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Investigating thermal regime on seawalls to maximise nature positive outcomes for encrusting tropical oysters

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ABSTRACT

Ecological niche theory poses that the arrangement of species in the environment is arranged by thresholds and tolerances to settings, though, when these conditions fall outside these (for example, temperature) a species is absent. Using an infra-red thermal sensor, we characterise the surface temperature in summer and autumn on the sun facing (no oysters present) and the shaded side of rock boulders (oysters present) used to build coastal seawall structures in central Queensland, Australia. The sun facing boulder surface was significantly hotter, up to 15 °C at any one time, compared with the boulder shaded side during both the summer and autumn surveys. Diel logging (30 min intervals) of surface temperature of sun facing boulder surfaces without oysters ranged between 24 and 50 °C, while boulders with oysters ranged between 25 and 35 °C. A Principal Component Analysis constructed using boulder dimensions (length, width, height, and surface angle orientation) showed a close positive correlation between length and width, however, height was poorly correlated with the other two dimensions. When this information is used to construct a boulder index no relationship is evident between the boulder size and the observed temperatures on the two sides of boulders. For seawalls to achieve nature positive outcomes in tropical settings, requires simply taking into consideration rock surface temperature settings during the design and construction phase. Implementing this ecological engineering consideration gives oysters a greater chance of colonisation, and thereby providing the ecosystem services that they are well known for.

1. Introduction

Oysters are subtidal reef building, or intertidal encrusting, eco-engineers that occupy shallow coastal and estuarine waters (Bartol et al., 1999; Fivash et al., 2021; Gilby et al., 2018). They provide a range of nature-based services such as food provision for fish (Martinez-Baena et al., 2023; Strain et al., 2018), process nutrients (Castle and Waltham, 2022; Grizzle et al., 2021) and also stabilise foreshores from coastal erosion (Grizzle et al., 2021; Pinnell et al., 2021). Despite these services, unfortunately, widespread oyster reef loss has occurred in response to water quality changes, but also directly as a result of overfishing and habitat modification in many places (Beck et al., 2011; Gillies et al., 2018). To compensate for these lost ecosystems, major investment has been made by government and non-government organisations to fund direct seeding restoration projects, building and deploying cages or transplanting, as well as improving coastal habitat and water quality to promote suitable conditions for natural recovery (Cook et al., 2021; Fivash et al., 2021; Gilby et al., 2019; Grizzle et al., 2021; Heggie and Ogburn, 2021; Keller et al., 2019). Despite these efforts, success has been varied (Hemraj et al., 2022). The basis of ecological niche theory poses that the spatial arrangement of species in the environment is defined by thresholds and tolerances to settings, such as biotic and abiotic conditions (Hobbs et al., 2009). Biotic examples include predation or the presence of invasive species, while abiotic examples comprise responding to environmental thresholds such as water quality. One contributing factor to the spatial arrangement of animals in nature is temperature (Brett, 1956; Harley et al., 2006; Mancuso et al., 2023), where the model is that species are occupying spatial (and temporal) locations because the environment supports conditions within a species-specific tolerance (Sunday et al., 2012; Minuti et al., 2021). With warmer temperatures projected under future climate, the challenge is that species must adjust to new environmental settings, either via a shift

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in range (Helmuth et al., 2006; James et al., 2017; Stewart et al., 2013; Welbergen et al., 2008), or else a species risks extinction (Thomas et al., 2004). The implications of warmer climate projections have included changes in metabolic rates, growth rates, resource allocation for reproduction, or even modified population size (Armstrong et al., 2013; Jobling, 1995). Under situations with extreme temperatures, acute hyperthermic responses are triggered requiring animals to engage thermoregulatory capacities (Cheng et al., 2013; Coulter et al., 2016; Williams and Morritt, 1995; (Minuti et al., 2021). This is best shown in sessile species including shellfish that hold fast on hard structures (Helmuth, 1998), their ability to move is prohibited such that individuals settling in locations supporting optimal thermal conditions will survive, but outside the threshold they will not. Expansion of coastal cities and agricultural areas (Jouffray et al., 2020; Sengupta et al., 2019) continues to directly reduce the extent of natural coastline habitats (Murray et al., 2022). A major proportion of coastal infrastructure includes breakwaters, seawalls, revetment, and bulkheads, that are engineered for the primary purpose of coastal protection (Bulleri et al., 2005; Burt and Bartholomew, 2019; Firth et al., 2024; Lai et al., 2018; Seitz et al., 2006), in response to sea level rise and serve weather events (Grilli et al., 2017). With the proliferation of these structures, the conviction is that they, too, offer habitat settings that mimic biodiverse natural hard habitat areas (Aguilera et al., 2022). The evidence is contrary, with the design and materials used (e.g., concrete) effectively supporting habitat settings that have fewer organisms (Bulleri et al., 2005; Chapman, 2003). To combat this, managers have incorporated eco-engineering approaches (Hall et al., 2018), such as increasing habitat complexity during the casting of concrete manufacturing of seawall blocks (Evans et al., 2016; Firth et al., 2014; Firth et al., 2013a), adding plates to seawalls (Loke and Todd, 2016; Strain et al., 2018), or attaching water retaining boxes that mirror inter-tidal rock pools found on reef platforms at low tide, with positive outcomes emerging (Browne and Chapman, 2011; Firth et al., 2013b; Waltham and Sheaves, 2018). While the focus has been on greening the grey (concrete) infrastructure to achieve nature positive outcomes for biodiversity, through the addition of habitat complexity (Browne and Chapman, 2014; Evans et al., 2016; Firth et al., 2024), a more recent focus has been on temperature refugia in the design of these urban structures (Aguilera et al., 2019; Bishop et al., 2022). In one study examining thermal exposure risks, plant boxes attached to a seawall were tilted to construct novel microhabitats including underledge surfaces. The hypothesis was that water retaining boxes attached to seawalls simulate rock pools, but in doing so achieve thermal conditions more aligned to local species tolerances (Waltham and Sheaves, 2020). Thermal refugia opportunities on seawalls which could be reached with ecological engineering is a relevant research field for the objective of nature positive outcomes for biodiversity on seawalls, and thereby are part of much needed improvement to living shorelines and nature-based solutions in the coastal zone (Airoldi et al., 2021; Todd et al., 2019; Morris et al., 2024). An important element to this nature-based success is that thermal refugia needs to be most effect during warmer summer months, but possibly it is also relevant in the cooler months of the year, which will be also warmer in the future (Kisacik et al., 2022). In addition, thermal relief is applicable to all design features on seawalls, though the orientation of seawalls and solar exposure has not been previously contemplated (Todd et al., 2019; Bishop et al., 2022).

In this study, we tested the hypothesis that oysters encrusting the surface of boulders used in the construction of a major seawall varies considerably, with boulder surfaces far hotter where oysters are not present compared to boulder surfaces where oysters are present. To test this hypothesis, we used an instantaneous surface temperature sensor to check on selected boulder surfaces (where oysters were and were not present), in addition to using high frequency thermal loggers to characterise diurnal surface temperature fluctuations on the boulders during both summer and autumn, and on seawalls that have different orientations and solar exposure. These results provide an understanding into the thermal exposure risks to oysters when designing and positioning boulders on seaways, and understanding this has important nature positive outcomes in the quest for seawalls to more closely mimic natural shoreline areas. These data are particularly useful for managers working in tropical locations where species maybe already living on their thermal thresholds.

2. Materials and methods

2.1. Study location

This research was completed in the Mackay marina (−21.112°S; 149.225°E), a semi enclosed facility providing safe water anchorage for more than 200 vessels, located in central Queensland Australia (Fig. 1). The marina is the main facility in the region for vessels ranging in size from hobby vessels/yachts (7 m) to major industry and commercial vessels (∼40 m). The region is sub-tropical with a distinct wet season where most rainfall occurs between December to March each year and an ambient air temperature reaching daily averages of 30 °C in summer and 22 °C in autumn (data sourced Australian Government, Bureau of Meteorology). The marina is located adjacent to the Great Barrier Reef World Heritage Area, a 2300 km interconnecting coral reef and coastal wetland ecosystem along the Queensland coastline, Australia. This reef ecosystem supports a diverse range of aquatic organisms and provides a lifestyle and livelihood industry worth more than $6 billion each year to the local economy (Deloitte Access Economics, 2017). While the marina is outside the world heritage area, these engineered features seem to support species observed on nearby reefs making these hybrid habitats functionally important (Bradley et al., 2023; Waltham et al., 2022).

2.2. Oyster boulder surface thermodynamics

The instant temperature of boulder surfaces where encrusting oysters (*Saccostrea cucullata*) were found growing (that after inspection were either found to be mostly alive, though some were dead) attached to the seawall boulders was measured using an Apogee IR sensor that has Research-Grade sensor with an accuracy of ±0.2 °C from −30 to 65 °C. The use of the infrared sensor and thermal imaging has advanced the way researchers measure and understand subtle temperature differences across intertidal shorelines (Judge et al., 2018). The Apogee infrared unit was attached to an extendable pole and lowered from a boat in the marina to measure the boulder surface temperature (it was not possible to access the boulder wall from land due to the dangers of crocodiles in northern Australia). The device was hovered over the boulder surface (approximately 5 cm) for 20 s, which was sufficient time (after field trials) for the surface temperature reading to stabilise. The surface temperature was recorded on the side of boulders, too, where oysters had colonised, with the same process repeated to measure the top surface of rock boulders where oysters were not observed (see Fig. 1) – note where possible the boulder surface temperature was measured instead of measuring directly the oyster temperature which may insulate boulder surface temperature). We measured 100 haphazardly chosen boulders positioned along each of the west and north facing walls (to decipher whether orientation of boulder walls to solar radiation was a contributing factor to the measured boulder surface temperatures) over a 2 h period (between 10 am and 12 pm – proximal to when the sun is at its highest solar radiance) on 17 November 2021. On 4 April 2022 the same sampling approach was repeated, but on 50 boulders, on the west and north facing boulder walls, again, over a 2 h period (between 10 am and 12 pm).

2.3. Continuous boulder surface temperature logging

The same Apogee unit was positioned on the boulder wall to record continuous surface temperatures on the upward facing and the oyster side of two boulders between 4th and 7th April 2022. The unit has a

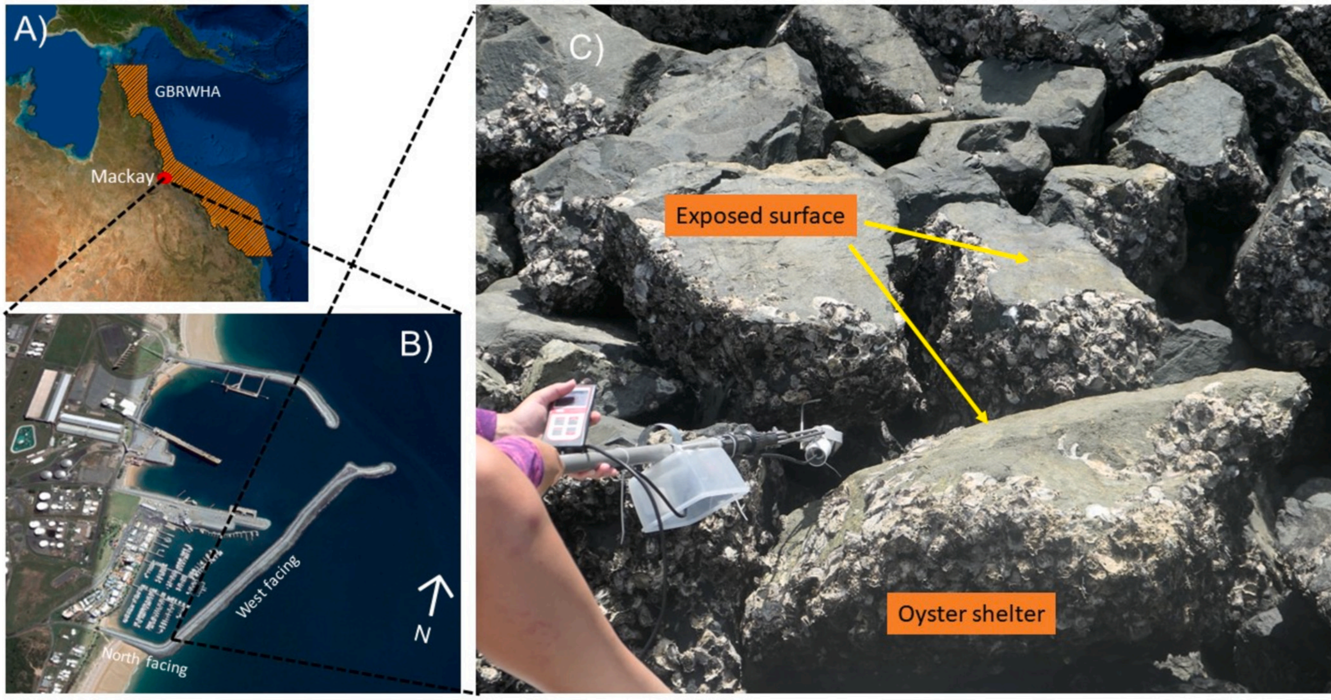

Fig. 1. (A) Location of the Mackay long the Queensland coast, adjacent to the Great Barrier Reef World Heritage Area (GBRWHA), Australia; (B) location of the Mackay marina and port facility; and (C) example of using the Apogee to measure surface temperature of boulders on the seawall.

logging setting to record surface temperatures every 30mins (calculated as an average from a burst of 20 spot measurements in 2mins before every 30 min logging step). A single extendable pole was positioned on the seawall with one apogee unit positioned 5 cm above the upward facing surface, while a second apogee unit was positioned 5 cm above the boulder on the oyster side. The logging was repeated over the survey period, with a single boulder at each of the north and west facing walls examined here.

2.4. Statistical analysis

The variability in boulder surface temperatures between the two boulder walls (west and north facing) and the surfaces with oysters and without oysters, in summer and autumn, were tested using a three-way ANOVA, where seasons, wall facing and oyster/without oysters all fixed factors. The assumptions of normality and homogeneity of variance were assessed by visual inspection of a quantile-quantile plot and a plot of residual vs. fitted values – no transformation of these data was necessary. Principal Component Analysis (PCA) was constructed to examine differences in boulder dimensions (maximum estimated length, width, height) along the seawall. The data were then used to construct an index between boulder size and the observed temperatures on the two sides of the boulder. All analysis was completed using SPSS (v22).

3. Results

3.1. Boulder surface temperature

The spot temperature checks of boulder surfaces conducted in November 2021 showed that the side of the boulder surfaces without oysters had on average 9.4 °C higher temperature when compared to the upward facing surface of the same boulder (Fig. 2). The April 2022 spot checks, corroborate this, with the upward facing boulder surface, again, having much higher temperature than the side with encrusting oysters. Differences in temperature between the two boulder sides with and without oysters was consistent regardless of seawall orientation (north or west facing) and season (Table 1), with the exception in temperatures between seawall orientation and boulder surface. There was a significant interaction in surface temperature difference between boulder surfaces with oysters and without oysters, seasons and orientation of the seawall, which is probably due to the particularly high temperature difference between seasons on boulders with and without oysters on the western facing wall (Fig. 3).

3.2. Solar radiance conditions during field surveys

Information for Mackay Harbour on sun exposure and temperature during the period the temperature loggers were deployed indicate that the sun exposure was mostly equivalent across the period with only April 2022 having a value just below 20 M/m*m, while the minimum and maximum temperature during that period was almost the same with a variability within +/− 1 °C (Fig. 4). This indicates that observable differences in trends between the seawall boulder surface are not a response to changes in environmental conditions occurring during the survey campaign.

3.3. Boulder diel surface temperatures

The temperature loggers deployed to examine diel variation in conditions on the two seawalls between the 4th and 7th of April 2022 confirm what was observed during the spot check assessments, that the side of the boulder with oysters have a lower thermal temperature, but also a lower daily amplitude with values ranging between 25° and 35 °C at both seawalls, as opposed to the sun facing side that recorded values as high as 50 °C during the day and as low as 24 °C at night (Fig. 5). Interestingly, temperature on boulders on the north facing wall start increasing earlier in the morning (about 8 am) compared to boulders on the west facing seawall (about 10 am).

3.4. Boulder dimension index

The PCA constructed using the boulder dimensions shows a close

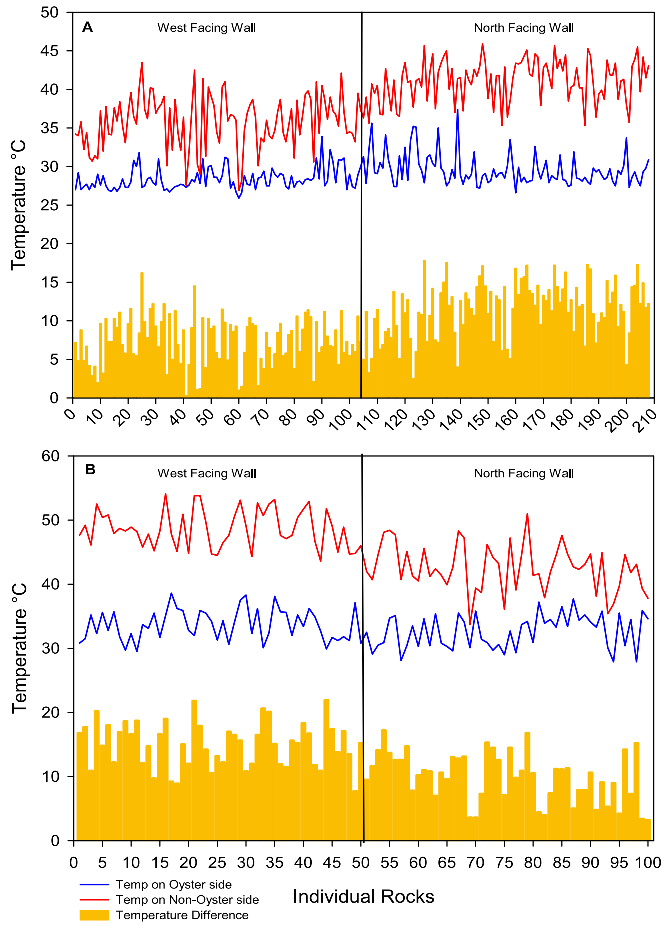

Fig. 2. (A) Spot check temperature of the seawalls facing north and west in November 2011; and (B) April 2022. Two measurements were taken on the same boulders; where oysters colonise the boulder (blue line) and where there are no oysters (red line). The yellow columns represent the relative difference (i.e., with oyster and without oyster) on the boulder temperature between the area that has colonising oysters and the one that do not. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

positive correlation between length and width, however, height of individual boulders is poorly correlated with the other two dimensions (Fig. 6). When this information is used to construct a boulder index no relationship is visible between the boulder size and the observed temperatures on the two sides of the boulder (the one colonised by oysters and the one that is not) (Fig. 7). However, focusing on boulder size alone does not account for oyster density and shade exposure, which are likely to influence the rate of colonisation which was not examined here.

4. Discussion

The expansion of urban and industrial development in the coastal zone means that more seawalls will be constructed, which presents managers with the opportunity to make more positive, greener, living seawalls decisions. The most striking result here was that the surface temperature on the oyster side of the boulders rarely exceeded the daytime minimum surface temperature recorded on the sun facing boulder surface. The high temperature probably means that even if new oyster recruits settle on the top of the boulder, such extreme temperatures probably limits the survival and growth of local oysters species – a pattern found for bivalves elsewhere when after-settlement and where conditions are not favourable for growth survival, species do not survive (Devakie and Ali, 2000; Nowland et al., 2019).

One way to maximise nature-based positive outcomes on seawalls is perhaps selecting boulders with specific shapes and organising their position/orientation during construction to be more temperature sensitive to the requirements of local oyster species. Understanding how to best design boulder seawalls is necessary for two reasons for promoting oyster colonisation: 1) their natural ability to filtrate water, means that having higher encrusting abundance increases filtration capabilities; and 2) with projected increases in global temperature, any microhabitat that is offered to intertidal organism species will provide an advantage to ameliorate thermal stress. Additional seawall research could focus on the microclimate dampening effects that oysters create (McAfee et al., 2022a; Sun et al., 2022), and enhancing micro-climate opportunities for other marine species, which makes constructing boulder seawalls even more nature positive habitats in the coastal zone. It is also acknowledged here that spot sampling of boulder surface temperatures occurred over a few hours on a single day in summer and autumn – future research might sample surface temperatures over multiple days and on additional seawalls in other locations to determine if these results are true more

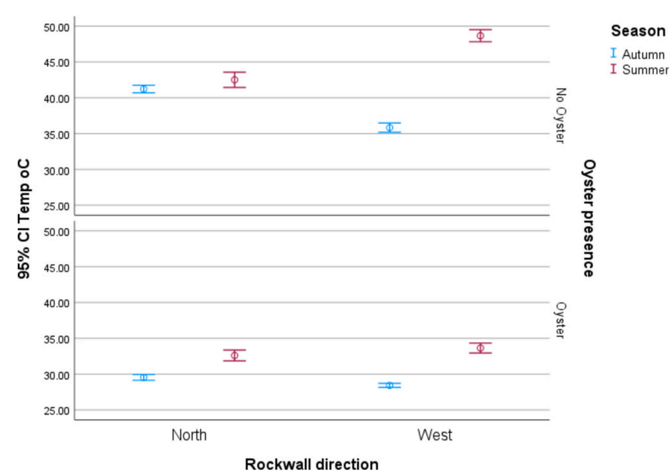

Fig. 3. Mean (± 95 % Confidence Interval; CI) boulder temperature on side with oysters growing and side without oysters at the two seawalls (west facing site and north facing) in November 2021; and April 2022.

Table 1
Three-way ANOVA comparing boulder spot temperatures on boulder surfaces with oysters, without oysters, on north and west facing walls in both summer and autumn seasons.

Source	Sum of squares	df	Mean square	F	Sig
Corrected model	23,950.7	7	3421.5	480.3	<0.001
Intercept	721,734.3	1	721,734.3	101,311.1	<0.001
Season * Oyster	287.9	1	287.9	40.4	<0.001
Season * Orientation	1583.6	1	1583.6	222.3	<0.001
Orientation * Oyster	6.2	1	744.7	0.8	0.353
Season*Oyster*Orientation	744.7	1	7.1	104.5	<0.001
Error	806,455.2	608			

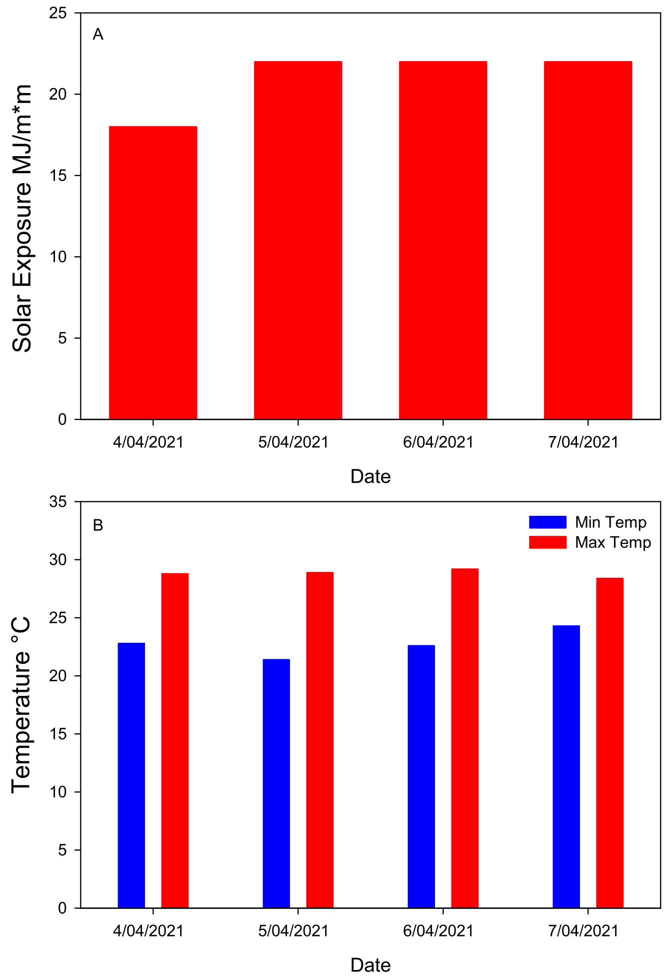

Fig. 4. (A) Information on Mackay harbour total solar irradiance; and (B) temperature range in April 2022 during temperature logger deployment.

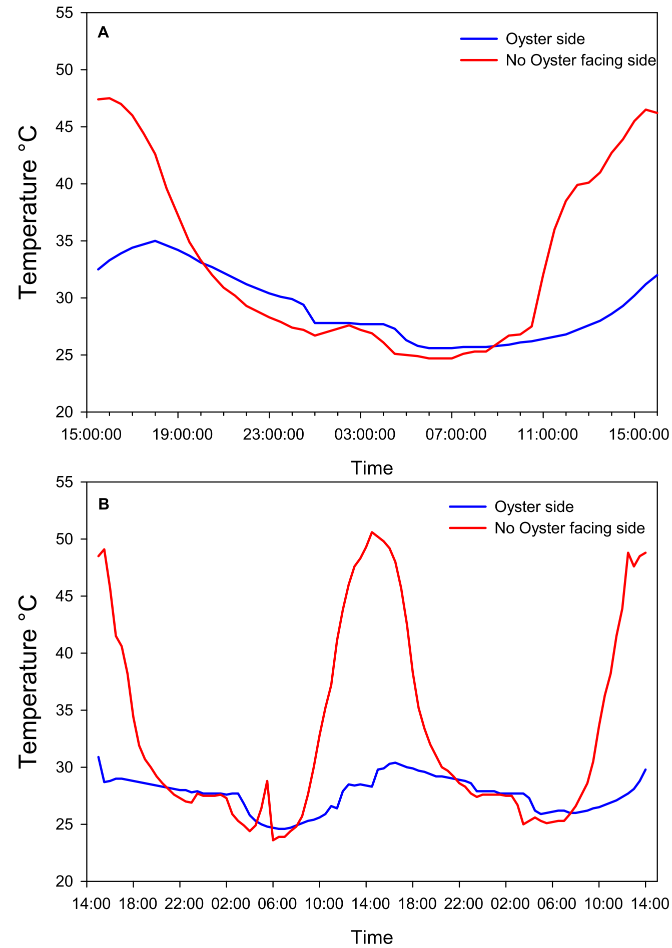

Fig. 5. Temperature trend on the side of the boulder: (A) facing the sun with no oysters (orange) and the side with colonising oysters (blue) for the west facing seawall; and (B) north facing seawall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

broadly.

The construction of seawalls for the protection of infrastructure and human life is going to continue in response to the lifestyle and livelihoods that the coastal zone provides to so many people around the globe (Ng et al., 2015; Vozzo et al., 2021). In some coastal regions, seawalls are an obvious feature – for example, China's 'new great wall' is a seawall that stretches hundreds of kilometers along the coast (Dong et al., 2016; Huang et al., 2015). Seawalls are also engineered to assist with increasing residential coastal areas with water frontage (Waltham and Connolly, 2011), with island land developments also expanding more recently in many places, such as Singapore, United Arab Emirates and Japan (Sengupta et al., 2019). Even along the Great Barrier Reef World Heritage Area and Marine Park, with its outstanding universal values (McCook et al., 2010), seawalls and other urban and port infrastructure are widespread, with coastal infrastructure having a linear distance equivalent to approximately 10 % of the entire reef coastline (Waltham and Sheaves, 2015). The Great Barrier Reef has one of the world's most biodiverse coastline and reef lagoon ecosystem (McCook et al., 2010), though in recent years this has been questioned in response to continuing impacts of warming climate change and coral bleaching (Hughes et al., 2015), in addition to deterioration in water quality and invasive species (Adame et al., 2019; Pearson et al., 2021; Vandergragt et al., 2020). While broader coral protection policies draw the link between reef ecosystem condition and accumulative impact of coastal development (State of Queensland, 2018), empirical data supporting this has only recently emerged (Bradley et al., 2023; Waltham et al., 2022; Waltham and Sheaves, 2017). What this means is that approval decisions in the past may not have been able to consider the full nature positive opportunities that this new infrastructure provides in the marine environment.

The prospects that living shorelines and shellfish reef restoration offer nature-based positive solutions is attracting significant restoration and rehabilitation investment from private corporations and government agencies (Fitzsimons et al., 2020; Kulp and Peterson, 2016), even Australia has a major national oyster reef restoration program (McAfee et al., 2022b). Such investment pipelines are focused on restoring to former natural oyster settings or at least some comparable hybrid setting (Kulp and Peterson, 2016), which is probably more likely given the low rates of restoration success because projects tend to be founded on a poor understanding of local settings and species trait requirements (Sheaves et al., 2021); including oyster restoration projects (Hemraj et al., 2022). An important reason for this restoration effort is not only for oyster conservation, but for the core-benefits provided, that are in addition to water filtration, including benefits such as habitat for fish (Fitzsimons et al., 2020). The fact that oysters quickly colonise engineered seawalls once settled (Aguilera et al., 2016; Scyphers et al., 2011), is a promising base for better use of seawalls as a habitat prospect in restoration ecology. However, our results illustrate that practitioners also need to be cognisant of thermal regimes for target species to increase successful outcomes (Giomi et al., 2016; Waltham and Sheaves, 2020). Designing infrastructure that is future climate ready is becoming more necessary (Sun et al., 2022). This readiness needs to be integrated

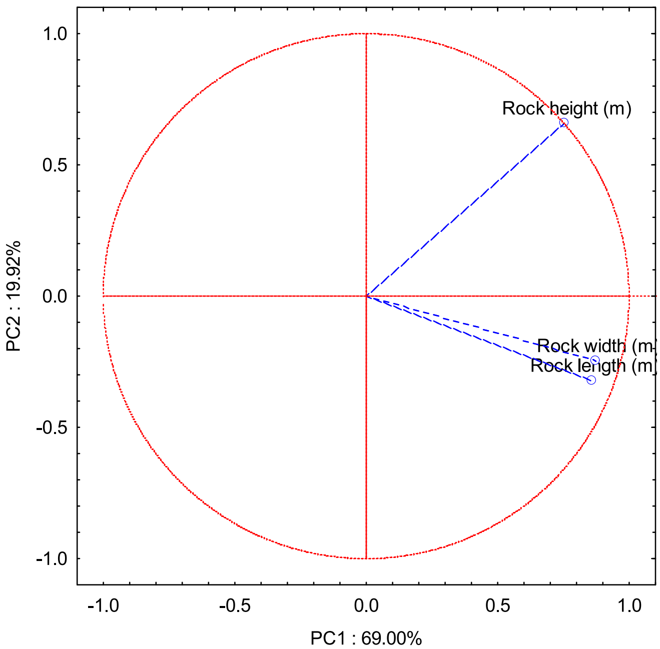

Fig. 6. Principal Component Analysis (PCA) constructed using the individual boulder dimensions.

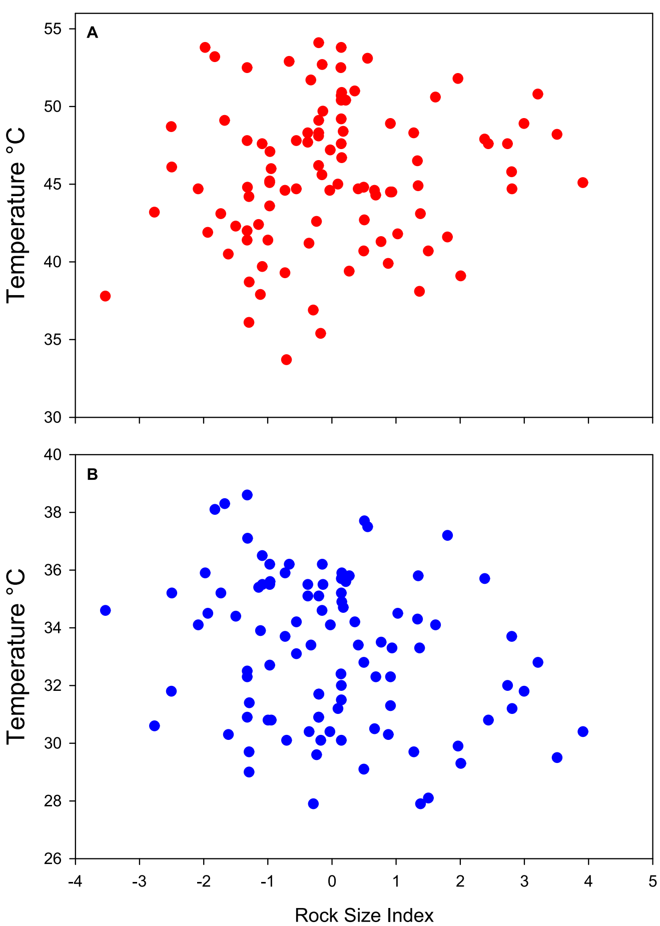

Fig. 7. (A) Distribution of temperatures on the side without oysters; and (B) the side with oysters, based on boulder size index constructed using the first component scores of the PCA (larger value = larger boulders).

into the early design of seawalls, but also during maintenance programs that are necessary following storm damage.

5. Management implications

The proposition that engineered seawalls mimic natural rocky shorelines has received much research attention, with evidence ranging from overlapping to very different assemblages, supporting the conclusion that seawalls simply harbour a subset of species found over rocky intertidal shorelines (Chapman, 2003). This has generated research into increasing habitat opportunities on seawalls through the addition of complex features such as tiles (Loke et al., 2015), water retaining boxes (Browne and Chapman, 2011; Strain et al., 2018; Waltham and Sheaves, 2018), and core holes (Chee et al., 2020; Evans et al., 2016), with some level of success recorded. However, there is evidence also of mass mortalities of species occupying natural rocky shorelines, particularly in response to temperature changes (Harley, 2008; Lathlean and Minchinton, 2012). Manipulative experiments have helped define thermal effect temperatures (acute and chronic) (Stirling, 1982; Sun et al., 2022), which has increased our understanding of the thermoregulatory capacities of intertidal rocky shore species (Waltham and Sheaves, 2020). While the focus of previous studies has been on mobile intertidal species (Marshall et al., 2015; Stirling, 1982), in contrast the present study focuses on sessile encrusting taxa. The current data provides a base for future research such as installing shade structures on seawalls to reduce the peak daytime solarradiance intensity (sun protection). Another option is to position boulders when constructing seawalls in a fashion that limits surface areas that are upward facing. Overall, for seawalls to be nature-based positive solutions, slight engineering improvements to the design of seawalls that are more aligned with species requirements and tolerances are recommended. Eco-engineering seawall that maximises biodiversity outcomes could assist countries, including Australia, to reach obligation targets in the Kunming-Montreal Global Biodiversity Framework (Obura et al., 2023).

CRediT authorship contribution statement

Nathan J. Waltham: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marcus Sheaves:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Nathan Waltham reports financial support was provided by James Cook University. Nathan Waltham reports a relationship with North Queensland Bulk Ports that includes: funding grants. Nathan Waltham has patent pending to Nil. Nil If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data generated in this research project can be made available upon request directly to the corresponding author.

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