)) have been proposed for reef corals to mitigate the drivers of coral bleaching and assist recovery after disturbances (Berg et al. 2020; Brown et al. 2000). However, the application of local-scale interventions to coral nurseries on the Great Barrier Reef and the potential benefits for nursery stock in situ during bleaching events has yet to be thoroughly tested.

While coral resilience to stress is variable, it is likely that some corals surviving through a bleaching event are natural ‘winners’ due to host genetics or beneficial symbioses (Dziedzic et al. 2019); however, it is also likely that some corals persist through bleaching events because they occupy natural refugia (Frade et al. 2018; Hoogenboom et al. 2017; Morgan et al. 2017; Gardner et al. 2019). Refugia for a coral may be a result of colony position on the reef, e.g., deeper and/or cooler waters (Muir et al. 2017; Baird et al. 2018; Frade et al. 2018) or if they are positioned—and hence shaded—under another coral (Hoogenboom et al. 2017). In fact, in situ coral nurseries have previously provided refuge for corals by buffering extreme temperature conditions in a cold-water event due to their location at deeper locations away from nearshore habitats (Schopmeyer et al. 2012). Artificially shading corals or lowering them to deeper water to reduce bleaching exacerbated by high irradiance during thermal stress is therefor of interest because they would be easy and relatively low-cost interventions to protect high value coral nursery stock.

Varied outcomes have been reported for studies testing shading to mitigate bleaching in aquaria (Coelho et al. 2017; Butcherine et al. 2023; Hendrickson et al. 2024) and in situ (Coelho et al. 2017) yet a recent meta-analysis of 143 studies concluded that any level of shading from peak UV exposure should ameliorate effects of light and thermal stress (Tagliafico et al. 2022). Nevertheless, the suggested benefits of applying such interventions for coral nurseries during heat-driven bleaching events on the Great Barrier Reef (GBR) remain unknown. Evaluating the effectiveness of providing shade to protect coral nursery stock during periods of sub-optimal environmental conditions therefore represents a timely and key knowledge gap to address. We hypothesised that shading and lowering coral nurseries will reduce mortality and coral paling during a mass bleaching event by concurrently reducing light and heat stress. To test this hypothesis, we conducted an in situ multi-factorial experiment through the 2023–2024 Austral summer on the GBR primarily measuring the effectiveness of shading as a tool to mitigate coral bleaching during periods of during heat stress (13 Degree Heating Weeks with temperatures up to 2 °C above average, NOAA, 2024). Specifically, we aimed to determine (i) if and how localised intervention methods differentially mitigate mortality or paling during a thermal stress event and (ii) whether this was consistent across two restoration sites. To quantify the effectiveness of shading and lowering coral nurseries to mitigate coral bleaching, we tracked nursery propagated corals under different treatments through a mass bleaching event at two sites in the Austral summer of 2023–2024.

Methods

In November 2023, eight mid-water coral nurseries were installed across two sites on Opal Reef, Great Barrier Reef (GBR). Four coral nurseries were installed at Long Bommie (16°22′24″44S 145°87′62″06 E) an isolated site west of main Opal Reef (detailed in Strudwick et al. 2024) and four coral nurseries were installed at Blue Lagoon (– 16°20′65″91S 145°89′82″01 E). Blue Lagoon is a site towards the North of Opal Reef near a deep-water channel leading to the Coral Sea, where strong tidal currents are typical (Strudwick personal obs, Fig. 1a, b.). The maximum depth at the base of the reef slope at Blue Lagoon is ~ 10 m consisting of a sandy bottom and patches of coral. Long Bommie is located to the west of Opal Reef (south of Blue Lagoon) and is separate to the main reef. Long Bommie was impacted by Cyclone Ita in 2014, which caused high structural degradation over most of the site. Despite widespread coral bleaching on the GBR in 2016/17, 2020 and 2022 recovery has been observed over the last two years on the reef flat and crest at Long Bommie (Fig S1c.) yet considerable areas of rubble remain. At Long Bommie the base of the reef slope begins at ~ 3 m and extends to 15–18 m deep. The sites were chosen to ensure nurseries could be lowered to consistent depths of at least 7 m deep and two sites were used to increase replication. Coral nursery frames had been preconditioned for 2 weeks in situ prior to the study. Of note is the occurrence of Category 2 Tropical Cyclone Jasper 33 days into the study, which passed through the region and made landfall ~ 100 km north of the study site. Heavy rainfall and damaging winds (< 70 km/h) occurred during this period and < 2 m of rainfall was recorded over 4 days which caused a significant injection of fresh water into the reef catchment (Fig. 1c, Bureau of Meteorology 2023).

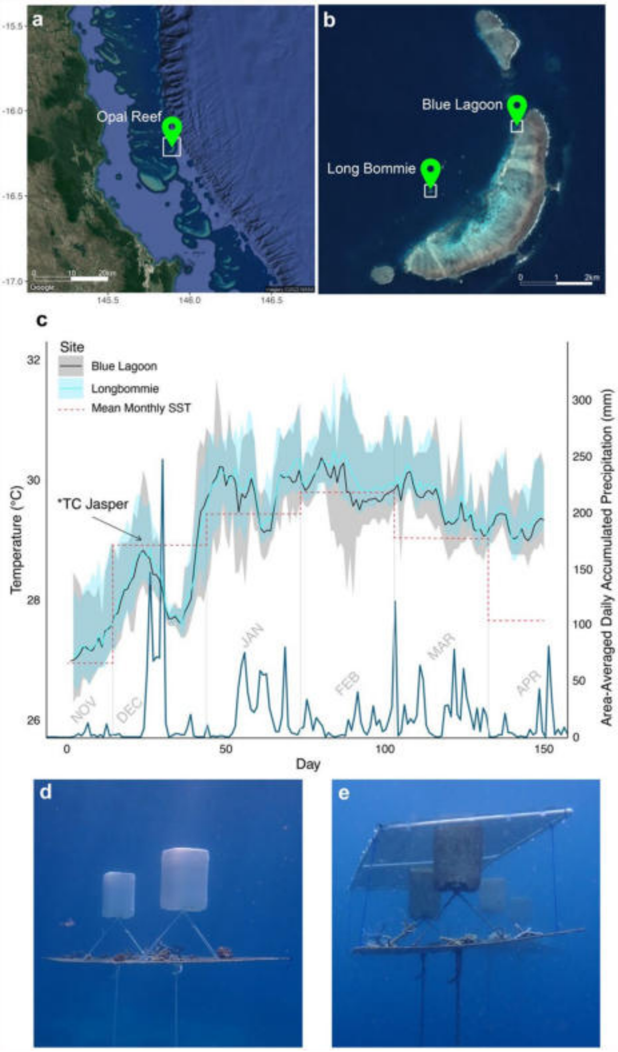

Fig. 1 **a** Map showing the location of Opal Reef in Northern Queensland on the Great Barrier Reef. **b** The locations of the study sites: Long Bommie and Blue Lagoon, Opal Reef. **c** line graphs of temperature (° C) over time at study sites Blue Lagoon or Long Bommie, and red dashed line indicates mean monthly sea surface temperature (SST) from 2002 to 2024 (NOAA Coral Reef Watch 2019; Skirving et al. 2020). Opal Reef **d** a mid-water floating nursery structure at the start of the study, and **e** A nursery with a shade structure installed. * Indicates the time when Tropical Cyclone Jasper made landfall with the north eastern Queensland Coast (~ 30 km) from the study site

Experimental set-up

Coral nurseries were constructed and set-up identically using 2.1 × 1.2 m aluminium diamond mesh for the frame, anchored with two 22 kg concrete masonry blocks and held afloat with two 20 L carboys (Fig. 1e.). Each nursery was marked with a numbered cattle tag and a Hobo Pendant® 64 K Temp-Light Data Logger installed facing upwards in the centre of the frame parallel to the water surface. No treatments were applied until increased temperatures reached 8 Degree Heating Weeks (DHWs). Whilst 4–8 DHWs is considered the range with which ecologically significant bleaching is predicted to occur (Skirving et al. 2017; Hughes et al. 2017a, b) previous heatwaves on the northern GBR that have resulted in bleaching at Opal Reef (Edmondson personal obs) have typically extended to 13 DHWs (data collected at Agincourt Reef 18 km from Opal Reef, Fig S3a., NOAA Coral Reef Watch 2019; Skirving et al. 2020) as such we deployed at 8 DHW to have shades installed for potential peak heat loading. DHW represents accumulated heat stress during a rolling 12 week period where sea surface temperatures (SST) reaches or exceeds a predetermined bleaching threshold or 1 °C above the maximum monthly mean (NOAA Coral Reef Watch 2018; Skirving et al. 2020). Twelve coral colonies from four different growth forms ($n=4$ colonies for *Acropora* branching, $n=3$ colonies for each *Acropora* plating and *Acropora* bushy, and $n=2$ colonies for *Pocillopora damicornis*) that were grown on nurseries at Blue Lagoon for up to two years were selected to represent the diversity of typical coral restoration nursery used by Coral Nurture Program on the GBR (Howlett et al. 2022). Eight fragments were taken from each donor colony. After harvesting, coral fragments were taken to the research vessel (*Wavelength* IV) in wire trays and held in a plastic container with aerated seawater for 30–90 min (to ensure consistency whether they were transported to a new site or the same site, Fig. 2). Coral fragments were then secured to one of the eight nursery frames (across the two sites) with plastic cable ties. At time zero (T_0) 6–8 coral fragments from each donor colony were photographed with a CoralWatch coral health chart card to quantify coral colour a.k.a. Mean Intensity Grey (MIG) % as detailed below. Upon the predetermined trigger of 8 DHWs on the 15th February 2024 a multi-factor experiment testing shade and depth to mitigate bleaching and mortality in coral nurseries was initiated.

Shade structure manufacture

Four shading and depth treatments were evaluated in this study; (1) shade structures secured to nursery at 4 m (Shaded + Shallow = S-S), (2) shade structures secured to nursery and lowered to 7 m (Shaded + Deep = S-D,

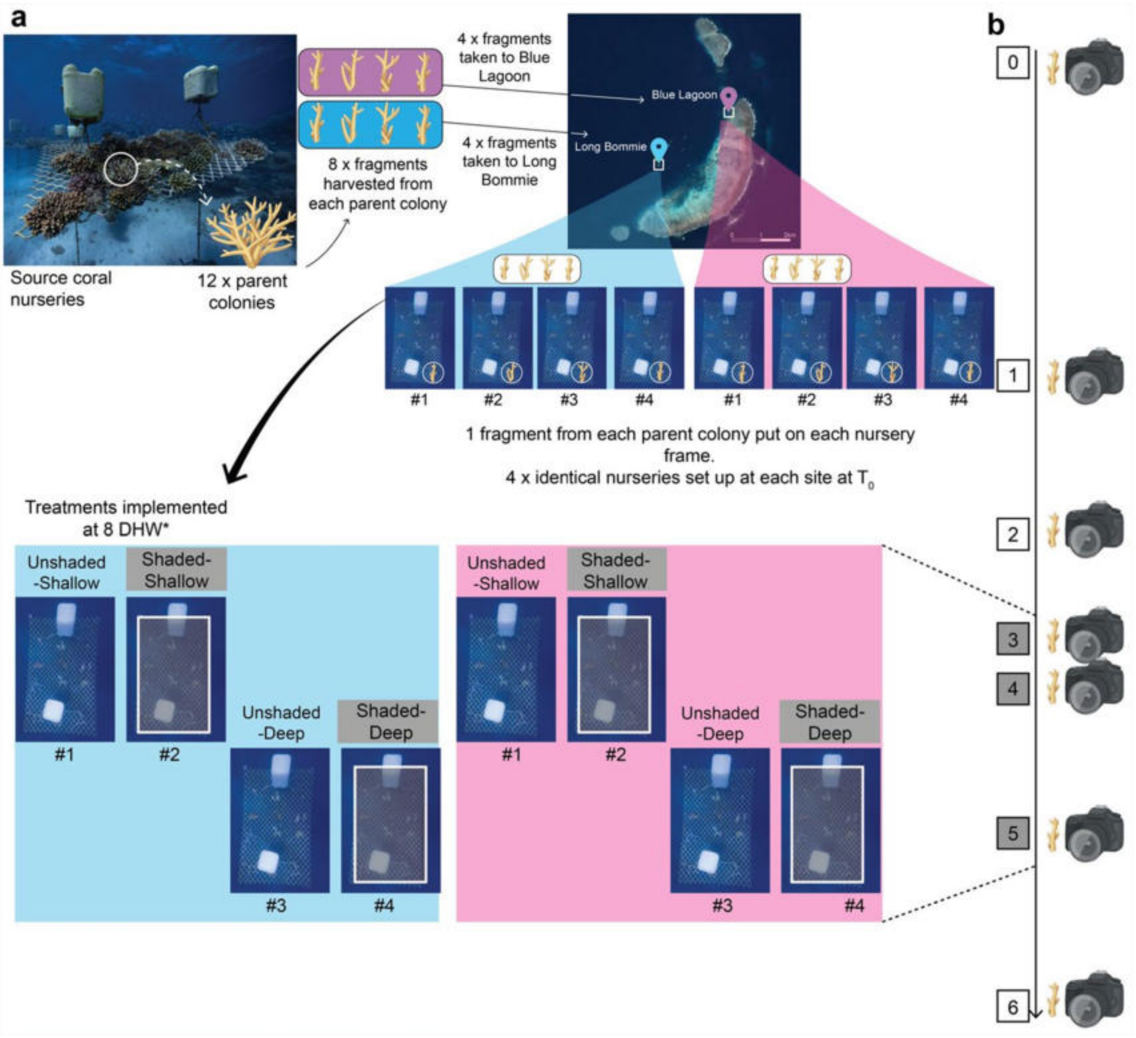

Fig. 2 Experimental design illustrating the harvest of coral fragments from mature coral nurseries, the transfer of these to four nurseries at two sites on Opal Reef (Blue Lagoon and Long Bommie), the four treatments applied and the timeline at which photographs were taken to quantify coral paling

(3) nursery lowered to 7 m without shading (Unshaded + Deep = U-D, and (4) nursery remained at 4 m without shading (Unshaded + Shallow = U-S) (Fig. 2a). Shade structures were manufactured from 20 mm PVC piping and 30% polyester shade cloth (Fig. 1d.) which has previously delayed coral bleaching responses by 3–4 DHWs during temperature stress (Butcherine et al. 2023), the shade cloth dimensions were 2.1 × 1.2 m to match the dimensions of the nursery frames, full costs are detailed in Supplementary Data Sheet 5. The frame was glued using a PVC adhesive to ensure the structure would be watertight and float. The shade structures were secured to the nursery frames with a tether at each of the four corners ~ 70 cm above the coral fragments (Fig. 1d). Shade structures remained installed for five weeks with routine algae removal at each sampling point and on ad hoc visits until 22nd March 2024 when temperatures began to decrease.

Coral health monitoring

Throughout the study each coral fragment was routinely photographed with an Olympus TG-6 digital camera alongside a CoralWatch coral health card to quantify the degree of coral bleaching of the fragment in a non-destructive way. Photographs were taken using the same settings (shallow white balance with no flash) at a consistent distance of ~ 30 cm from the coral with natural lighting (Fig S2a). ImageJ was used to determine mean intensity grey (MIG) percentage as a proxy for chlorophyll a content (as detailed in Amid et al. 2018; Mclachlan et al. 2021; Chow et al. 2016). In brief, the image was converted to 8-bit greyscale, a circle (~ 3 mm) was drawn on five different non-shaded areas of the coral fragment and the white of the CoralWatch card was measured as the 'white standard'(Fig S2a-b). The mean grey values were normalised to the white reference standard to calculate the MIG as a percentage ($(\mathrm{MIG} = \frac{\text{standard mean grey}}{\text{fragment mean grey}} \times 100)$, Supplementary Data Sheet 3). A higher value of MIG percentage indicates a paler fragment. Fragments were monitored at seven time points T_0, $T_1 = 43$ d, $T_2 = 65$ d, $T_3 = 79$ d, $T_4 = 85$ d, $T_5 = 108$ d, and for a final time at $T_6 = 134$ d which was five weeks after shades were removed to capture recovery. On one occasion during the monitoring period (13th March 2024) the shade structures installed at Blue Lagoon required repairs where shade cloth had partially torn from the PVC frame so was re-secured with additional cable ties or the PVC frame partially failed at the joints and were reconnected in situ. Further, on occasions during monitoring smaller repairs were made to the shade cloth that tore as a result of algae removal from the shades.

Environmental data

Temperature (°C) and light (lux) were recorded every 10 min using a HOBO Pendant® 64 K Temp-Light Data Logger (Onset, accuracy: ± 0.53 °C from 0° to 50 °C) secured at the centre of each nursery frame (Supplementary Data Sheet 7). The entire dataset was used for temperature analysis to compare differences between sites and treatments. However, due to fouling, the complete light dataset could not be used. Hence, at each monitoring time point the loggers were thoroughly cleaned and only the data collected during the 3 days following each monitoring point was used for analysis to ensure the light sensor was unobstructed by any fouling. Number of DHW for the region was collected from the NOAA Coral Reef Watch Virtual 5 km station located at the nearest reef, Agincourt Reef which is 18 km north of Opal (Fig S3a).

Statistical analysis: coral data

All statistical analyses were conducted using R version 4.4.0 (R Core Team 2024). All *Acropora* coral growth forms were pooled for analysis of survival and paling and *Pocillopora* bushy (*Pocillopora damicornis*) was excluded to avoid masking treatment effects as *P. damicornis* demonstrated distinct trends to the *Acropora* spp. For *P. damicornis* paling trajectories were visualised with line graphs (detailed below) but no other statistical analysis were conducted as replication for this group was low ($n = 2$). All subsequent analyses refer to pooled *Acropora* growth forms unless otherwise stated. Kaplan–Meier survival curves were estimated for each treatment at both sites including mortality events for the whole study and only from T_3 (when treatments were installed) onwards (Supplementary Data Sheet 1). To determine significance of differences in survival across treatments and sites we conducted a pairwise log-rank test on the Kaplan–Meier survival probabilities, *p*-values were adjusted by applying a Benjamini and Hochberg (a.k.a. False Discovery Rate) correction. To determine the significance of differences in emergent phenotypes (e.g. presentation of thermal stress as paling of the coral) across treatments and sites we calculated ± delta from MIG T_0 (ΔMIG) by subtracting MIG values at each timepoint from MIG at T_0 for each fragment (indicating whether a fragment paled, darkened or remained unchanged). Change in MIG (ΔMIG) was visualised with a line graph generated with ggplot2 in *R* (version 4.4.0). Homogeneity of variance and normality were tested for using Levene's and Shapiro–Wilk test, respectively, in R (version 4.4.0). Assumptions of homogeneity of variance and normality required were not met; therefore, the nonparametric Analysis of Variance of Aligned Rank Transformed data test was used to determine the statistical significance of differences in ΔMIG between treatments and sites at different stages of the study (e.g., T_3–T_6 when treatments were deployed).

Statistical analysis: environmental data

To determine whether temperature differed between sites and treatments normality and homogeneity of variance were tested (and were not met) therefor a nonparametric Art-ANOVA and subsequent art-con pairwise comparisons were applied (when p values > 0.05). A mean value for light irradiance (lux) on the first day loggers were installed was calculated for each site to account for differences in loggers, and lux values were then corrected depending on their difference to the mean on day 1. A subset of the light (lux) data was then created by selecting the 3-days after loggers had been cleaned at each sampling timepoint (as described above, days = 2, 3, 4, 60, 61, 62, 63, 82, 83, 84, 85, 96, 97, 98, 99, 102, 103, 104, 105, 125, 126, 127, 128). To calculate mean midday PAR the light (lux) data was first multiplied by 0.0185 (as per Thimijan et al. 1983 and Scordo et al. 2024 to convert lux to PAR) and then PAR values from 30 min either side of solar noon were averaged (Supplementary Data Sheet 6a) (Fig. 3).

Results

Environmental data

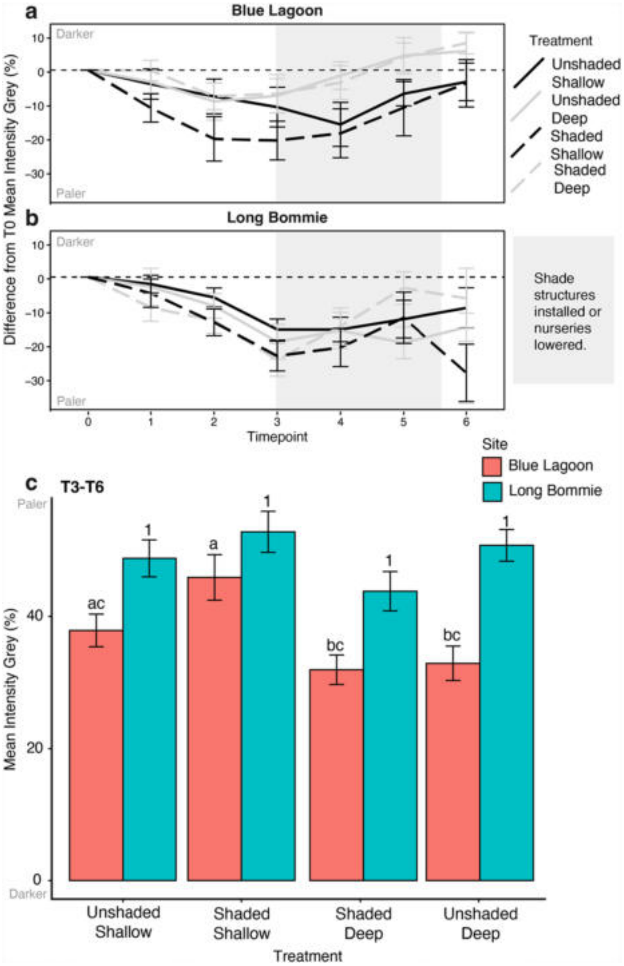

Fig. 3 **a**, **b** Line graphs of mean difference from T_0 MIG (error bars indicate ± standard error of the mean (SEM)) over time for nursery coral fragments under various intervention treatments (e.g. unshaded-shallow = U-S, shaded-shallow = S-S, unshaded-deep = U-D, and shaded-deep = S-D) over six time points. Different letters and numbers represent relevant statistical significance ($p < 0.05$) from Art-ANOVA contrasts pairwise comparison statistical test within Sites (Supplementary Data Sheet 4). **c** Barplot of mean MIG (lower value indicated paler coral) from T3 to T6 when interventions were installed at Blue Lagoon and Long Bommie, Opal Reef

Temperature at Blue Lagoon (Mean Temp = 29.17 °C, Min Temp = 26.29 °C, Max Temp = 31.68 °C) was significantly lower than Long Bommie (Mean Temp = 29.25 °C, Min Temp = 26.39 °C, Max Temp = 31.78 °C) (all time points and treatments pooled, Art-ANOVA, $F = 8.23$, $p = 0.004$, Fig S1c). However, the reported difference is within accuracy limits reported by the HOBO data logger manufacturer (Onset, accuracy: ± 0.53 °C from 0° to 50 °C). No differences in temperature were observed between treatments at both sites (T_3–T_6 only, Art-ANOVA, $F = 1.89$, $p = 0.130$, Fig S3B-C). Similarly, light (Lux) was not different between sites (treatment and time pooled, Blue Lagoon average Lux = 3834.03 lm/m^2, mean midday PAR = 255.63 µmol photons m^{-2} s^{-1} and Long Bommie average Lux = 3750.8 lm/m^2, mean midday PAR = 255.53 µmol photons m^{-2} s^{-1}; Art-ANOVA $F = 0.17$ $p = 0.683$), but did differ between treatments (Art-ANOVA $F = 9.50$, $p < 0.001$, Supplementary Data Sheet 6a & 6d-e, Fig. 4a). At both sites, the U-S nurseries (Blue Lagoon average Lux = 4565.4 lm/m^2; Long Bommie average Lux = 4697.2 lm/m^2) were subject to 21.6–36.0% higher irradiance (lux) than the shaded nurseries (S–S and S-D) (T_3–T_6 only, Art-ANOVA pairwise test, $p < 0.001$, Supplementary Data Sheet 6a & 6e-d, Fig. 4a). Though not significant, U-D nurseries were subject to 9.2–15.9% lower irradiance than U-S nurseries (at Long Bommie and Blue Lagoon respectively, Art-ANOVA pairwise test, $p > 0.05$, Supplementary Data Sheet 6a, Fig. 4a). Light reduction by the shade cloth was specified at 30% by the manufacturer; however, mean reduction in overall irradiance (lux) in S-S nurseries ranged from 25.68 to 29.05% (at Blue Lagoon and Long Bommie respectively) compared to unshaded U-S, the S-D nursery at Long Bommie had the largest reduction in mean irradiance (35.98%), yet the S-D nursery at Blue Lagoon only had 21.6% reduction in mean irradiance (Supplementary Data Sheet 6a) and the U-D nurseries irradiance (lux) was reduced by 16.8–15.56% (at Blue Lagoon and Long Bommie respectively). Further, the

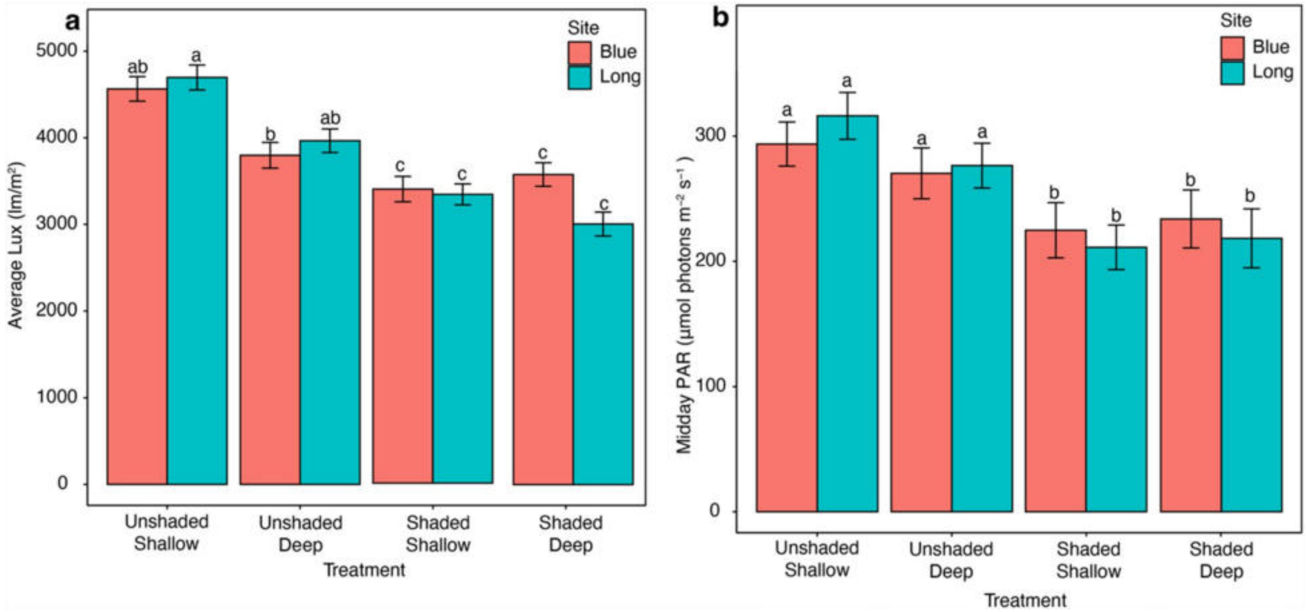

Fig. 4 Bar plots of **a** mean irradiance (light (lux lm/m^2)) ± standard error of the mean (SEM). Different letters and numbers represent relevant statistical significance between treatments within sites from Art-ANOVA contrasts pairwise statistical test ($p<0.05$) (Supplementary Data Sheet 4, and **b** mean midday PAR (μmol photons m^{-2} s^{-1}) ± SEM calculated from the 30 min either side of solar noon during the treatment period (T_3–T_6),

mean midday PAR was reduced by 7.97–23.46% for S-D, S-S and U-D nurseries (233.8, 224.78, and 270.27 μmol photons m^{-2} s^{-1} respectively) compared to the U-S nursery (293.66 μmol photons m^{-2} s^{-1}) at Blue Lagoon and the mean midday PAR was reduced by 12.57–33.22% for S-D, S–S and U-D nurseries (218.33,211.15,276.46 μmol photons m^{-2} s^{-1} respectively) compared to the U-S nursery (316.20 μmol photons m^{-2} s^{-1}) at Long Bommie (Supplementary Data Sheet 6a. & 6f, Fig. 4b & S4). Overall, installation of shading structures significantly reduced the incident irradiance and in some cases the mean midday PAR to the nursery corals, whereas lowering nurseries to the depth used in this study (7 m) reduced incident irradiance and mean midday PAR but the difference to U-S nurseries was not significant. As such, where irradiance was a major concern in exacerbating bleaching severity, the depth used at these study sites may not offer the refuge required but shading could.

Survival was higher for corals in deeper nurseries

Coral survival on the nurseries was higher at Blue Lagoon than Long Bommie across all treatments when amalgamating data from all morphological categories (81.3% compared to 75% respectively), i.e. the site where temperature was significantly lower. Notably, in contrast to *Acropora* spp. *Pocillopora damicornis* in all treatments across both sites exhibited 100% survival and consequently *P. damicornis* were excluded from the subsequent analyses to resolve any *Acropora* spp.-specific trends. Despite differences in overall survival, Kaplan–Meier (KM) survival probability curves did not significantly differ between sites (χ^2 (1, $N=300$) = 1, $p=0.6$, Fig S5a. Supplementary Data Sheet 2a). Mortality was observed in some nurseries before and after implementation of the treatments (S-S, S-D, U-D, and U-S). However, the majority occurred during or after the treatments were implemented (between T_3 and T_6, Fig S5d-e). Nevertheless, analysis of total and KM survival curves between treatments was also separately conducted on data between T_3–T_6 (during and after treatments were implemented, Fig S5b-c) to remove any potential bias in survivorship rates (e.g. reflective of mortality not linked to the treatment). For this, survival (%) was calculated against the number of fragments remaining at T_3 for each treatment. Survival trajectories were similar across treatments at Long Bommie (χ^2 (3, $N=40$) = 0.9, $p=0.8$, Fig S5c. Supplementary Data Sheet 2b) yet total survival ranged from 60% (S-D) to 80% (U-S). In contrast, Kaplan–Meier survival curves differed between treatments at Blue Lagoon (χ^2 (3, $N=40$) = 18.6, $p=0.0003$, Fig S5b), specifically the survival probability for corals in S-S nurseries was significantly lower than U-S, U-D and S-D nurseries (Log-rank pairwise test, $p_{adj}<0.05$, Supplementary Data Sheet 2c). By the end of the study at Blue Lagoon total survival was highest for deeper nurseries (U-D = 100%, S-D = 90%) and lowest in shallow nurseries (U-S = 87.5%, S-S = 66.6%). As such, our results do not indicate shading coral nurseries reduced coral mortality during the mass bleaching event. Further, survival was highest in deeper nurseries at Blue Lagoon suggesting depth was likely more important for mitigating coral mortality in this instance or excess light was not a primary stressor.

Corals on deep nurseries exhibited less paling than shallower nurseries

Overall, corals were paler at Long Bommie (mean MIG = 44.15% for pooled timepoints and treatments) than at Blue Lagoon (mean MIG = 36.66% for pooled timepoints and treatments) (Art-ANOVA$_{\text{site}}$ $F = 24.579$, $p < 0.0001$). Coral colour (MIG) differed between genotypes at T_0 (Art-ANOVA $F = 8.2594$, $p < 0.01$); therefore, all subsequent analysis was conducted on 'Difference from T_0 MIG' rather than MIG and the difference from T_0 MIG was also used to visualise the trajectory of coral paling (Fig. 3a-b.). For the period when interventions were deployed (T_3–T_6), the extent of coral paling (Difference from T_0 MIG values) also differed between sites and nursery treatments (Art-ANOVA $p < 0.001$, Fig. 3c & S6., Supplementary Data Sheet 4b). At T_3–T_6 Blue Lagoon corals on shallower nurseries overall exhibited a greater difference to MIG at T_0 (i.e. paler corals) than deeper nurseries (T_{3-6} mean change in MIG from $\text{T}_0 = -12.8\%$ (S–S) and -10.1% (U-S) versus U-D = -0.4% and S-D = $+1.0\%$, Fig. 3a); however, only the difference between S-S and U-D/S-D was significant (Art-ANOVA CON $p < 0.05$, Fig. 3c, Supplementary Data Sheet 4b). Coral paling was similar across treatments at Long Bommie with mean change in MIG from T_0 ranging from -12.4% in S-D nurseries to -19.7% in S–S nurseries (Art-ANOVA CON $p > 0.05$, Fig. 3b, c). At the final time point corals in all treatments at Long Bommie were paler than at the start of the study (mean change in MIG from $\text{T}_0 = -5.9$ to -15.9%), whereas at Blue Lagoon corals in all but the U-S nursery were darker than at T_0 (mean change in MIG from T_0 S-S = $+1.0$, U-D = $+3.76$ and, S-D $+10.1\%$) with the greatest change in coral colour recorded in the deeper shaded nursery (Fig. 3a, b & Fig S6). The trends in emergent phenotype (paler versus darker) in this study were site- and treatment-specific, where treatment did not impact coral paling at Long Bommie, yet differences in paling were recorded between depths at Blue Lagoon (e.g., more paling in shallower nurseries and greater recovery after paling in deeper nurseries).

Discussion

Shading has been proposed to mitigate the effects of thermal stress in corals (Coehlo, et al. 2017; Hoogenboom et al. 2017; Muir et al. 2017; Tagliafico et al. 2022). However, our experiments during the 2024 heatwave on the GBR showed that although shading and lowering coral nurseries lead to reductions in irradiance, overall shading coral nurseries did not reduce coral mortality or paling of corals under propagation at two sites on the northern GBR. Survival and paling of nursery corals differed significantly between sites, yet differences in survival and coral paling across treatments only differed between nursery depths at one site (Blue Lagoon), where higher survival and less coral paling was recorded in deeper nurseries. As such, our observations suggest that for the 2024 heat stress period, irradiance was not a primary regulatory factor or deployment of 30% shade at DHWs for 5 weeks was insufficient to overcome heat stress. We therefore hypothesise that differences in broad scale abiotic and biotic conditions such as exposure to storm waves, temperature, currents, tidal dynamics or disease prevalence on adjacent reefs—between Blue Lagoon and Long Bommie (Edmondson personal obs), likely had a larger influence on coral survival and paling in comparison to irradiance (Nakamura et al. 2003). Further, potentially an unmeasured additional depth-dependent environmental variable, such as salinity (which is known to be differently impacted along a depth gradient after cyclonic activity, van Woesik et al. 1995; Moberg et al. 1997; Devlin et al. 2001), possibly influenced coral survival and paling more than irradiance at Blue Lagoon where differences were primarily between deep and shallow nurseries. We also consider that the optimal window to install shades to maximise bleaching mitigation was potentially missed in this study. However, external factors such as the post-cyclone recovery period would have precluded earlier shade deployment.

Shading may be beneficial if environmental conditions exceed critical thresholds

Natural and artificial shading of corals has shown to be beneficial to coral fitness (e.g. increasing growth, maximising photobiological processes, and expediting bleaching recovery) in some instances, such as corals in shaded mangrove systems (Kellogg et al. 2020; Stewart et al. 2021; Yates et al. 2014) or for corals exposed to intermittent artificial shading regimes (e.g., installing shade cloth above corals to reduce irradiance, Coelho et al. 2017; Butcherine et al. 2023). In other instances, shading has provided no benefits (Bessell-Browne et al. 2017; Hendrickson et al. 2024; Juhi et al. 2021) for example, if mean midday PAR does not exceed the light saturation threshold for photosynthesis (E_k), and hence the minimum irradiance at which photosystem damage in corals could occur (e.g., 250–600 + µmol photons $\text{m}^{-2}\ \text{s}^{-1}$ for corals in the 2–4 m zone on Opal Reef; Suggett et al. 2022) then shading provides no benefit (Hendrickson et al. 2024). In this study reductions in paling or mortality were not observed from shading nurseries. Mean midday PAR for the unshaded shallow nurseries at the two sites in this study (293.66–316.2 µmol photons m^{-2} s^{-1}) may not have been high enough (or for long enough) to exceed E_k and exacerbate thermal stress for the coral species in this study and hence shading (and depth) would not have offered reprieve. However, we acknowledge that the extent to which thermal stress would have lowered E_k (e.g. Tunala et al. 2019; Ellis et al. 2024) closer to these mean midday PAR levels remains unknown. On the other hand, if the mean midday PAR levels were in some capacity stress inducing, the percentage of shade cloth (30%) used in this study may not have provided enough reduction in midday PAR (20.4–33.2%) compared to unshaded treatments, and using a higher percentage (50–75%) shade cloth may have reduced bleaching and mortality (Coelho et al. 2017; Butcherine et al. 2023). All of this said, it is important to note a minimum level of light is required by corals to both ensure enough energy for metabolic repair (Ottaviani et al. 2020; Blanckaert et al. 2021) and to maximise oxygenic buffering capacity within tissues to withstand night time deoxygenation (Alderdice et al. 2021), which must be considered when trialling higher percentage shade cloths. It therefore remains unclear what the optimal degree of shading (e.g., percentage of shade cloth) is required to maximise benefits; however, it likely varies with environmental conditions such as mean midday PAR and hinges upon conditions exceeding critical thresholds. As such, future evaluations of varying degrees of shading (30% +) in situ under a range of environmental conditions will further assist evaluation of shading benefits.

Species-specific responses to shading warrant further investigation

Although critical thresholds for light irradiance are not known for all species, our findings highlight that unless irradiance exceeds critical thresholds (Skirving et al. 2017) or occurs concurrently with heat-driven photosystem damage (Hoogenboom et al., 2012) then shading is unlikely to provide benefits. The generally cloudy and wavey conditions and absence of doldrum days (known to lead to severe bleaching; Baird et al. 2017; DeCarlo et al. 2017; Raymundo et al. 2017) over the 2023–24 summer in the study region (Strudwick and Edmondson personal obs) and the mean midday PAR data support that irradiance was unlikely a primary stressor at the study sites and further explains why shading did not reduce bleaching responses. However, variable outcomes of shading during thermal stress can occur between *Acropora* spp. (Muir et al. 2017; Ellis et al. 2024) and as such is it plausible that species-specific responses within the *Acropora* spp. grouped in our study may have further masked treatment effects. Consequently, we suggest future efforts representing generic multi-taxa nurseries ensure higher replication within species to tease out species-specific responses.

Balancing risks versus rewards

Despite the likelihood that irradiance was not a primary stressor or severe enough for shading to mitigate bleaching responses in this study, there is also the possibility that results would have differed if shades had been deployed at a different time (e.g., earlier or for longer). Corals had already begun to pale in this study prior to deployment of shading, and while shades were deployed later to protect against irradiance during the peak temperatures, it is possible if shades had been deployed as early as 1 DHW (opposed to 8 DHW) less paling may have been observed, per Coelho et al., (2017). However, benefits of shading have been suggested to decline after 4–5 DHW (Coelho et al. 2017); therefore, practitioners must act strategically to balance the risks versus potential rewards when deciding if and when to deploy shades. If structures are only permitted to remain in situ for a finite period of time or become heavily fouled after a short installation a decision on whether to shade early and risk missing peak temperatures or shade later and risk early paling must be made. For instance, in our study, shades became fouled with algae within 1 week of installation and, although the nursery installations without shades were undamaged by Cyclone Jasper, once they were installed at one site they were prone to tipping in tidal currents due to the additional water resistance of the shades. These were additional risks that not only required management but also impact irradiance, and hence deserve consideration by practitioners when choosing whether to use shades (see Fig S7 & Fig S8a-b). As with any intervention, potential benefits must be weighed against practitioner dependent contexts and costs, associated risks of action (e.g., deploying additional structures during cyclone season and costs associated with maintenance such as cleaning). The precise benefits to nursery corals from shading remain uncertain on the Great Barrier Reef specifically and arguably in this practitioner-specific circumstance unlikely justified the investment (AUD $400 per shade for manufacture, installation and maintenance, see Supplementary Data Sheet 5 for full cost breakdown). On the other hand, in more extreme abiotic conditions, or in other locations with lower labour costs (such as volunteers), or the relative cost of manufacturing, maintaining and installing shades compared to value of the nursery stock may justify shading nurseries where it is not possible to lower them (e.g., at shallow sites) during heatwaves where irradiance is predicted to exceed critical thresholds.

Conclusion

Shading coral nurseries during the 2024 mass bleaching event did not reduce bleaching or improve survival rates for nursery corals at two sites on the northern Great Barrier Reef. However, lowering coral nurseries to deeper water resulted in less paling and mortality (at one site) indicating environmental factors other than irradiance were regulating bleaching severity. Therefore, as practitioners continue to invest time and effort into high value coral nursery stock an evaluative site-specific decisions making framework and consideration of risks (e.g., Fig S7 and Fig S8a-b respectively) should be used to determine whether shading (or lowering) nurseries is likely to provide benefits (e.g., mitigate bleaching), and is subsequently worth the risks and investment (time and money). For example, benefits from shading may be more apparent if irradiance (mean midday PAR) exceeds critical thresholds and if light and heat stress occur synergistically, especially in locations where it is not feasible to lower nurseries to deeper water. Moreover, where minimal light stress is forecast, lowering nurseries may indeed provide adequate protection and would be the preferred strategy. As such, further investigation of the effectiveness for interventions to mitigate bleaching under a range of conditions in different locations and under higher irradiance is warranted. Gathering valuable information on coral nursery sites could be achieved by compiling historical records of impacts at sites in conjunction with modelling tools that predict trajectories for a range of potential stressors (e.g. salinity, light, rainfall, winds, and tides (Bainbridge 2019; DeCarlo 2020)) at high spatial resolution such as the ‘Doldrum’ and ‘Light Stress Damage’ remote sensing tools previously developed by NOAA (Eakin et al. 2018; Skirving et al. 2017). In conclusion, lowering coral nurseries where possible ahead of predicted bleaching conditions (e.g., based on NOAA Coral Reef Watch Alerts) may provide a low-effort and cost benefit. In the meantime, factors such as the importance of the nursery stock, the practitioner context, and weather projections will aid in assessing the risk/reward of shading coral nurseries to protect nursery stock from unfavourable environmental conditions. Our results also further reinforce the importance of considering such site conditions when installing nurseries (Goergen et al. 2020) to ensure suitable steps can be taken in the future to protect stock.

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Author contribution P.S, E.C, D.S and J.E conceived the study design, P.S and J.E conducted experimental set-up and monitoring, P.S wrote the main manuscript text, conducted all processing and analysis, and prepared all figures. D.S and E.C provided primary editing of the manuscript. All authors reviewed the manuscript.

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Data availability Data is provided within the manuscript or supplementary information files, additional supporting data and processing files can be accessed via https://github.com/pstrud/shading.

Declarations

Conflict of interest The authors declare no competing interests.

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