



Research article

Major global ports alter light regimes for marine biofouling communities



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A B S T R A C T

Globally, there are more than 17,000 cargo-handling ports that are expected to double in capacity by 2030. Overwater structures are common in ports and create permanently shaded environments that can produce ecological shifts from primary-producer to consumer dominated communities. Yet, the extent of these structures across ports and their impact on light conditions and associated communities in different areas beneath has not been quantified. Here we quantified the spatial extent of overwater structures in 17 major global ports and found a total estimated area of >13.96 km² of seabed to be shaded. We then surveyed *in situ* overwater structures in Sydney Harbour, Australia, to directly measure the impacts of these structures on light intensity and marine communities. We show that overwater structures can reduce light levels between 37 and 83% and shift ecological communities from mixed algal-invertebrate communities towards invertebrate dominance. This study provides critical evidence of the impacts of port structures on natural light regimes and ecological communities, and highlights the need for sustainable solutions (e.g. light penetrating surfaces, artificial light) to restore natural light regimes to global ports to maintain algal communities and associated ecosystem services in areas that are shaded by overwater structures.

1. Introduction

Marine construction is growing at an alarming rate with 1.0–3.4 million km² of seascape already modified by built structures (Bugnot et al., 2021) and 50–76% global increase in coastal infrastructure forecast by 2043 (Floerl et al., 2021). Ports currently represent a major contributor of marine built structures (~14%, Bugnot et al., 2021) and the construction and operation of ports is associated with changes in the biophysical environment, including changes in natural light regimes, hydrodynamic and sediment transport processes, contamination, and noise pollution (Franzen et al., 2021; Ban et al., 2010; Yu et al., 2017; Munsch et al., 2017), which can impact associated ecological communities. In line with increasing populations and demands for international goods, port capacity is predicted to double by 2030 (Bugnot et al., 2021), with potential severe future ecological consequences.

Overwater structures such as wharves, jetties and pontoons comprise a major proportion of marine infrastructure in urban marine

environments (Floerl et al., 2021) and create conditions of unnatural light regimes. They reduce the incidence and intensity of light reaching the marine habitat beneath, in some cases permanently (Blockley, 2007; Ono and Simenstad, 2014; Glasby, 1999) (Fig. 1). The reduction in light intensity varies with position under the structure (i.e., edge versus center), and with the size and height of the structure above water and aspect towards the sun (Nightingale and Simenstad, 2001). For example, structures that cover large areas and sit close to the water surface (e.g., pontoons or wharves) create particularly low light conditions, which can impact associated communities and the ecosystem services they underpin.

Shading can lead to profound shifts in community structure, reducing the abundance of macrophytes while promoting an invertebrate-dominated community (Miller and Etter, 2008; Thorson, 1964). This is related to recruitment preferences of larvae and competitive advantage of invertebrates compared to algae, as they do not require light for survival and growth (Miller and Etter, 2008;

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Thorson, 1964). These shifts in community structure can cause changes in nutrient cycling and reduce carbon sequestration and primary productivity (Kiibler and Raven, 1994; Gordon et al., 1994; Collier et al., 2012; Malerba et al., 2019). Additionally, macrophytes impact local water circulation by trapping sediments and attenuating currents (De Boer, 2007; Eckman et al., 1989; Wernberg et al., 2005). Shading by infrastructure is likely therefore to reduce the abundance of macrophytes, freeing space for non-native colonists, many of which are sessile invertebrates (Williamson and Griffiths, 1996). This is particularly important in port areas, where overwater structures are in close proximity to NIS arriving on transport vectors (Johnston et al., 2017; Hulme, 2021). This may be further exacerbated by limiting the capacity of visual predators - reducing their predation success-in shaded conditions (Duffy-Anderson and Able, 2001; Munsch et al., 2014, 2017) that can increase biotic resistance through top-down control (Freestone et al., 2013). Once established in the port, invaders have the potential to then spread further via natural dispersal or local translocation (Airoldi et al., 2015; Hilliam et al., 2024) where they can have devastating impacts on native communities (Bax et al., 2003).

Despite the potential negative impacts of shading and the substantial and growing marine infrastructure associated with commercial ports globally (Bugnot et al., 2021; Floerl et al., 2021), there is limited knowledge about whether overwater structures cover extensive areas of seabed within ports, and how light regimes and thus communities are impacted across different parts of the structures. Understanding the current extent and impacts can provide the critical evidence necessary to support the need for change and to develop informed strategies to reverse, mitigate or minimise impacts when port infrastructure is rebuild, retrofitted, or newly constructed.

Here we quantified the spatial extent of overwater structures in 17 major coastal ports worldwide and, using publicly accessible overwater structures in Sydney Harbour, Australia conducted a case study to determine their impacts on light regimes and marine biofouling communities on pylons. We hypothesised that light reduction by overwater structures would increase with distance under the structure, and that this light reduction would impact the structure of biofouling communities growing on pylons, shifting them from algae-to invertebrate-dominated. Together these two study components are a first step in

evaluating the extent and magnitude of ecological impacts of port infrastructure on biofouling communities, and in identifying design modifications to infrastructure that may lessen ecological impacts. Based on the results of this study, we discuss the barriers and opportunities for implementation of sustainable designs that mitigate shading by overwater structures.

2. Methods

2.1. Spatial extent of overwater structures in major global ports

To estimate the extent of overwater infrastructure present within major global ports, we conducted a desktop-based survey of overwater structures for the 20 largest ports (based on throughput) in the world. The consideration of 20 ports was intended to enable consideration of port infrastructure across a range of jurisdictions and geographies, and provide an estimate of the potential area of impact at the most disturbed locations. The 20 largest ports were identified using Lloyds List of 100 container ports 2023 (Lloyds List, 2024), and were situated in Asia (14), Europe (2), in USA (3) and Middle East (1) (Table 1).

Port websites were used to delineate the total extent of each of the ports and their facilities. When port websites provided insufficient detail, online imagery GoogleEarth® was assessed and infrastructure that supported commercial ships within the port region was used. When sufficient detail was provided, only infrastructure specifically named on the port website was included. The area of overwater structures within the bounds of each port was then measured in GoogleEarth® up to the visible shoreline. While GoogleEarth® may allow relatively coarse level estimates of distances and area compared to satellite imagery, it was used because images of comparable quality were freely available for all locations. Overwater structures (as determined by GoogleEarth® and image searches of infrastructure/port areas) included major platforms as well as associated structures (e.g., access ramps, pipes, pontoons, dolphin pylons) with the potential to shade the underlying marine waters and ecosystem. When the width of an overwater structure could not be determined visually by a shoreline, differences in pavement surface colour, pavement markings as well as railings for cranes were used for guidance. This may have resulted in slightly inflated estimates of



Fig. 1. Conceptual diagram of shading of underlying habitats by port infrastructure. The amount of shading influences the marine community development and composition.

Table 1

Estimated spatial extent (km²) of overwater structures within the 20 biggest container ports in 2023 identified by Lloyds (Lloyds List, 2024). Structures included for each port, assumptions and notes can be found in the supplementary file "Port Infrastructure". N/A depicts ports that were excluded due to insufficient port infrastructure information and/or imagery.

Rank	Port	Country	Estimated spatial extent (km ²)
1	Port of Shanghai	China	3.44
2	Port of Singapore	Singapore	1.29
3	Port of Ningbo-Zhoushan	China	2.79
4	Port of Shenzhen	China	0.72
5	Port of Qingdao	China	0.21
6	Port of Guangzhou	China	N/A
7	Port of Busan	South Korea	N/A
8	Port of Tianjin	China	2.11
9	Port of Hong Kong	China	0.33
10	Port of Rotterdam	Netherlands	0.22
11	Jebel Ali	United Arab Emirates	0
12	Port of Antwerp	Belgium	0.10
13	Port of Port Klang	Malaysia	0.87
14	Port of Xiamen	China	0.05
15	Tanjung Pelepas	Malaysia	0.36
16	Port of Los Angeles	USA	0.47
17	Port of New York/New Jersey	USA	0.42
18	Port of Kaohsiung	Taiwan	N/A
19	Port of Long Beach	USA	0.31
20	Laem Chabang	Thailand	0.29

overwater structures in some cases. Structures built past the shoreline (e.g. jetties, terminals) were assumed to be fixed or floating overwater structures. Three ports had to be excluded due to insufficient port infrastructure information and/or imagery. A list of structures included for each of the 17 ports is provided in the Supplementary Table ('Port Infrastructure').

2.2. Light regimes and ecological communities

A case study was conducted in Sydney Harbour, New South Wales, Australia (33.8462° S, 151.2489° E) to estimate the magnitude of subtidal shading caused by overwater structures, and the resulting impacts on ecological biofouling communities. Sydney Harbour was once the focal site of Sydney's commercial shipping industry and although operations have now largely been relocated to Port Botany, overwater structures persist, covering an area of 0.04 km² (Port Authority NSW, 2024). These legacy structures, though not presently part of an active port, are of similar construction, shoreline orientation and within the size range of overwater structures identified from our survey of major global ports, and can therefore be viewed as representative of their shading impacts. Whereas the stringent health and safety regulations necessitated by vessel and cargo operations in active ports limit the type of in-water survey work that can be done, access and permits for sampling (e.g., landowner consent and health and safety) Sydney Harbour legacy structures could be readily attained enabling relevant measurements to be taken. The case study spanned 10 sites, each of which comprised an overwater structure of comparable size and shoreline orientation to those in the global ports, distributed across 5 locations in Sydney Harbour (Fig. 2). Orientation and ecological data were obtained for all nine sites, while light conditions were assessed at six (Fig. 2).

The construction material and cardinal direction (16 cardinal points) of each structure was recorded because of its potential influence on ecological communities and light availability, respectively (see Table S1 for a more detailed description of the infrastructure sampled). Though no turbidity data at the site were taken at the time of the experiment (Jul–Aug 2022), monthly monitoring of waters situated in the middle of the harbour between Balmain and Waverton from Dec-2021 to Dec-2023 showed that turbidity never exceeded 1.7 NTU (NSW DCCEEW, 2023).

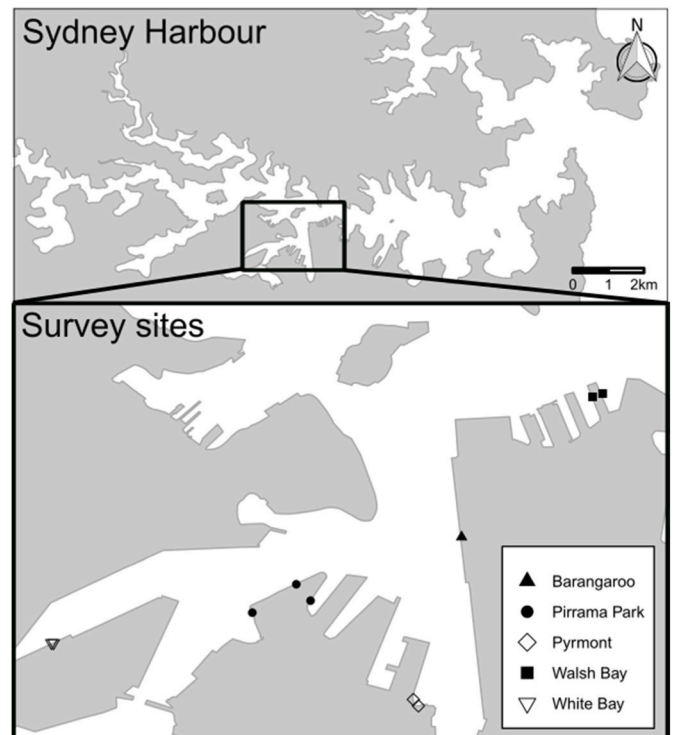


Fig. 2. Map of Sydney Harbour showing the location of the nine sites surveyed. Different shapes denote locations in which sites were grouped for statistical analyses due to spatial proximity to one another. Filled shapes denote sites which were used for both ecological and light assessments, whereas open shapes were used for ecological assessments only.

Although water depth generally decreased from the edge (~5–11 m) to the back (~2–5 m, ~10 m at one site) of the overwater structures, which could influence turbidity, there is likely no significant difference in turbidity due to the short distance between the pylons and limited boat activity and associated sediment disturbance at each site (Table S1).

To characterise light intensity (lux), and its sources of spatial variation, beneath the overwater structures, Hobo® light loggers (MX2202, Onset) were deployed on pylons beneath overwater structures at six sites spanning three locations (Pirrama Park – 3 sites, Barangaroo – 1 site, Walsh Bay – 2 sites). Loggers were attached to pylons using cable ties at a water depth of ~2 m (below mean low water). This depth was chosen for study because light intensity rapidly attenuates with water depth, such that impacts of overwater structures on light were expected to be greatest in surface waters. To assess variation in light levels with orientation and distance under structures, a total of six loggers were deployed per site – one each on the seaward (front, lit) and landward (back, shaded) side of a single randomly selected pylon of the seaward most 'row' of pylons under the structure and the next two rows moving progressively further under the structure (positions = edge, middle, back; Figs. S1 and S2, Table S1). The front (lit) surfaces of pylons in the edge row were generally unshaded and were considered a baseline against which spatial comparisons could be made. For light (as well as biota) surveys, pylons along the edges of structures were avoided to ensure pylons would only be lit from one direction. Light loggers (logging interval: 15 min) were deployed simultaneously at all sites within a location for at least 5 days during the Austral Winter (between 25 Jul and Aug 16, 2022; Table S2). The order of locations was chosen randomly.

Ecological communities growing subtidally (2 m depth below mean sea level) on the overwater structures were surveyed at all nine sites (Fig. 2) using SCUBA in the Austral Winter between Jul 20, 2022 and Aug 16, 2022 (Table S2). The seaward and landward side of four

randomly selected pylons from sequential 'rows' (position: edge, middle, back) were sampled using a 15×15 cm (225 cm^2) quadrat with an evenly spaced grid of 25 intersections (Fig. S3). The seaward side of the pylons on the edge of the infrastructure was assumed to be closer to natural light levels than those covered by the overwater structure. The organism under each intersection was identified to a coarse taxonomic level (a combination of taxonomic group and morphology), as the focus was on differences in community composition that were related to functional groups (invertebrates versus algae) rather than species identity (Table S3). Due to the difficulty of identifying some filaments covered in sediment *in situ*, these taxa were combined and referred to as 'filament-sediment matrix', which may have included cryptic organisms (e.g., hydroids). When primary and secondary cover were present, only the secondary cover was noted (unless it was 'filament-sediment matrix') as these would be mainly affected by differences in light regimes.

2.3. Statistical analyses

We employed mixed models due to the presence of both fixed and random factors. Linear models were applied for continuous data that followed a normal distribution, while generalized linear mixed models were utilized to accommodate the binomial distribution. All analyses were done using R (version 4.1.0). Analyses were performed separately for the seaward (front) and landward (back) side of pylons due to spatial non-independence.

To investigate how light varied with distance underneath the overwater structure (i.e., position on the edge, middle, back), we used linear mixed models using the R packages 'lme4' (Bates et al., 2007). Maximum light intensity per day (i.e. one measure per day (excluding deployment days)) was used as a response variable. Residual and qqplots were used to check the homoscedasticity and normality assumptions of the data using the R package 'DHARMA' (Hartig and Hartig, 2017). Light values were log-transformed to improve residual plots and a gaussian distribution was used. Due to differences in the duration of deployment, only 3 days in the middle of each deployment were used per site. Due to flooding of two loggers, no data were available for the seaward side of the edge pylon for the site 'Pirrama Park 1' and landward side of the back pylon for the site 'Pirrama Park 3'. The models included the fixed categorical factor position (edge, middle, back), whereas location, site (nested in location) and day were included as random categorical factors to account for temporal autocorrelation. Cardinal direction was included as a covariate.

To investigate how cover of algae and sessile invertebrates varied with distance underneath the overwater structure (i.e., position on the edge, middle, back), we used generalized linear mixed models (biota) in the R package 'glmmTMB' (Magnusson et al., 2017). A binomial distribution was assumed in all analyses. Separate analyses were performed for algae and sessile invertebrates (live and dead) and excluded the 'filament-sediment matrix', due to the lack of formal identification. The models included the fixed categorical factor position (edge, middle, back). Location and site (nested in location) were included as random categorical factors to account for potential spatial autocorrelation of pylons coming from the same site and for sites within the same location. Cardinal direction as a proxy for duration of sun exposure was included as a covariate and represented as a continuous variable from 0 to 1, indicating the direction and thus duration of sun exposure experienced at the edge of overwater structures at each site, where 1 represents structures facing directly north, i.e., longest exposure to the sun, and 0 represents structures facing directly south, i.e., shortest exposure to the sun. Values for directions/duration of sun exposure between north and south (i.e., north east = 0.75) were extrapolated accordingly. As such, there was no distinction between west- and east-facing sites. To account for differences in pylon material, material type (timber, HDPE, concrete, steel) was included as a covariate as well. An individual effect size identifier (unique per data row) was used as a random factor to improve residual plots.

P-values were obtained using the Anova function in the R package 'car' (Fox et al., 2012). Pairwise comparisons between positions (edge, middle, back) were performed using the R package 'emmeans' (Lenth and Lenth, 2018).

3. Results

3.1. Spatial extent of overwater infrastructure in major global ports

Overwater structures across 17 of the world's 20 largest ports covered a total of 13.96 km^2 of seafloor (Table 1, "Port Infrastructure", Supplementary Material 7.1). Four ports (Shanghai, Singapore, Ningbo-Zhoushan, Tianjin) supported $>1.2 \text{ km}^2$ of overwater structures each, and 11 ports supported at least 0.1 km^2 of overwater structures each. The Port of Jebel Ali in Dubai was the only port that had no overwater structures, with revetment walls instead. Three of the world's 20 largest ports (Guangzhou, Busan and Kaohsiung) were excluded from mapping due to insufficient information and/or publicly available imagery.

3.2. Light regimes and ecological communities associated with overwater structures

3.2.1. Light

Light intensity beneath the overwater structures in Sydney Harbour was highest on pylons on the edge of overwater structures and decreased with distance under the structure (pylons in the middle and back) on both the seaward and landward sides of the pylons (Fig. 3, Fig. S4). Light intensity was most variable on the seaward side of pylons along the edge ($2164\text{--}13,399 \text{ lux}$) and in the middle ($547\text{--}6571 \text{ lux}$) of the structure and was considerably lower and least variable on pylons positioned at the back ($91\text{--}1881 \text{ lux}$). On the landward side of the pylons, regardless of position (edge, middle, back), light intensity was comparable to that of the seaward side in pylons located at the back and remained consistently below 2659 lux .

Maximum light intensity varied significantly among pylon positions (Table S4). On the well-lit seaward side, light intensity was reduced by 37% and 83% between pylons on the edge and those in the middle and back, respectively (Fig. S4). For the landward side of the pylons, light intensity reduced by 84% and 92% between pylons on the edge and those in the middle and back, respectively (Fig. S4).

3.2.2. Biota

Overall, communities on the seaward side of pylons were a mix of algae (mainly brown branching and brown and red turfing and filamentous algae) and invertebrates (largely comprising of barnacles, colonial ascidians, encrusting bryozoans, and hydroids), whereas those on the landward side consisted almost exclusively of invertebrates (Fig. 4, Fig. S5). Brown turfing algae were only detected on the landward side of pylons at a single site (Pymont 1) (Fig. S5). There was also a trend of increased cover of the filament-sediment matrix with increasing distance from the edge (Fig. 4).

On the well-lit, seaward side of edge pylons, algae occupied 57% and invertebrates occupied 30% of space, with the remaining space covered by a 'filament-sediment matrix' (Fig. 4, Fig. S6). Under overwater structures, algal cover was significantly lower on pylons in the middle (22%) and back (1%), while sessile invertebrate cover significantly increased and approximately doubled (middle: 57%; back: 61%) (Table S5, Fig. S6). On the landward side of pylons, invertebrates occupied most of the space across all pylons ($>80\%$) and no difference in cover was found between positions, whereas algae were almost completely absent (Table S5, Fig. S6).

4. Discussion

Port construction is growing at an increasing rate in response to global shipping demands and to accommodate the large infrastructure

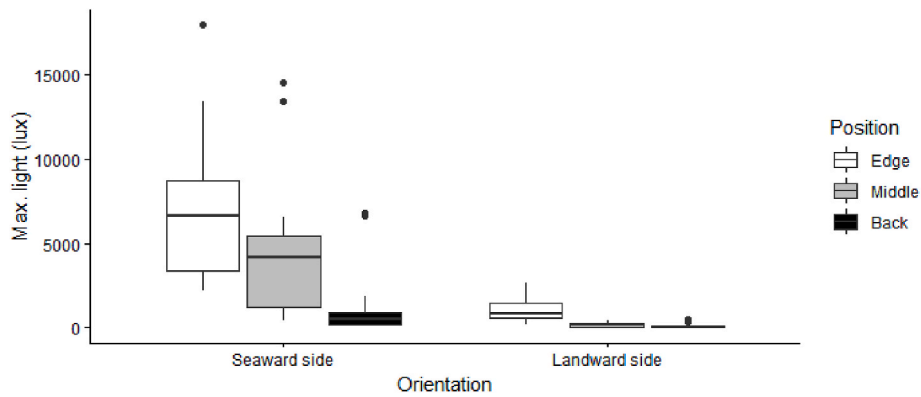


Fig. 3. Maximum light intensity (lux) on the seaward and landward side of pylons positioned on the edge, middle, and back of the overwater structure. Boxplots showing the minimum score, first (lower) quartile, median, third (upper) quartile, and maximum score.

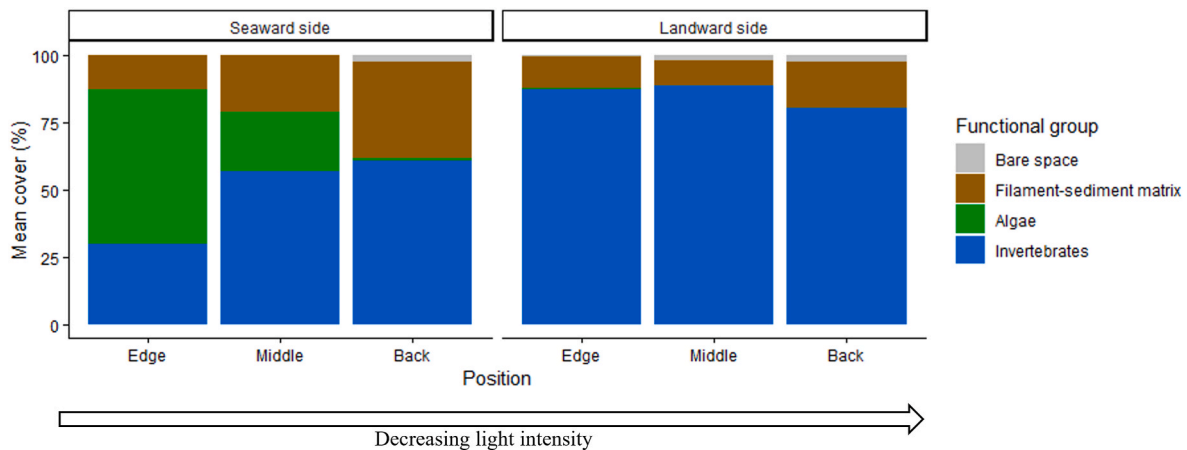


Fig. 4. Mean cover of bare space, algae, invertebrates and ‘filament-sediment matrix’ on the front (lit side) and back (shaded side) of pylons per position, averaged across all sites. Positions are arranged in order of decreasing light intensity.

required in support of the growing blue economy (Bugnot et al., 2021; Jouffray et al., 2020). Activities during construction and subsequent operation can alter environmental conditions such as light availability (Sornn-Friese et al., 2021) and have impacts on the ecological communities associated with port structures (Dafforn et al., 2015; Glasby, 1999). Overwater structures of 17 of the world’s largest ports shade an estimated 13.96 km² and *in situ* surveys of similar structures revealed that those can reduce light by up to 83% compared to unshaded conditions. *In situ* biota assessments showed that the reduction in light intensity corresponds to decreased algal cover (57%–1%) and increased invertebrate cover (30%–61%) on pylons that support these structures. Our results show that overwater structures can have significant impacts on the communities inhabiting artificial structures beneath. Given projected increases in port developments and the potential consequences to ecosystem service provision strategies to sustainably manage the impacts of shading from built structures are urgently needed.

There are at least 17,000 cargo-handling ports globally (Sornn-Friese et al., 2021), and new ports and port expansions are planned in many parts of the world. The extent of overwater structures varied among ports, but was generally >0.2 km²/port (14/17 ports assessed). In many cases, this was likely an underestimate, as not all overwater structures were visible on publicly imagery from Google Earth and used for large commercial trade were listed on port websites (personal observation). Use of higher-resolution satellite imagery would enhance the precision of these identifications. Additionally, the impact of shading by overwater structures within ports is extended by large vessels moored alongside, which has not been accounted for here. Therefore, overwater

structures can be viewed as a major contributor to the modification of marine habitats. There were, however, also ports with little or no overwater structures, such as the port of Jebel Ali in Dubai, as the port infrastructure is solely based on revetment walls rather than overwater structures. While this reduces extent of shaded marine environment, the reclamation of land during port construction destroys natural habitat, which can also have a multitude of negative impacts on surrounding communities (Subraealu et al., 2022).

Our field surveys found that light intensity was drastically reduced on pylons underneath overwater structures compared to unshaded pylons on the seaward edge of the structures, which is in line with results from other studies that looked at the impact of overwater structures (Blockley, 2007; Glasby, 1999). There were distinct differences in the light intensity between seaward (lit) and landward (shaded) side of pylons, reducing light intensity by ~90%, even on pylons closest to the edge of overwater structures. Similarly, light intensities decreased on the seaward (lit) side of pylons by ~90% over ~5m distance from the edge. The differences in light intensity were reflected in the communities inhabiting the pylons, with well-lit pylons on the seaward edges of structures supporting higher abundances of algae than pylons in shaded conditions (underneath the overwater structure), the latter of which were dominated by sessile marine invertebrates. With one exception (Pyrmont 1), no algae were found on the shaded side of pylons. This change is associated with favourable environmental conditions for sessile invertebrates in shaded areas, and has also been documented in other studies that assessed impacts of overwater structures (Blockley and Chapman, 2006; Dafforn et al., 2012; Glasby, 1999). Reduced algal

cover under shaded conditions is related to reduced photosynthesis and survival with decreasing light conditions (Miller and Etter, 2008; Daforn et al., 2012; Levring, 1966), which reduces overall primary productivity. In contrast, invertebrates that do not have such light requirements take advantage of reduced competition for space with algae, displaying greater abundance in shaded areas (Miller and Etter, 2008). The exception at one of the surveyed sites (Pymont) may be related to the north-facing direction of the structure, which could have led to the back of the pylons getting some light from the side in the mornings and afternoons. The turfing algae found at this site require less light than macroalgae, which has likely allowed them to grow despite the lower light conditions (Markager and Sand-Jensen, 1992). These results show that, depending on the types of communities present under natural light conditions, overwater structures can significantly impact local communities.

In environments that would naturally support autotrophs, the introduction of shade can have a multitude of negative consequences. Loss of seaweeds and seagrass - important habitats and food source for epifauna (Larkum et al., 2006; Tano et al., 2016) - may potentially cascade to impact higher trophic levels (Newcombe and Taylor, 2010). A reduction of natural light intensities may also aid in the establishment of invasive species, as pest marine invertebrate species comprise the majority of NIS globally (Williamson and Griffiths, 1996). This is a particular concern for ports, as they are entry points for non-indigenous species (NIS) introductions through ballast water and hull fouling, (Molnar et al., 2008). Their large area of artificial structures provides a substrate for colonisation of NIS, that can serve as stepping stones for spread of non-indigenous species (NIS) (Airoidi et al., 2015; Glasby et al., 2007). These impacts of ports may be exacerbated by their highly urbanised setting, in which other sources of physical and chemical disturbance (i.e. contamination, sedimentation) are also acting to decrease the abundance and diversity of native species, and facilitate environmentally tolerant, opportunistic NIS (Johnston et al., 2017). Additionally, reduced fish predation under overwater structures (Bolton et al., 2017; Munsch et al., 2014) may reduce top-down control of invasive species (Freestone et al., 2013), which are often poorly chemically and morphologically defended. Regular cleaning of artificial structures for maintenance/inspection of port infrastructure further frees up space that is free of competitors, which is an essential resource for invaders for successful establishment (Shea and Chesson, 2002). However, the surveys conducted in Sydney Harbour showed that even fully lit structures provide suitable substrates for both native and non-indigenous invertebrates, so that light increase underneath overwater structures would not eliminate the risk of colonisation by invertebrates (both native and invasive).

Overall, turbidity within the sampling region in Sydney Harbour was low, which does not reflect conditions in all ports. Water clarity is influenced by tidal oscillations, which is related to the tidal resuspensions of materials, and as such, regions with tide-dominated estuaries and deltas are naturally turbid, whereas wave-dominated areas along the coast are less turbid (Harris and Heap, 2003; Heap et al., 2001). Additionally, areas with significant riverine input are more prone to high turbidity (i.e., low water clarity) (Harris and Heap, 2003; Heap et al., 2001). In port environments, turbidity levels are generally high due to their location (e.g. estuarine or riverine environments) and constant vessel movements and dredging (Soczka Mandac et al., 2023). Therefore, impacts of overwater structures on biofouling communities are likely to be reduced or non-existent in areas where high turbidity naturally prevents light penetration into the water and macrophytes are in low abundance.

4.1. Implications for port management

Globally, the number and extent of ports is increasing, and with it the introduction of overwater structures to marine environments. For ports to be more sustainably developed and managed, it is essential to

consider the resident ecological communities, and the potential ecological impacts of the structures and operations associated with ports as early as possible to minimise impacts. Though impacts on marine communities are likely inevitable, direct impacts from overwater structures can be mitigated through smart and innovative designs that minimise shading impacts (Fig. 5).

To increase natural light penetration into the water, and minimise shading effects of overwater structures, turbidity should be reduced by increasing settlement of filter-feeders, through mechanical filtration or by reducing urban-run off. In areas where growth of native macroalgae and seagrass is desired, and the risk of non-indigenous algal proliferation is low, overwater structures could be constructed to include light transmissive and light reflective surfaces, or artificial light, to increase the value of under-pier habitat for fish and to promote growth of algae and seagrass (Blanton et al., 2002; Ono and Simenstad, 2014; Cordell et al., 2017; Munsch et al., 2017). However, light transmissive grids should only be used in areas where there is no potential for pollution of the water column from fallout of different types of cargo. Where practical, for example in areas with low tidal amplitude, deck heights of wharves and jetties should be raised and narrowed to increase light levels underneath. In areas where non-indigenous species are of concern, reducing settlement surfaces through appropriate engineering designs (e.g., lower number of pylons, cantilevers) should be considered. Similarly, seeding substrates with native organisms could be considered, though this approach may not be feasible on very large scales.

The opportunities to reduce the ecological impact of overwater structures need to be carefully balanced against operational, engineering and maintenance constraints and requirements that may limit the use of specific solutions (e.g., light reflective surfaces in areas of moored ships) (Fig. 5). Additionally, engineering opportunities need to be responsive to local environmental conditions. For example, besides overwater structures, local water depth and turbidity affect the depth to which natural light levels can reach biotic communities such that light-wells are ineffective at turbid sites, or in enhancing light penetration to deeper communities which were not examined in the present study. Artificial light could be used at locations where water depths exceed natural light penetration depths, though the maintenance requirements and durability of engineered designs and materials in saltwater and under biofouling pressure need to be considered. To ensure uptake of eco-engineering solutions, cost-analyses for the different technologies and engineering solutions compared to traditional designs and life cycle analyses for these solutions are essential and should be the next step in moving forward once larger scale testing has been completed.

The effects of shading by overwater structures on marine communities within ports can be compounded by other changes in the abiotic environment associated with port infrastructure and operations, such as changes in hydrodynamics, sedimentation and turbidity, and noise caused by vessel movement, dredging and built artificial structures, and artificial light pollution at night (Franzen et al., 2021; Erfteimeijer and Lewis III, 2006; Soczka Mandac et al., 2023; Ban et al., 2010; Davies et al., 2014). Therefore, a multifaceted, holistic approach in marine spatial planning of new ports and port expansions and mitigation strategies through ecological engineering solutions that create multifunctional designs should be considered so that negative impacts can be minimised (Dafforn et al., 2015; Taljaard et al., 2021).

5. Conclusions

This study highlights that overwater structures, such as wharves, piers can cover vast expanses of water within commercial ports worldwide. The presence of these structures can alter the light conditions beneath the water's surface, which in turn affects the growth and composition of biofouling organisms. In areas with low turbidity, where sunlight penetration is more pronounced, the introduction of overwater structures can create significant changes in the environmental conditions, potentially leading to the disruption of existing ecosystems and

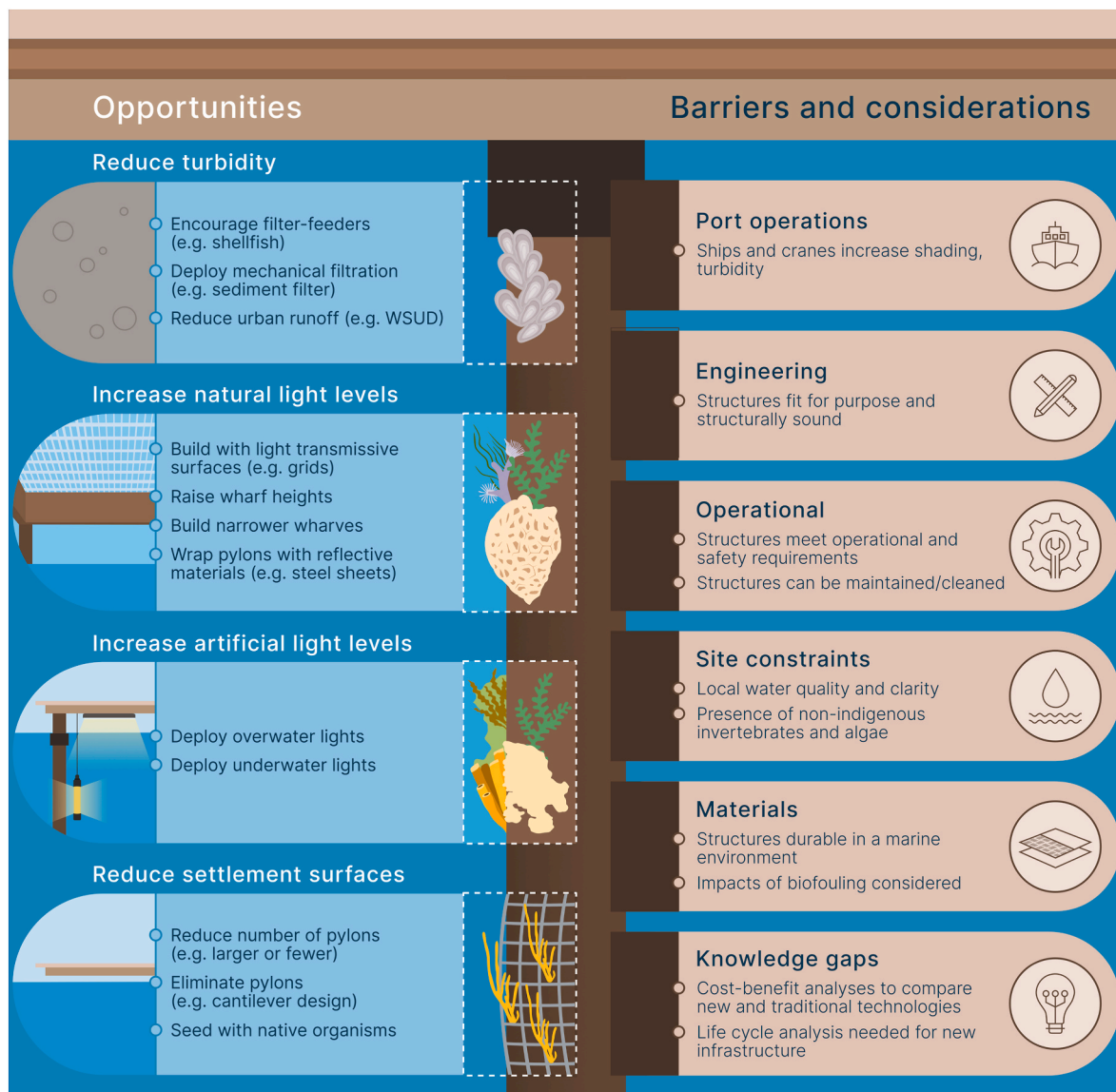


Fig. 5. Opportunities and barriers to reduce settlement space for non-indigenous species (NIS) and reduce shading by overwater structures.

services. However, there are sustainable solutions available to reduce the negative impacts of shading caused by these structures (e.g. light penetrating surfaces, artificial light) which should be incorporated into the design and construction of overwater structures to minimise impacts.

CRediT authorship contribution statement

Nina Schaefer: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Melanie J. Bishop:** Writing – review & editing, Methodology, Conceptualization. **Brett Herbert:** Writing – review & editing, Methodology, Conceptualization. **Andrew S. Hoey:** Writing – review & editing, Methodology, Conceptualization. **Mariana Mayer-Pinto:** Writing – review & editing, Methodology, Conceptualization. **Craig D. H. Sherman:** Writing – review & editing, Methodology, Conceptualization. **Cian Foster-Thorpe:** Writing – review & editing, Methodology, Conceptualization. **Maria L. Vozzo:** Writing – review & editing, Methodology, Conceptualization. **Katherine A. Dafforn:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2025.124119>.

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Data availability

Data can be viewed in the GitHub repository: <https://github.com/NinaSchaefer/Major-global-ports-alter-light-regimes-for-marine-benthic-communities.git>.

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