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# Biodeterioration and bioprotection of concrete assets in the coastal environment

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ABSTRACT

The deleterious effects (biodeterioration) and the protective benefits (bioprotection) of biological colonisation on manmade structures have long been debated. Lichens, biofilms, algae, bivalves and gastropods contribute both directly and indirectly to damaging substrata in the coastal zone which can enhance abiotic erosive forces that exploit biologically induced superficial damage. There is mounting evidence that these same species may also provide protective benefits. This debate often impacts approaches to managing fouling on concrete assets in the coastal environment. The net benefit or detriment a species or assemblage has on a structure is spatially and temporally dynamic and subject to the influence of various abiotic and biotic factors at different scales. However, the net outcome may be more pronounced under different contexts, particularly under warming and ocean acidifying climate change scenarios which is where further research should focus. Additionally, as bioprotection represents a potentially valuable ecosystem service, it supports the argument for increasing and improving habitat availability and biodiversity on artificial coastal structures via ecological enhancement. Quantifying bioprotection in useful metrics, such as monetary value or time added to serviceable life, would help demonstrate the benefits of bioprotective species in a meaningful way.

Outline:

## 1. Introduction

The two-way interactions between ecology and geomorphology are intimately linked, with biogeomorphic mechanisms known to be key drivers of change in multiple ecosystems and landscapes (Viles 1988a; Corenblit et al., 2011; Fei et al., 2014; Hu et al., 2022). A concept introduced in the 1980s (Trudgill and Crabtree 1987; Trudgill 1988; Viles 1988b; Viles 1988b, 1988b), the discipline of biogeomorphology has accelerated in scope in the intervening years and today it is a burgeoning interdisciplinary field that integrates geomorphology, ecology, evolutionary biology, palaeogeomorphology and ecology, and materials science (Corenblit et al., 2011; Viles 2020). The concepts of 'biodeterioration' and 'bioprotection' have undergone much development since the turn of the millennia (Naylor et al., 2002; Carter and Viles 2005; Naylor 2005; Fei et al., 2014), with more work focussing on the impact of biological colonisation on artificial structures and how biogeomorphic mechanisms impact vulnerable assets such as heritage buildings (Viles et al., 2014; Gadd and Dyer 2017; Favero-Longo and Viles 2020; Baxter et al., 2022a) and artificial coastal structures (Scott et al., 1988; Jayakumar and Saravanane 2009, 2010; Baxter et al. 2022b).

The biological colonisation of artificial coastal structures is subject to a conflict depending on the perspective. Either biological colonisation is to be discouraged and avoided (biofouling) to prevent deleterious effects on the concrete substrate (biodeterioration, bioerosion, biocorrosion etc.) (Lebret et al., 2009; Hughes et al. 2013a, 2013b), or it is to be facilitated to mitigate and/or compensate for habitat loss or create biodiversity gain and the ecosystem services associated with potential protective effects (bioprotection). Often, the porosity and surface roughness that asset managers and engineers cite as the main drivers for biofouling and seek to ameliorate (Harilal et al., 2020), eco-engineers and ecologists wish to enhance to promote biological colonisation (Guillitte, 1995; Coombes et al., 2015).

Much research has focussed on either discouraging or promoting biological colonisation of concrete structures but often does not consider the potential benefits of the other. Reduced porosity in concrete usually equates to denser and stronger concrete (Claisse et al., 2001; Neville 2011; Singh et al., 2018; Othman et al., 2021) which also makes it more

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challenging for biofilms and epibiota to colonise. Colonising biota are known to have potentially deleterious effects due to boring activity, the secretion of organic and inorganic acids, and penetration of attachment structures such as rhizomes and byssal threads (see Biodeteriorative Effects). When designing bioreceptive structures, greater porosity is recommended to promote colonisation of biofilms (Guillitte and Dreesen 1995; Morin et al., 2018) which facilitate successive organisms, such as macrophytes and invertebrates (Dubosc et al., 2001). Absent from much of the latter research is consideration for the biodeteriorative effects on concrete structures, how this may affect service life and thus the associated ongoing maintenance costs and labour. Subsequently, it is not yet fully accepted in industry how biological colonisation might offer protective benefits, such as moderating thermal and humidity regimes and wetting/drying cycles (Coombes et al., 2013, 2017), as well as buffering weather-induced stressors such as wind and wave action (Gowell et al., 2015).

The long-term goal of ecological engineering research is to incorporate artificial habitat features into coastal infrastructure from the design and planning stage, as opposed to the more commonly occurring retrofit, but first the concerns of asset owners must be addressed before acceptance and integration can occur on an industry-wide scale. The biodeteriorative and bioprotective effects of biological colonisation on intertidal hard substrates will be reviewed and the conflict will be addressed and discussed, with a focus on concrete materials. Finally, suggestions for further research will be made.

## 2. Scope of the paper

Online searches were performed using websites Web of Science and Google Scholar, using terms that would return relevant research and the references therein. 'Bioprotection' and 'biodeterioration' are synonymous with many other similar terms depending on the field of expertise and author perspective. These terms, where applicable, were searched in both UK and US English, hyphenated forms (i.e., 'bioprotection' and 'bio-protection') and different tenses (i.e., 'bioprotected', 'bioprotective'). The following terms were used in literature searches: biostabilisation, biological protection, biological stabilisation, bioconstruction, bioerosion, biological erosion, biodegradation, biological degradation, biogenic dissolution, biological decomposition. 'Biofouling' and 'fouling' are terms used to describe the undesired colonisation of built structures and were also used to search for literature on the impacts organisms have on hard coastal substrates. 'Biodeterioration' in this review is used as a proxy for an agglomeration of synonymic words including but not limited to: bioerosion, biodegradation, biogenic dissolution, biological decomposition/erosion and the processes and mechanisms associated with these terms (sensu Davidson et al., 2018) and includes active (direct removal of material) and passive (facilitation/acceleration of other weathering and erosive action) mechanisms (Naylor et al. 2002, 2012).

This review will focus on concrete structures in the intertidal zone but will draw on research into the biodeterioration and bioprotection of rock substrates (natural or heritage) in the broader field of biogeomorphology, and in terrestrial and freshwater environments to provide additional context where the equivalent research in a marine setting is lacking. It includes a mixture of lab-based and field-based experiments and observations from a range of academic peer-reviewed journals. 'Concrete' here refers to a composite material formed by mixing cement, both coarse and fine aggregate and water (British Standards Institute, 2013) and may contain further admixtures. 'Mortar' is similar to this but does not include coarse aggregate. Extrapolating impacts of biological colonisation on rock substrates to concrete should be interpreted cautiously. However, given that concrete often contains, in varying quantities and grades, rock aggregates, there can be a fair assumption that it may also be vulnerable to the same biodeteriorative forces, particularly in a chemically aggressive intertidal environment.

The coastal environments included in this review focus is the intertidal environment between Extreme Low-Water Springs and Extreme High-Water Springs but can include the splash zone i.e., the area above Extreme High Water Springs that may be wetted by salt spray (also known as the supralittoral zone). It includes coasts of varying aspect to sunshine and exposure to wave action. It also includes fully saline habitats, and estuaries where the salinity would be significantly reduced and highly variable, depending on volume of water discharge from the rivers. Most papers are from temperate environments, or where laboratory experiments have attempted to simulate temperate conditions, but a limited number of tropical examples also feature. Nearly all are conducted in field sites in the Northern Hemisphere, and predominantly in the North Atlantic (Fig. 1). Concrete in the marine environment is vulnerable to a wide variety of deteriorative forces which are well summarised in Santhanam and Otieno (2016), with concrete in the intertidal and splash zone often considered the worst exposure categories. The ingress of chloride ions from seawater salts leads to the corrosion of steel embedded within reinforced concrete, which can result in rapid surface deterioration through spalling, where a section of concrete delaminates from the substrate. The chemical attack from chloride and sulphates can alter the microstructure of the cementitious composites (Neville 2004), which can increase the risk of cracking and loss of strength. Chemical attack reduces the integrity of the concrete at its surface, increasing its vulnerability to salt weathering, where salt from the sea is deposited following a period of drying in intertidal conditions, causing expansive pressure and damage. Here we acknowledge that bioerosion and other physical and chemical forms of weathering often occur in tandem (Coombes 2014), particularly in the coastal environment where organisms may facilitate weathering and erosion through their activity or removal (Naylor et al. 2002, 2012), but these interacting mechanisms are not explored in depth and the focus remains on direct biological deterioration.

## 3. Biodeteriorative effects

Organisms can facilitate physico-chemical weathering and erosion but their impacts on hard substrates can also promote the colonisation or behaviour of other organisms, as explained by Coombes (2014), and the dominance of a given taxonomic group or morphology will depend on tidal height (Trudgill 1987; Simms 1990). For example, weakened substrate surfaces from boring organisms can enhance the removal of particulate material by grazers (Schneider and Torunski 1983). The implications for concrete intertidal infrastructure are dependent on the lithologies of the aggregates and the chemical composition of cement used.

### *3.1. Microorganisms*

Microorganisms, such as bacteria, fungi, micro-algae, and composite organisms, such as lichen, have bioerosive effects on both soft and hard rock and marine-grade concrete (Krumbein 1988; Morton and Surman 1994). These form 'biofilms', a mucilaginous matrix of extra-cellular polymeric substances (EPS) containing bacteria, protozoa, and diatoms (Wetherbee et al., 1998; Decho 2000). The metabolic activities of the organisms within this matrix play a role in the solubilisation of metal ions and the decomposition of substrate materials (Eckhardt 1985; Flemming 1993; Morton and Surman 1994; Cwalina 2008; Scheerer et al., 2009). Euendoliths (boring microorganisms) can be exceptionally abundant on limestone coastal rock, with up to half a million euendolithic filaments present in a single square centimetre (Schneider and Le Campion-Alsumard 1999). Biophysical weathering by biofilms can occur through the expansion and contraction of cells through wetting and drying cycles (Moses and Smith 1993; Gomez-Pujol et al., 2007) and the extension of hyphae (branching filaments) and growth into faults between rock crystals, and cement paste and aggregate. This leads to the creation of fissures and cracks, which are further weathered by mechanical erosion.

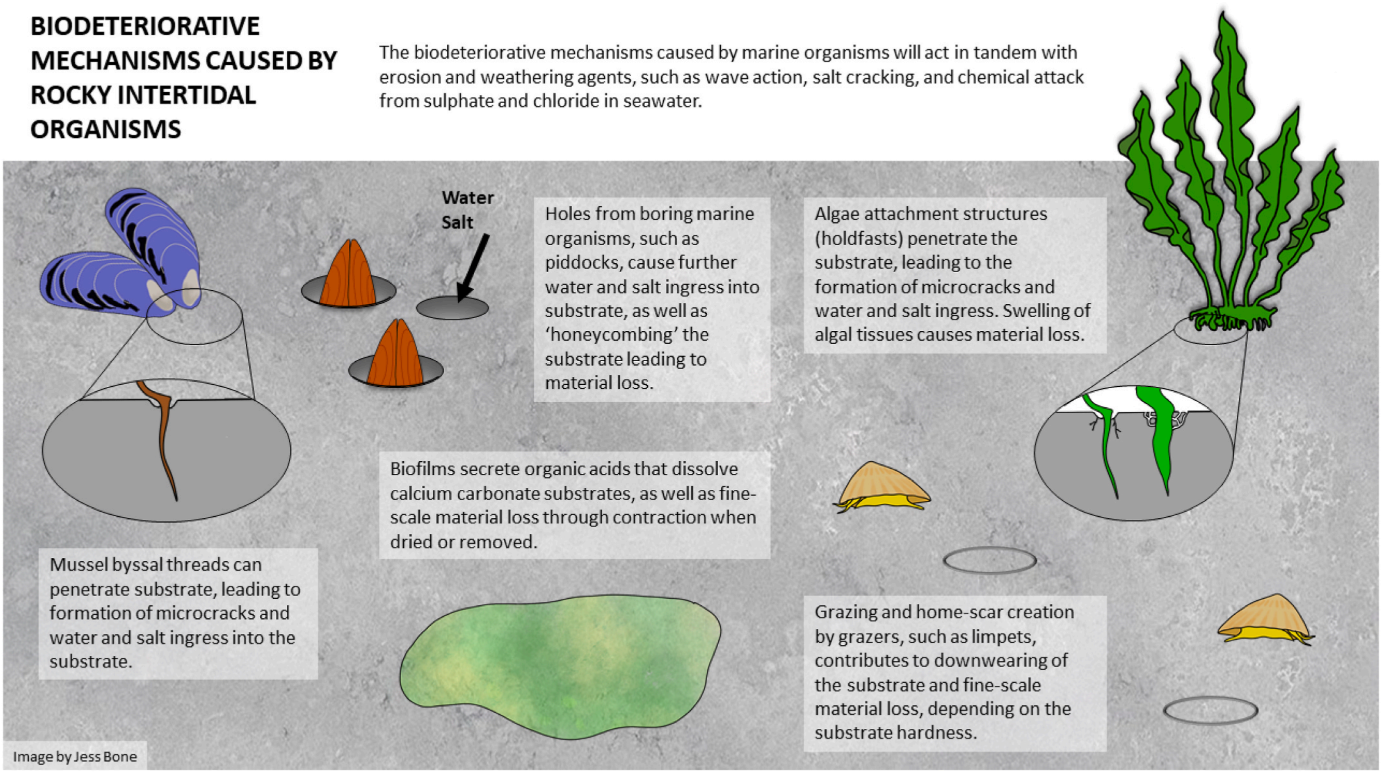


**Fig. 1.** The biodeteriorative action of rocky intertidal organisms. Note that while substrate is indicative of concrete, the magnitude of biodeteriorative action is dependent on the substrate material and spatiotemporal variations in population size of the organism. Not to scale. See also 'Shore Shapers' (Naylor et al., 2014).

Coombes et al. (2011) studied the biophysical erosion of Cornish granite, Portland limestone and marine-grade concrete deployed in the intertidal in Cornwall, UK. EPS growth was present on all materials, but the spatial pattern of colonisation and erosive mechanisms differed between them. Microscopic boreholes were superabundant on the limestone and abundant on the concrete but almost absent on granite. Where boreholes were particularly dense, they coalesced, leading to collapse and loss of surface material, subsequently producing a fine-scale surface roughness not present at the start of the study. EPS thickness on granite was greatest when microtopographical features, such as mineral grain boundaries and ridges, were present. Owing to granite's hardness, endolithic growth was not recorded in the samples but was present in limestone and concrete. Biological crusts were superabundant on the concrete as a result of the chemical reaction between seawater salts and cement paste, leading to precipitates such as gypsum and brucite. The leaching of these precipitates ultimately leads to minor material loss, with brucite exhibiting dichotomous characteristics; expansion within the cement paste, increasing risk of cracking, but also sealing pores as an insoluble precipitate and thus preventing further leaching and seawater penetration (Costa and Appleton 1999; Neville 2004). Concretes that have greater porosity may exhibit greater EPS growth and penetration than dense concretes due to increased moisture retention and the ability for organisms to adhere to inner surfaces, and thus favourable growth conditions (Tamai et al., 1992; Ohshima et al., 1999; Dubosc et al., 2001; Vivier et al., 2021). This enhanced porosity, for example in CEMV concrete, can allow greater penetration of biodeteriorative agents (Georges et al., 2021). The lithological microorganism colonisation on these materials dictates in the long term their surface geomorphology as well as the subsequent ecological succession and the indirect bioerosive effects this will incur. The desiccation of biofilms themselves may also result in the loss of surface material, as the contraction of the EPS removes mineral grains from the substrate (Guillitte and Dreesen 1995). Coombes et al. (2011) did not deem EPS colonisation to pose a significant risk to the durability of a coastal defence structure over its service life.

### 3.2. Macroalgae

Macrophytic algae are ubiquitously regarded as fouling organisms due to the increased drag (Fletcher 1988; Yebra et al., 2004; Schultz 2007), loading and fatigue damage (Edyvean et al., 1988; Yan et al., 2006), blocking of pipes, and slip hazard for the public (Lebret et al., 2009). They also contribute to bioerosion of coastal structures. The biophysical weathering that occurs as a result of algae colonisation is primarily via the penetration of attachment structures such as hyphae and holdfasts (Morrison et al., 2009). The penetration of the holdfasts of the temperate brown seaweeds (*Ascophyllum nodosum* and *Fucus vesiculosus*) of up to 1.5 mm and 4 mm respectively has been observed in Galway granite and Carboniferous limestone in the northeast Atlantic on the west coast of Ireland, with the crustose algae *Lithothamnion* sp. also demonstrating changes to rock surfaces (Morrison et al., 2009). Structured light microscopy (SLIM) and scanning electron microscopy (SEM) showed both *A. nodosum* and *F. vesiculosus* holdfasts exploited microfractures within the rock, such as intercrystalline boundaries and cleavage planes, and prized minerals apart as well as engulfing disaggregated fragments into algae tissue. It was anticipated that the intermittent wetting/drying of the intertidal alga would enhance their bioerosive capacity on a micro-scale due to the expansion and contraction of alga tissue (Fig. 1). This phenomenon was also observed by Hughes et al. (2013a) who found microscopic *Ulva* sp. filaments penetrating the cement paste and adhering to exposed fine aggregate particles of a concrete revetment in the North Sea, northwest England. As with rock, it is evident that algae attachment structures can exploit weaknesses between cement paste and aggregate interface. As observed by Coombes et al., (2011) with EPS growth exploiting microtopographical features on granite, Hughes et al. (2013b) demonstrated with SEM micrographs algal filaments behaving in a similar manner on degraded concrete surfaces with exposed aggregate fibres. Where cement paste had eroded, leaving aggregates exposed, algae filaments were better able to adhere to and penetrate the concrete surface.

Large brown algae species, such as bull-kelp (*Durvillaea antarctica*), may contribute to coastal erosion via a phenomenon known as 'kelp plucking'. Following storm activity, Smith and Bayliss-Smith (1998) found that dislodged kelp removed rock attached to their holdfasts, contributing to intertidal downwearing of rock platforms on Macquarie Island in the southwest Pacific Ocean. The force of removal may also introduce faults in the local rock, increasing the area vulnerable to further weathering.

Jayakumar and Saravanane (2009) identified that concrete subjected to epiphytic growth of the subtropical macroalgae *Chaetomorpha antennina* lead to the dissolution of calcium within the concrete and alteration of the surface material in the Bay of Bengal on the Indian coast. They demonstrated that *C. antennina* contained organic acids, but comparisons of the concrete condition were made between concrete samples in potable water in the lab, colonised concrete samples in seawater in the lab, and colonised concrete samples from the intertidal zone. Subsequently, without an uncolonised concrete sample in seawater to compare results to, the relationship between how the combination of *C. antennina* and seawater affect the concrete is unclear. Further work by Jayakumar and Saravanane (2010) and Jayakumar et al. (2011) replicate the study with *Ulva fasciata.* In one study (Jayakumar et al., 2011) control concrete in potable water is analysed, and in another (Jayakumar and Saravanane 2010) the control concrete is kept in saline water. The energy-dispersive X-ray spectroscopy (EDAX) graphs show remarkable similarities between the mineralogy of the colonised concrete samples in seawater and the control concrete in saline water. Comparing the EDAX graphs of the potable water and saline controls from the 2010 and 2011 papers, it is possible to see that the mineralogy of the saline water concrete and potable water concrete differ. This suggests that saline/seawater also plays a role in the dissolution of calcium from the concrete in these studies, which is known to occur (Buenfeld 1984). It is also unknown if the organic acids identified in the alga are present in a chemically significant concentration and how these acids come into contact with the concrete (e.g., diffused into the water or leached into concrete via holdfast tissue). Additionally, the studies ignore the impact of biophysical weathering by algal attachment structures which can enhance abiotic chemical weathering (Griffin et al., 1991). Welton et al. (2003) demonstrated that when calcium rich stone was immersed in autoclaved tap water, calcium was released into the liquid. When microalgae were present, calcium was absorbed from the liquid indicating that microalgae utilise calcium from the substrate but incorporate it indirectly via its leaching in the presence of water. This is emphasised in Guillitte and Dreesen's (1995) study which examined the bioreceptivity of common building materials in lab conditions. Upon using a nutrient-rich solution to enhance colonisation, they noted that the polystyrene rests in which the building materials were held were also colonised by vegetation, suggesting that colonisation was primarily dependent on exogenous nutrients and not the inherent nutrient content of the material.

The decay of marine algae causes the release of hydrogen sulphide and dimethyl sulphide (Keller 1989) with concentrations of up 600 ppm recorded in decomposing seaweed in seawater (Edyvean et al., 1988), which can aggressively corrode steel in reinforced concrete. However, unless the seaweed is significantly aggregated in a closed system, the significance of this is likely to be low as high concentrations will be rapidly dissipated in open systems by waves and currents (Buenfeld 1984). Additionally, this will only be of detriment if the concrete facing is already deteriorated, and the rebar is exposed to seawater.

### 3.3. Invertebrates

#### 3.3.1. Biophysical

Grazers, such as gastropod molluscs and particularly *Patella* spp. and *Littorina littorea*, are known to have a bio-erosive effect on soft rock, such as limestone (Schneider and Torunski 1983; Trudgill 1988; Swantesson et al., 2006b). Through their feeding activity and excavation of 'home scars', limpets (*Patella vulgata*) on the shores of East Sussex, southeast England, were found to be responsible for lowering the chalk platform on average 0.15 mm per year depending on their density (Andrews and Williams 2000). Notably, high concentrations of calcium were present in faecal pellets of limpets also grazing on siliceous rock, suggesting much of the calcium was derived from the algae consumed, and not necessarily due to the ingestion of particulate rock. Various assumptions made about the faecal pellet method of estimating limpet erosion mean these results should be interpreted cautiously and possibly overestimate the bioerosive impact of limpet grazing. However, where soft rock and concrete surfaces have been agitated via grazing or home scar formation, they are likely to be more vulnerable to other weathering agents.

Bivalve molluscs can also contribute to concrete deterioration through the invasive nature of attachment structures such as byssal threads. Perez et al. (2003) used SEM and energy-dispersive X-ray spectroscopy to analyse concrete colonised by the freshwater golden mussel (*Limnoperna fortunei*) in Argentina where it is a non-native species. Results demonstrated the byssal threads, which the mussels use to remain attached to the substrate, penetrate the material surface and can cause fissures which increases the likelihood of water ingress and other erosive pathways. This was supported by similar findings by Yao et al. (2017) who found that colonisation of *L. fortunei* on concrete reduced compressive strength. Concrete calcium content where mussels had colonised was reduced and both Perez et al. (2003) and Yao et al. (2017) deduced that the mussels leach calcium from the concrete for their shell growth. However, mussels derive calcium from the water and do not absorb it from the substrate (Ramesh et al., 2017). It is more likely that increased water ingress via byssal thread penetration in the concrete had led to the dissolution of calcium leachate.

Some boring bivalves, such as piddocks, secrete a substance that enables chelation, a chemical process that bonds molecules to metal ions and dissolves calcareous substrata in which the piddocks burrow. Other piddock and clam species burrow mechanically by abrading the rock with their shells (Trudgill and Crabtree 1987; Bromley and Heinberg 2006). In conjunction with abiotic weathering mechanisms, bivalve boring can represent a significant bioerosive risk to carbonate-based coastal infrastructure (Pinn et al., 2005; Moura et al., 2012; Coombes 2014). Boring activity also occurs in concrete. Scott et al. (1988) recorded boring activity from polychaete worms, sponges and bivalve molluscs in tropical limestone and concrete in the Caribbean Sea on the coast of Jamaica. This activity was concentrated where the limestone aggregate in the concrete matrix was densest, with the sponges avoiding the cement paste altogether.

#### 3.3.2. Biochemical

Carbon dioxide increases within seawater overnight as a result of respiration and the cessation of photosynthetic activity (Emery 1946; Trudgill 1976; Lundberg 1977; Moses 2002), which may increase dissolution of calcareous rock and cement nocturnally (Griffin et al., 1991; Sand 1997; Garcia-Pichel 2006). However, this is only likely to impact relatively closed systems, such as rockpools, on a very minor local scale and is likely to have little impact on vertical concrete structures.

## 4. Bioprotective effects

Bioprotection can be achieved via three main mechanisms: stabilisation of the substrate, microclimate mediation, and attenuating weathering and other deteriorative effects (Fig. 2). Substrate stabilisation can involve the aggregation of particulate matter within biofilms, the secretion of insoluble precipitates on the substrate surface, such as oxalates, and the retention of sediment in algae. Buffering hygrothermal regimes and reducing the frequency of extreme temperature events can be achieved through the colonisation of sessile and epilithic biota, which

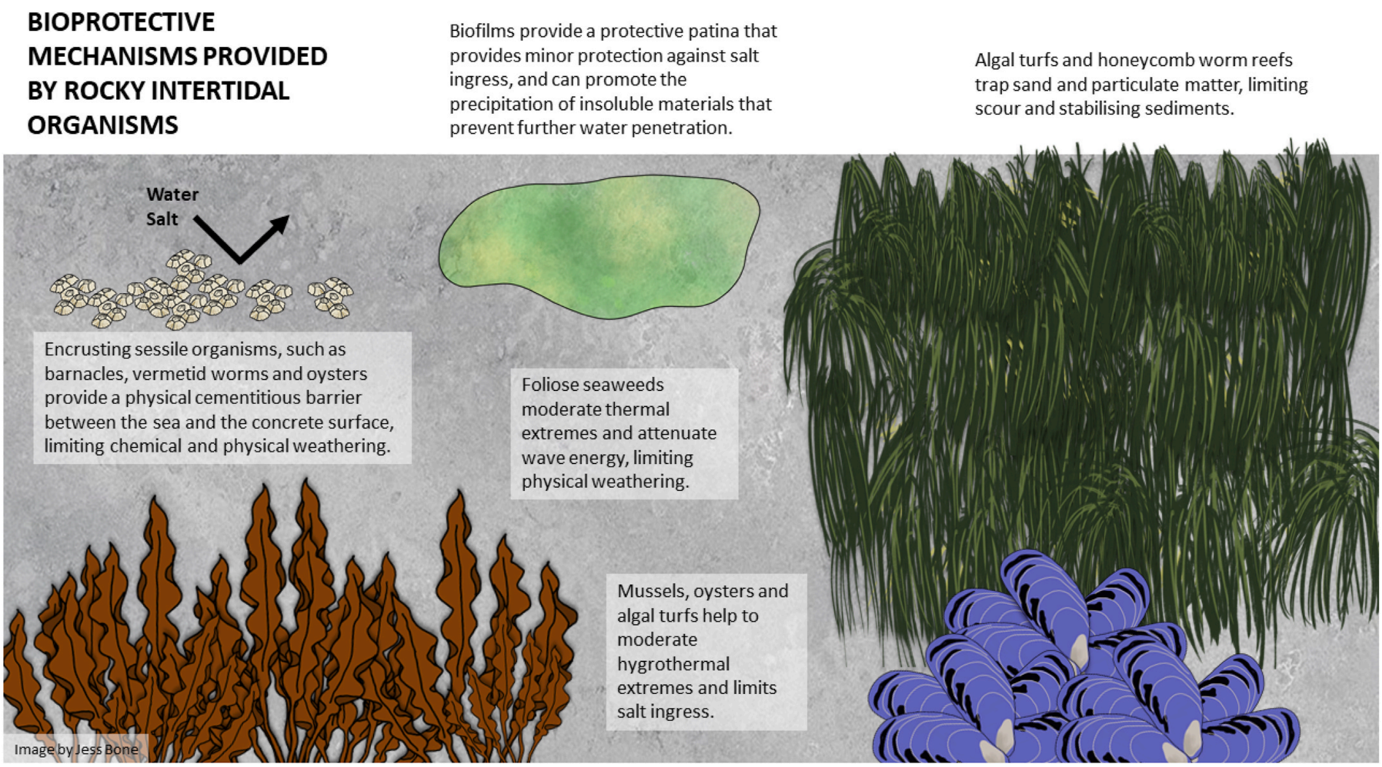


**Fig. 2.** The bioprotective effects of rocky intertidal organisms. Note that while substrate is indicative of concrete, the magnitude of bioprotective benefits is dependent on substrate material, whether the organism is live, and the spatiotemporal variations in population size and density. See also 'Shore Shapers' (Naylor et al., 2014).

mediates microclimate compared to bare substrate. Additionally, colonisation can mitigate against other weathering mechanisms, including chemical, physical and biological erosion.

Several studies that examine the bioprotective effect of entire sessile assemblages on coastal concrete can attest to its enhanced resistance to chloride ion (salt) penetration (Maruya et al., 2003; Kawabata et al., 2012; Georges et al., 2021). El-Hawary et al. (2000) compared epoxy-repaired concrete samples in the intertidal zone of the Persian Gulf on the Kuwait coast and in the lab and found that, unlike the lab samples, the field samples did not show degradation or a reduction in tensile strength during the entire 18-month study period. It was assumed that the thick build-up of sessile organisms protected the field concrete from exposure to seawater and the associated chemical deterioration. The majority of bioprotection studies tend to focus on specific morphology (e.g., biofilms, macroalgae) or individual species. While this adds validity to the bioprotection argument for that species or morphology, it does mean the dynamism of its existence through time and space and among wider assemblages is often not considered. However, it is important to demonstrate that although many species and life forms may cause biodeterioration, they often dichotomously demonstrate the ability to offer some level of bioprotection (Table 1).

### *4.1. Microorganisms, biofilms and lichen*

There is extensive work quantifying the bioprotective effects of lichen on terrestrial cultural heritage (Carter and Viles 2003), some of which is reviewed here to provide wider context for marine application. Such bioprotective effects may be relevant in the supralittoral fringe (splash/spray zone) on artificial coastal structures where marine lichens can be found (Ryan 1988).

Lichens and fungal biofilms have been found to enhance biomineralization (or bioremediation) in stone cultural heritage (Gadd and Dyer 2017). Many microorganisms are able to perform this ecosystem service by precipitating carbonates which result in cementation, or the formation of insoluble minerals known as microbially induced calcite precipitation (MICP) (Di-Bonaventura et al., 1999; Dittrich and Sibler 2010; Al-Salloum et al., 2017). Although some marine microorganisms are known to precipitate calcites and MICP is known to occur on concrete, no study to date directly attributes 'healing' of cracks in intertidal concrete from the natural colonisation of microorganisms or EPS communities. Lv et al. (2015a) demonstrated that marine bacteria could form protective biofilms by retarding the permeation of chloride and magnesium ions into ordinary Portland cement mortar and inhibiting $OH^-$ leachate. This is supported by Gao and Tang (2018) who found that chloride penetration in concrete in the intertidal was reduced where biofilms were present. Additionally, the superficial invasion of hyphae into the pore spaces of limestone was found to reduce the ingress of water and solubilizing chemicals (Garcia-Valles et al., 2003). On lab based mesocosm experiments conducted at >90% humidity, Fiol et al. (1996) found that dissolved and particulate loss of limestone material was greater on bare rock than lichen covered rock. This was supported by Carter and Viles (2003) who found that lichens retain moisture and subsequently reduce thermal stress and the magnitude of thermal fluctuations on substrate surfaces. Arino et al. (1995) addressed the balance of biodeterioration versus bioprotection when comparing areas of lichen covered Roman pavement with bare pavement in Spain. Although lichen colonisation did show biological weathering to the pavement surface, these biodeteriorative effects were deemed to be slower acting than abiotic weathering, which showed significant impacts in bare areas not covered by lichen. Although this evidence suggests that lichens may play a similar role in the supralittoral zone, no studies to date have clearly demonstrated this. However, terrestrial lichens show promising bioprotective properties, which should encourage further study of lichens and similarly structured life forms in the intertidal to confirm this.

### *4.2. Plants and macroalgae*

Plants and macroalgae are already well known for their bioprotective

**Table 1**
The mechanisms by which rocky intertidal organisms may provide bioprotective or biodeteriorative effects.

| | Biodeteriorative Action | Substrate Affected | References (Field Location) | Bioprotective Action | Substrate Affected | References |
|---|---|---|---|---|---|---|
| **Microorganisms, biofilms, and extra-cellular polymeric substances** | Solubilisation of metal ions and substrate decomposition/secretion of organic acids | Limestone, coastal rock | Eckhardt (1985); Flemming (1993); Schneider and Le Campion-Alsumard (1999); Scheerer et al., (2009) | Lichen hyphal penetration of pore spaces can inhibit the ingress of water and solubilizing chemicals | Tuff (igneous rock) | Garcia-Valles et al., (2003) (Turkey) |
| | | Concrete | Cwalina (2008) | | | |
| | Creation of microscopic boreholes that can coalesce and lead to material loss | Limestone | Schneider and Le Campion-Alsumard (1999) | Precipitation of insoluble material or promotion of cementation inhibiting further water ingress | Concrete | Costa and Appleton (1999) (W Portugal); Neville (2004); Gadd and Dyer (2017) |
| | | Limestone, granite, concrete | Coombes et al., (2011) (SW England) | | Limestone, sandstone | Di-Bonaventura et al., (1999) (Italy); Gadd and Dyer (2017) |
| | Expansion and contraction of cells through wetting and drying cycles leading to microcrack formation | Limestone | Moses and Smith (1993) (NW Ireland) | Lichen coverage can retain moisture and reduce thermal fluctuations, protecting against weathering | Limestone | Fiol et al., (1996) (Mallorca); Carter and Viles (2003) (England) |
| | | Sandstone | Gomez-Pujol et al., (2007) (SE Australia) | | Sandstone | Arino et al., (1995) (SW Spain) |
| | | Limestone, granite, concrete | Coombes et al., (2011) (SW England) | | | |
| | Enhancement of biological crust formation leading to precipitation of gypsum and brucite increasing risk of microcracks | Concrete | Costa and Appleton (1999) (W Portugal); Neville (2004) | Biofilms can form protective layer to retard salt penetration | Marine mortar | Lv et al., (2015a); Gao and Tang (2018) |
| | Desiccation of biofilms leads to removal of mineral grains from subtrate surface as biofilm contracts | Limestone, brick, mortar | Guillitte and Dreesen (1995) | | | |
| **Macroalgae** | Penetration of attachment structures leads to fine-scale material loss | Granite, limestone | Morrison et al., (2009) (W Ireland) | Colonisation of macroalgae reduces the space vulnerable to biodeteriorative action from cyanobacteria | Limestone | Naylor and Viles (2002) (Crete) |
| | | Concrete | Hughes et al., (2013a) (NW England); Hughes et al., (2013b) (NW England) | | | |
| | Expansion and contraction of surface penetrating tissues through wetting and drying cycles leading to particle disaggregation | Granite, limestone | Morrison et al., (2009) (W Ireland) | Algal turf reduces downwearing rates | Carbonate rock | Moura et al., (2012) (Portugal) |
| | Secretion of organic acids can lead to chemical etching and may lead to dissolution of calcium | Calcereous rock | Welton et al. (2003) | Algal canopies moderated temperature extremes and buffered humidity variability | Concrete, limestone | Coombes et al., (2013) (SW England) |
| | | | | | Mudstone | Gowell et al., (2015) (SW England) |
| | | | | | Intertidal rocky shore | Scrosati and Ellrich (2018) (E Canada) |
| | | Concrete | Jayakumar and Saravanane (2009), 2010; Jayakumar et al., (2011) (SE India) | Crustose algae may provide a protective layer and cement loose material to the substrate surface | Sedimentary rock | Trenhaile (2017); Kennedy et al., (2019) |
| **Invertebrates** | Scouring of substrate via limpet feeding activity and home scar formation | Chalk coastal platforms | Andrews and Williams (2000) (SE England) | Barnacle cover inhibits other weathering mechanisms by forming a protective layer | Limestone | Moura et al., (2006) (Mallorca) |
| | | | | | Sandstone | Pappalardo et al., (2018) (NW Italy) |
| | Penetration of attachment structures such as byssal threads of mussels can lead to formation of fissures and reduction in compressive strength | Concrete | Perez et al., (2003) (N Argentina); Yao et al., (2017) (SE China) | Barnacle, vermetid worm, mussel and oyster cover moderates thermal extremes and inhibits salt penetration by forming a protective layer. Barnacle and oyster secretions and adhesives reduce concrete porosity. | Granite | Coombes et al. (2017) |
| | | | | | Concrete | Risinger (2012); La Marca et al., (2015) (SW England); Lv et al., 2015b (NE China); Coombes et al., (2017); Chlayon et al., (2018) (Japan); Lv et al., (2021) (NE China); Lv et al., (2022) (NE China) |
| | | | | | Mafic, sedimentary rock | McAfee et al., (2016) (SE Australia) |
| | | | | | Limestone | Coombes et al., (2017); La Marca (2017) (Sicily) |

(*continued on next page*)

**Table 1** (*continued*)

| | Biodeteriorative Action | Substrate Affected | References (Field Location) | Bioprotective Action | Substrate Affected | References |
|---|---|---|---|---|---|---|
| | | | | | Sandstone, mudstone, graywacke granitic | Jurgens and Gaylord (2018) (W USA) |
| | Boring activity from piddocks, worms and sponges lead to material loss and further water ingress | Limestone, concrete | Scott et al., (1988) (Jamaica); | Mussel and oyster beds dissipate wave energy | Siltstone | Gonzalez et al., (2021) (Argentina) |
| | | | | | Mudstone | Baxter et al., (2022d) (Wales) |
| | | Limestone, carbonate rock, granite | Bromley and Heinberg (2006) | Piddocks secrete insoluble calcite within boreholes which inhibits further water ingress | Carbonate rock | Moura et al., (2012) (Portugal) |
| | | Chalk, clay | Pinn et al., (2005) (S England) | Honeycomb worms stabilise sediment, reducing abrasion and attenuating wave energy | Coastal rock | Naylor and Viles (2000) (Wales); Braithwaite et al., (2006) (NE Scotland); White (2011) (Wales) |
| | | Carbonate rock | Moura et al., (2012) (Portugal) | | | |
| **Entire sessile assemblages** | Unknown | Unknown | Unknown | The build-up of organisms creates a physical barrier against other weathering mechanisms and salt penetration | Marine concrete | El-Hawary et al., (2000) (Kuwait); Maruya et al., (2003); Kawabata et al., (2012) (Japan); Georges et al., (2021) (N France) |

effects on a larger, landscape spatial scale, particularly mangroves, seagrass meadows, saltmarshes and kelp beds, due to wave attenuation (Mazda et al., 1997; Massel et al., 1999; Quartel et al., 2006; Chen et al., 2007; Bradley and Houser 2009; McIvor et al., 2012; Anderson and Smith 2014; Horstman et al., 2014; Tambroni et al., 2016), storm mitigation (Moller et al., 2014; James et al., 2021), and sediment retention (Adame et al., 2010) and accretion (Gacia et al., 1999). There is mounting evidence that macrophytes also protect substrata on a smaller, localised spatial scale particularly via microclimate mitigation and acting as an 'umbrella', which has been observed in both terrestrial plants (Sternberg et al., 2010) and macroalgae.

Naylor and Viles (2002) found that biodeteriorative effects of cyanobacteria colonisation and weathering were reduced once macroalgae had established on blocks of limestone installed on the rocky shore of Falsarna, Crete in the eastern Mediterranean. Filamentous and foliose algae on exposed limestone blocks appeared to limit other biodeteriorative forces and macroalgal abundance was inversely related to bioerosion from cyanobacteria at the study close, suggesting that macroalgal colonisation provides some level of bioprotection.

Moura et al. (2012) examined downwearing rates of two carbonate rock platforms on the Algarve coast of Portugal in the northeast Atlantic. Downwearing rates were lower on substrate covered in algal turf compared to bare rock, suggesting that macroalgae offered bioprotective benefits via wave attenuation and trapping sand that would otherwise scour the rock surface.

The brown canopy-forming algae *Fucus* spp. was found to moderate the range and maxima of daily summer temperatures on concrete and limestone artificial coastal structures in the southwest of England (The Channel, northeast Atlantic) compared to control areas that had been cleared (Coombes et al., 2013). Short term temperature and humidity variability was reduced by up to >70% under *Fucus* canopies during low tide. The amelioration of wetting and drying cycles associated with tidal regimes could represent a reduction in salt weathering (Goudie and Viles 1997; Stephenson and Kirk 2000), and the reduction in direct solar radiation and thermal stress could limit other weathering effects. Gowell et al. (2015) compared the hardness and surface condition of mudstone with artificial macroalgal canopy compared to an uncovered control under simulated intertidal conditions. It was found that the artificial macroalgae buffered microclimatic fluctuations by modifying temperature and humidity at the mudstone surface. Compared to the uncovered control, the covered mudstone lost 80% less debris and did not undergo as great a reduction in hardness. The artificial algae canopy also retained moisture and shaded the mudstone surface, reducing the frequency of salt crystallization events. Reducing the salt ingress in the material surface would be a key benefit in concrete artificial coastal structures as chloride attack on steel reinforcement in concrete is a leading cause of structural decay (Neville 2011). *Ascophyllum nodosum* canopies were found to insulate intertidal substrate in winter on the Atlantic Canadian coast with temperatures on bare substrate up to 10° lower than canopy-covered substrate (Scrosati and Ellrich 2018). It can be inferred that algal cover has the potential to therefore provide insulation to substrata throughout the year in temperate regions, buffering thermal regimes which may subsequently ameliorate other deteriorative forces. Baxter et al. (2022c) found that *Fucus* spp. cover on natural cement-based mortar samples on the south coast of England did not encourage substrate deterioration but instead potentially enhanced the curing process and structural integrity of the material. It should be noted that seaweed cover in this case does not refer to *Fucus* spp. attached to the mortar samples; 'cover' was provided by existing fucoid canopy from the surrounding rock. Crustose algae may also play a key bioprotective role. Kennedy et al. (2019) observed that the red coralline algae *Lithophyllum incrustans* appeared to protect an intertidal platform in the North Sea on the Yorkshire coast, UK, from weathering. Coralline and encrusting algae on artificial coastal structures may perform similar roles by providing a protective patina (Trenhaile 2017).

### 4.3. Invertebrates

The invertebrates that have thus far been determined to play a bioprotective role are generally gregarious and sessile, and include barnacles, calcareous tube-building worms, mussels and oysters. The calcareous structures formed by these species (shells, tests) form a solid and rough layer on the substrate surface.

The rocky shore topography of Algarve, Portugal (northeast Atlantic) was characterised by Moura et al. (2006) who observed that barnacle dominated rock platforms were typically very irregular as areas not covered by barnacles were physically weathered by wave action. It was concluded that barnacle cover provided some protection from wave erosion and thus contributed to the topographical heterogeneity of the shore platforms. Varying percentage cover of *Chthalamus* sp. barnacles were compared on limestone, granite and marine-grade concrete substrates under simulated intertidal conditions by Coombes et al. (2017). Subsurface peak temperatures were reduced by > 5 °C in concrete with near total coverage of barnacles compared to bare concrete with no barnacle cover. There was a statistically significant negative relationship between thermal breakdown and barnacle cover. Chloride ion migration was lower in materials covered by barnacles, suggesting a reduction in salt ingress. Additionally, evaporative cooling occurred with barnacle covered materials, due to the loss of water retained in the empty barnacle tests. The thermal regime observed here may differ *in situ* with live barnacles as the moisture is retained within the tests at low tide and so the evaporative cooling may be reduced. However, the inhibited chloride ion migration under barnacle cover may hint at bioprotective effects which are supported by La Marca et al. (2015), particularly on reinforced concrete where steel rebar is vulnerable to corrosion. Pappalardo et al. (2018) conducted a manipulative field experiment on the northwest coast of Italy in the Mediterranean Sea by comparing the hardness and weathering of areas colonised by *Chthalamus* sp. and bare areas scraped clear. After four months, the bare exposed rock was less hard and showed more weathering than barnacle covered rock. Similar effects have been observed in calcareous tube-building worms. Vermetid worm encrustations were found to reduce peak temperatures of rock compared to uncolonised bare rock in a mesocosm experiment by La Marca (2017), in addition to reducing salt ingress. Chlayon et al. (2018) found that the barnacle *Chthamalus challengeri* improved concrete durability on an intertidal concrete jetty in Tokyo Bay on the coast of Japan by sealing microcracks and limiting chloride diffusion. Lv et al. (2022) found barnacles provided concrete in the marine environment in the Yellow Sea on the north coast of China 'three lines of defence' with their tests, adhesive and the penetration of their adhesive, enhancing resistance of water absorption and chloride ion penetration and improving the concrete durability.

Mussel (*Mytilus californianus*) aggregations in the Pacific Ocean on the Washington, north Californian and south Californian coast, US, were found to functionally eliminate lethal and sublethal temperatures for intertidal biota compared to bare rock, regardless of tidal elevation and latitude (Jurgens and Gaylord 2018). Gonzalez et al. (2021) and Baxter et al. (2022d) demonstrated that mussels perform a similar bioprotective function on coastal substrates as barnacles. Gonzalez et al. (2021) found that experimental removal of mussels (*Brachidontes rodriguezii*) on a shore platform on the Argentinian coast (south Atlantic Ocean) led to a 10% decrease in surface hardness after 5 months. Baxter et al. (2022d) supports these findings by comparing mussel-covered (*Mytilus edulis)* intertidal rock on the Welsh coast (Irish Sea, northeast Atlantic) with bare rock. It was found that mussel-covered rock was significantly harder than bare rock, with mussels moderating microclimate regimes, water motion and turbulence at the rock surface. Oysters are also known to facilitate thermal buffering at the substrate surface by shading and trapping moisture in the interstices between shells in the Pacific Ocean on the east Australian coast (McAfee et al., 2016, 2017, 2018) and thus it can be inferred they may play a similar bioprotective role (Risinger 2012). Oyster cementation inhibits chloride ion permeability, enhances concrete durability, reduces pore structure at the concrete surface (Lv et al., 2015b), reduces water absorption and enhances resistance to carbonation (Lv et al., 2021). Additionally, both oyster (Wiberg et al., 2019) and mussel (Donker et al., 2013) beds are known to dissipate wave energy in the intertidal zone. Unlike mussels and barnacles, the cementitious secretions of oysters to facilitate attachment are predominantly inorganic and resistant to acid solubilisation (Burkett et al., 2010; Tibabuzo Perdomo et al., 2018) and therefore may persist as a protective biogenic layer on the substrate following death.

The honeycomb worm (*Sabellaria* spp.) is a reef-building gregarious organism that settles on hard intertidal substrates and can produce reefs several centimetres in height (Naylor and Viles 2000) and several metres in diameter. Their bioconstructions are comprised of tubes made from sand grains cemented together via secretions, which play a potentially bioprotective role by stabilising sand that would otherwise abrade hard substrates and attenuating wave energy (White 2011). Braithwaite et al. (2006) noted that expansive honeycomb worm reefs were growing on concrete-jacketed subsea pipelines off the coast of Scotland (North-east Atlantic), effectively burying them. There were initially concerns that the reefs would increase loading pressure on the pipelines but following measurements of the reef mass, risks to pipeline integrity were considered low and may provide benefits such as surface protection and additional weighting.

## 5. Overview

It is evident that virtually all marine biota possess a biodeteriorative capacity for intertidal substrata, often via multiple mechanisms. However, many of these species, such as macroalgae and barnacles, also jointly offer bioprotective effects. It has been noted by several authors (Naylor et al., 2002; Naylor 2005; Carter and Viles 2005; McIlroy de la Rosa et al., 2012; Favero-Longo and Viles 2020) that biodeterioration and bioprotection should not be viewed as conflicting, dichotomous, isolated positions; rather they are two ends of the same scale with both acting in tandem. The biodeteriorative effects inflicted by a given species may be outweighed by bioprotective effects that inhibit and retard more severe and faster acting weathering as observed with lichen (McIlroy de la Rosa et al., 2014) on Angkor temples in Cambodia by Bartoli et al. (2014). The hyphal penetration of lichen was deemed overall less deleterious than if the lichen was absent and the stone substrate was exposed to direct sunlight and weathering.

Importantly, determining if a given species or assemblage is providing overall net bioprotective or deteriorative effects is dependent on many complex, dynamic and interrelated biotic and abiotic factors that are temporally and spatially variable. For example, the net bioprotective benefits of barnacles depend on their percentage cover, whether they are live (Coombes et al., 2017), their age, and their attachment method as some barnacle species etch into the substrate and seal their tests directly to the substrate (Donn and Boardman 1988; Bromley and Heinberg 2006) and other species use adhesive (Pappalardo et al., 2018; Liang et al., 2019). Naturally, their percentage cover will also vary over time and space. Further, biodeteriorative and bioprotective forces are mediated by the material they are acting on and at different scales, with different lithologies and concretes more or less vulnerable to different biogenic processes than others (Coombes 2014; MacArthur et al., 2020). As noted by Coombes et al. (2013), wave-driven erosion is likely to have a greater impact on less durable materials, such as carbonate rock, than limpet grazing.

### 5.1. Managing biological colonisation

Facilitative bioerosion alters the properties of the substrate material, for example by reducing material strength or exploiting discontinuities and joint planes, making it more vulnerable to weathering and erosive forces (sensu Naylor et al., 2012). Therefore, consideration must also be given to the management of fouling organisms as the removal of colonisation may accelerate other deteriorative forces. The removal of lichen on Angkor temples was considered inadvisable, as the damage caused by the lichen hyphae increased the substrate's vulnerability to weathering once the lichen was removed, a consideration supported by McIlroy de la Rosa et al. (2012). This may also be observed on concrete coastal structures where the removal of barnacles and macroalgae, which would require abrasive action such as power washing (Hughes et al., 2013b), may expose and exacerbate surface damage caused by biodeterioration (Pappalardo et al., 2018), such as expanded pores and microcracks. Such damage may permit deeper water and salt ingress and expose the substrate to the deleterious hygrothermal regimes recorded on bare rock (McAfee et al. 2016, 2017, 2018; Coombes et al., 2017; La Marca 2017; Jurgens and Gaylord 2018; Pappalardo et al., 2018). Additionally, it should be noted that management that entails the periodic removal of biofouling assemblages may lead to the domination and spread of non-native invasive species and loss of biogenic habitat and biodiversity. Coombes et al. (2013) suggested that loss of macroalgal cover shifted the substrate from a stable state to an unstable state, due to not only the return of aggressive mechanical weathering but enhanced ecological stress. McIlroy de la Rosa et al. (2012) demonstrated with conceptual modelling that instability and rapid topographical change occurs on substrates following the death and decay of epilithic lichen. Subsequently, bioprotective species and assemblages can provide crucial stabilisation for substrata. The bioprotective effects of some species are however, easily outweighed by their net biodeteriorative effects. For example, boreholes in the rocky coast of Portugal were stabilised by insoluble calcite precipitated by the piddocks responsible, which protected against further water ingress but contributed to significant material loss (Moura et al., 2012). In addition to weighing up the biodeteriorative versus bioprotective effects of a given species or assemblage, the effects of their absence (and particularly removal) should also be included in the analysis. As stressed by Coombes (2014), biogenic and physico-chemical processes occur synergistically and it is the cumulative impact, or total weathering outcome (Hall et al., 2012), of these interactions that should be assessed. Liu et al. (2022, in press) proposed a bioprotection ratio for biofilms heritage stone monuments that considers natural weathering as all structures are impacted by this.

### 5.2. Considering other impacts

When attempting to determine if a species or assemblage offers a net bioprotective gain or biodeteriorative loss, acknowledgement of the additional ecosystem services offered by it should be considered (Fig. 3). For example, carbon dioxide sequestration and water filtration (Layman et al., 2014), habitat and food provision (Vaughn 2018), contribution to 'natural' aesthetic (Fairchild et al., 2022), and cultural and socio-economic benefits (education, tourism, recreation, fisheries industry) may be provided (Naylor et al. 2014, 2017) and could tip the scales in favour of encouraging or retaining existing colonisation (Coombes and Viles 2021). Ultimately, a bioprotective assemblage is not guaranteed as colonisation of a substrate is dependent on spatiotemporally variable factors, such as latitude, climate, orientation, aspect, substrate material, larval supply, predator-prey dynamics, competition, and habitat and food availability. As noted by Gadd and Dyer (2017) there is no guarantee that target species will colonise or perform in the expected and desired manner. However, promoting a diverse community on artificial coastal structures is likely to increase the number of bioprotective species and their percentage cover, tipping the scale towards net bioprotection and away from biodeteriorative species such as cyanobacteria (Naylor et al., 2012). Typically, artificial coastal structures do not represent diverse habitats and their communities are not analogous to natural communities (Connell and Glasby 1999; Chapman 2003; Moschella et al., 2005; Vaselli et al., 2008; Pister 2009). However, through considered eco-engineering, rock material choice (Coombes et al., 2011; MacArthur et al., 2020) and bioreceptivity enhancement (Coombes et al., 2015, 2017; MacArthur et al., 2019; Bone et al., 2022a) and with appropriate consultation with marine ecologists and biogeomorphologists, artificial coastal structures can host a diverse suite of species with high percentage cover that offer additional ecosystem services to substrate bioprotection (Chapman and Underwood 2011; Dafforn et al., 2015; Bishop et al. 2017; O'Shaughnessy et al., 2020). Coombes et al. (2013) suggested that features enhancing the recolonisation of canopy-forming macroalgae, such as artificial rockpools (Hall et al., 2019) and mud pools (Bone et al., 2022b), on highly disturbed artificial coastal structures in the UK should be an eco-engineering priority. Conversely, Chlayon et al. (2020) argued that sessile crusts, consisting of calcareous invertebrates, should be prioritised over algae after comparing the bioprotective and biodeteriorative properties of both on concrete surfaces in Japan. Biodeterioration can also be considered beneficial to improve microclimatic conditions and substrate surface texture for colonising organisms (Coombes et al., 2011; Naylor et al., 2012).

When considering how to facilitate bioprotective species, it is worth first understanding how their colonisation may work collaboratively with the artificial coastal structures. For example, vertical seawalls that provide flood defence could benefit from colonisation of canopy-forming macroalgae, such as fucoids, to attenuate wave energy and associated risks (Coombes et al., 2013), such as overtopping. By permitting the colonisation or continuation of existing assemblages, maintenance costs associated with biofouling management will reduce, although condition checks may subsequently increase. Naturally, where colonisation poses risk to the public (e.g., algae on pathways) or loss of

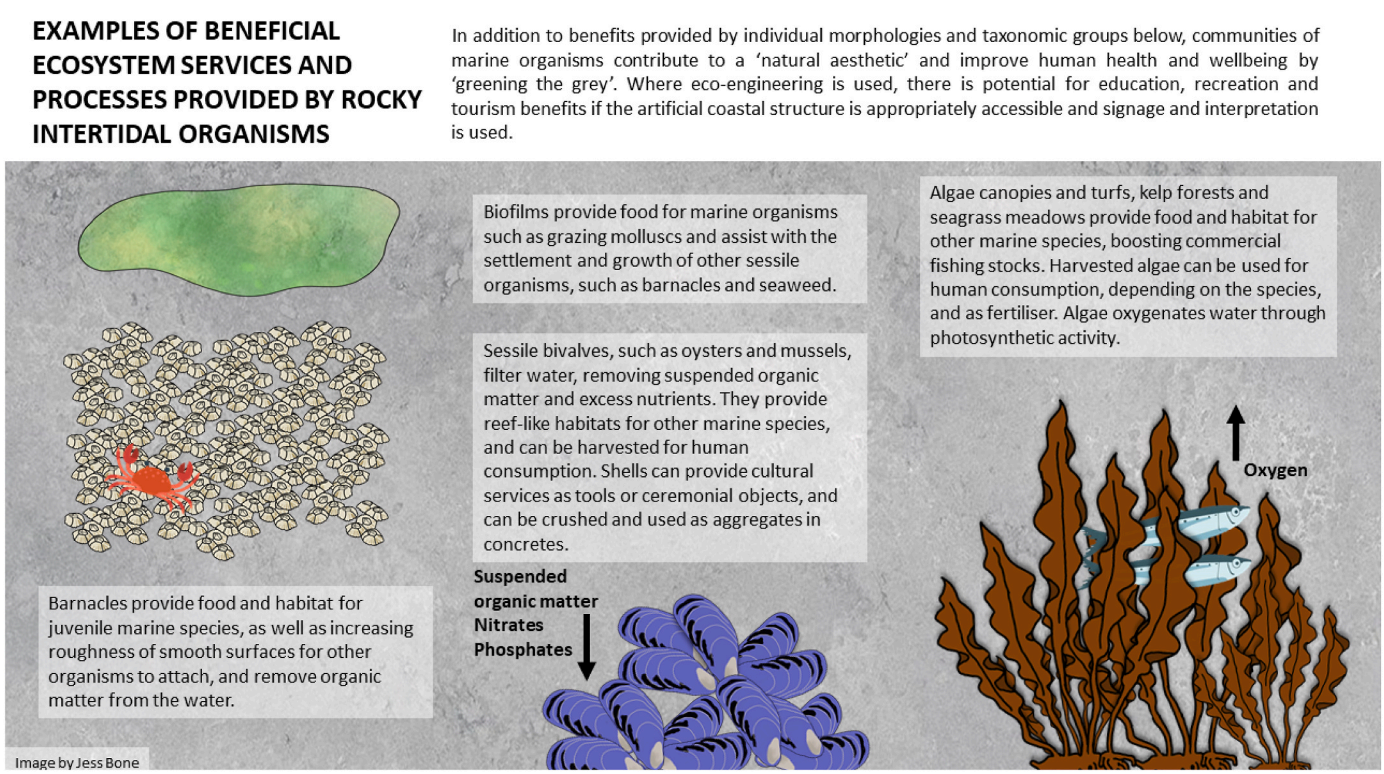


**Fig. 3.** Examples of some of the beneficial ecosystem services and processes provided by the rocky intertidal organisms mentioned in this review.

function (e.g., power plant water intake), the removal of biofouling communities must continue.

In a warming, acidifying ocean, bioprotection may play an important role in creating a physical barrier between alkaline substrata and acidic seawater. It has been demonstrated that concrete may provide superior substrate for algal turf cover and photosynthetic efficiency compared to granite under acidification scenarios (Davis et al., 2017). The dissolution of $CaCO_3$ was deemed a key factor in concrete performance as substrate in acidifying oceans. This is supported by Mos et al. (2019) who found that although settlement rates of juvenile tropical sea urchins (*Tripneustes gratilla*) were lower on concrete compared to granite and greywacke (a hard sandstone) under simulated ocean acidification scenarios, post-settlement juveniles on concrete were larger and had higher survival rates after two weeks. The alkali leachate was thought to buffer the low pH conditions of the ambient seawater, creating favourable conditions. Given the potential bioprotection offered by calcareous organisms, such as barnacles, oysters, and mussels, that would benefit from alkali buffering in acidifying oceans, there is justification for enhancing bioreceptivity of concrete artificial coastal structures. Further, increasing air temperatures and frequency of storms due to climate change (IPCC 2014) may modify the net bioprotective capabilities of intertidal organisms, such as buffering hygrothermal regimes (Coombes et al., 2013, 2017) and attenuating waves (Gowell et al., 2015).

### 5.3. Future research

Further research should determine the bioprotective effects of whole assemblages *in situ*, as studies thus far have focussed on single taxa or functional group but should assess percentage cover of key morphologies/taxonomic groups to help apportion variations in biogenic impacts to different organisms. Additionally, further work should also consider how bioprotection benefits may present subtidally and in tropical and polar regions, as the deleterious effects associated with intertidal wetting/drying cycles and salt crystallization will differ in these contexts. Mesocosm experiments should also shift focus to how colonisation may inhibit deleterious effects associated with ocean acidification and warming scenarios by creating a physical barrier at the water substrate interface and preventing dissolution of concrete material. Such studies should apply caution and avoid bias towards reporting bioprotective results as it is evident from this review that biological colonisation can be dually biodeteriorative and bioprotective. The interests of coastal managers and asset owner should be considered and maintained, as their collaboration is fundamental to permit new or continued colonisation on artificial coastal structures. Consequentially, it would be beneficial to translate quantitative results of bioprotection studies (e.g., substrate hardness, material loss) into metrics that are useful for coastal asset owners and managers, such as time added to a structures serviceable life, or monetary value. There have been existing attempts and recommendations at both metrics and monetary value (Fei et al., 2014; Naylor et al., 2017; Bridges et al., 2022) but further work is needed.

## 6. Concluding remarks

The 'biodeterioration vs. bioprotection' debate has been on-going in terrestrial and aquatic fields for several decades, but it is evident that the reality of a species or assemblages' net impact is more nuanced and spatiotemporally dynamic. Evidence shows that biological colonisation of concrete coastal structures can cause deleterious effects that affect superficial topography and enhance abiotic weathering. Conversely, common intertidal species have been shown to buffer microclimatic conditions and retard weathering on coastal substrates and their colonisation may provide net bioprotective benefits compared to bare hard substrate. In an era where greater attention is being paid to mitigating habitat loss and reducing the carbon footprint of artificial coastal structures, bioprotection is another ecosystem service provided by marine species that can support the argument for eco-engineering and enhancing bioreceptivity. Further research is required to reinforce the conclusions of existing research in different contexts; particularly future casting under climate change scenarios, and care should be taken to communicate this to coastal asset owners and managers in a meaningful and useful way.

## 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.

## Data availability

The authors do not have permission to share data.

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