

## Bioprotection and disturbance: Seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone

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### ABSTRACT

As well as their destructive roles, plants, animals and microorganisms contribute to geomorphology and ecology via direct and indirect bioprotection, which can reduce weathering and erosion. For example, indirect bioprotection can operate via biotic influences on microclimate whereby physical decay processes associated with fluctuations in temperature and moisture (salt crystallization, thermal fatigue and wetting–drying), are limited. In the intertidal zone, the spatial and temporal distribution of macroalgae (seaweeds) is patchy, related to physical and ecological conditions for colonization and growth, and the nature and frequency of natural and anthropogenic disturbance. We examined the influence of seaweed canopies (*Fucus* spp.) on near-surface microclimate and, by implication, on conditions for mechanical rock decay and under-canopy ecology. Monitoring on hard artificial coastal structures in South West England, UK, built from limestone and concrete showed that both the range and maxima of daily summertime temperatures were significantly lower, by an average of 56% and 25%, respectively, in areas colonized by seaweed compared to experimentally cleared areas. Short-term microclimatic variability (minutes–hours) was also significantly reduced, by an average of 78% for temperature and 71% for humidity, under algal canopies during low-tide events. Using seaweed as an example, we develop a conceptual model of the relationship between biological cover and microclimate in the intertidal zone. Disturbance events that remove or drastically reduce seaweed cover mediate shifts between relatively stable and unstable states with respect to mechanical decay and ecological stress associated with heat and desiccation. In urban coastal environments where disturbance may be frequent, facilitating the establishment and recovery of canopy-forming species on rocks and engineered structures could enhance the durability of construction materials as well as support conservation, planning and policy targets for biodiversity enhancement.

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### 1. Introduction

At small spatial (<meter) and temporal (minutes–hours) scales, rock surface temperature and humidity are highly variable in the natural and built environment (e.g., Jenkins and Smith, 1990; McGreevy et al., 2000; Viles, 2005). This is important geomorphologically because the efficiency of mechanical, chemical and biological processes acting to break down is influenced to some extent by temperature and moisture (e.g., Sumner and Loubser, 2008; Angeli et al., 2010). Microclimatic changes of sufficiently high magnitude, and repeated short-term fluctuations, are thought to contribute to the mechanical decay of rock through expansion and contraction (e.g., Halsey et al., 1998; Gómez-Heras et al., 2006). In this respect, the intertidal zone is a unique ‘weathering’ environment (see Hall et al., 2012 for a recent discussion of weathering nomenclature) owing to repeated cycles of inundation by seawater and exposure to the air (e.g., Porter and

Trenhaile, 2007). Here, microclimate is particularly critical for rock decay, influencing the formation of salt crystals and associated haloclastic breakdown (e.g., Davison, 1986; Cardell et al., 2003; Trenhaile, 2011; Mottershead, in press).

Microclimate is equally important for ecology in the intertidal zone. Environmental stress gradients relating to heat and desiccation, biological disturbance (e.g., predation and competition), and physical disturbance (e.g., removal of organisms by erosion events and wave dislodgement) lead to often well-defined biological zones on rocky shores (Menge and Sutherland, 1987; Harley and Helmuth, 2003) and a patchy mosaic of colonized and bare space (Sousa, 1985; Hutchinson and Williams, 2003). In this way, disturbance processes moderate ecological interactions that are important for the maintenance of ecosystem functioning and biodiversity (e.g., Wetthey, 2002) and alter the spatial and temporal variability of biological cover (e.g., Dayton, 1971).

The spatial distribution and nature of biological activity on rocky shores are important geomorphologically because this defines the likely efficiency of biological weathering as well as other mechanical and chemical decay processes that may be moderated by organisms (e.g., Trudgill, 1987, 1988; Viles, 1995; Coombes et al., 2011; Naylor et al., 2012a). The

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distribution and abundance of organisms should also define the potential for bioprotective effects in time and space (Naylor and Viles, 2002; Carter and Viles, 2005). Feedbacks also exist between geomorphological disturbance, driven by erosion and weathering, and habitat heterogeneity on rocky shores from the millimeter to the kilometer scale. These are in turn major controls on species' distribution, abundance and diversity (e.g., Thrush et al., 2011). Conversely, the potential roles of organisms in facilitating micro- and meso-scale geomorphic disturbance are also beginning to be explored in more detail in the rocky intertidal zone (e.g., Gómez-Pujol et al., 2006; Moura et al., 2012; Naylor et al., 2012a).

Importantly, microclimatic conditions may vary considerably between bare and colonized rock surfaces. In the terrestrial built environment, laboratory and field trials have shown that soiling and colonization by microorganisms and lichens influence rock thermal regimes and associated weathering conditions (Warke et al., 1996; Carter and Viles, 2003, 2004). Microorganisms have also been found to cause measurable changes in the thermal behavior of rocks under simulated intertidal conditions (Coombes, 2011b; Coombes and Naylor, 2012). These changes were attributed to albedo effects and the influence of micro-scale bioerosion ( $\mu\text{m}$ ) on the absorption and evaporation of water.

The influence of macro-organisms on microclimate remains understudied in the context of subaerial rock decay. One exception is the study of ivy canopies on historic buildings, which are suggested to have a bioprotective role via shading and thermal blanketing, and the absorption of particulate pollution (Sternberg et al., 2011; Viles et al., 2011). On rocky shores, the importance of macroalgae in reducing the frequency of wetting and drying cycles has been recognized (e.g., Stephenson and Kirk, 2000) but has not been studied directly. Furthermore, canopy-forming species may have a similar role on engineered structures in the intertidal zone, but to our knowledge this has never been examined. Comparatively, the ecological importance of shading by intertidal vegetation, which creates cooler and wetter habitat conditions, is an important facilitative interaction that mediates the establishment and survival of other species (e.g., Leonard, 1999). Such interactions on rocky shores may be placed within the framework of 'ecosystem engineering' (Jones et al., 1994; Harley, 2006; Gutiérrez et al., 2010).

In an applied context, building engineered structures in urban areas represents localized and very often permanent, high-magnitude disturbance beyond any natural event. This involves the introduction of new hard substrata (whether rock or concrete) and often the replacement or modification of entire habitats. This is recognized as a major conservation issue of global concern (Thompson et al., 2002; Airolidi and Beck, 2007). Based on previous field observations (Sternberg et al., 2011) and laboratory simulations (Coombes, 2011b; Coombes and Naylor, 2012), microclimatic conditions at the surface of uncolonized (i.e., newly built) coastal structures are expected to differ from colonized rocks exposed under the same environmental regimes. Habitat conditions and near-surface conditions relevant to rock decay may therefore be very different between natural rocks and artificial structures, probably contributing to the typically impoverished ecological communities found on engineered surfaces (Chapman, 2003; Bulleri and Chapman, 2010). Microclimatic conditions at the surface of new structures are also expected to change through time as they become colonized and, where conditions allow, as succession proceeds (e.g., Coombes and Naylor, 2012). As well as providing favorable habitat for other species, if macroalgae have a bioprotective role in a similar way to ivy in the terrestrial environment (via microclimatic dampening for example) this would represent a previously unrecognized ecosystem service (e.g., Costanza et al., 1997) that can support wider efforts to enhance coastal structures for biodiversity conservation (Bulleri and Chapman, 2010; Naylor et al., 2012b).

We examined the influence of canopy-forming macroalgae (fucoid seaweed) on microclimate at the surface of intertidal engineered

structures in South West England, UK. Specifically, we aimed to measure the extent to which algal canopies moderate summertime temperature extremes and short-term (minutes–hours) microclimatic variability. In doing this, we aimed to provide evidence of the mechanism by which intertidal vegetation may protect surfaces from mechanical rock decay, and how this varies in time and space. We then use these results to develop a conceptual model of the interactions and feedbacks between biological cover and microclimate, as mediated by biological and physical disturbance, and discuss the implications of the model for the mechanical breakdown of materials in the intertidal zone.

## 2. Methods

### 2.1. Study sites

Temperature and relative humidity were monitored on hard engineered structures at three sites in South West England, UK, during summer 2011 (Fig. 1). The work was undertaken in summer when organisms can influence microclimatic conditions associated with mechanical decay processes such as thermoclasty (e.g., Sternberg et al., 2011) and when heat and desiccation stresses experienced by epibiota can be significant (Helmuth and Hofmann, 2001). One structure at each of the sites was chosen based on having an existing cover of algae, ease of obtaining access and permissions, and to include a mix of structure types for comparability (Table 1). As a common material used in coastal engineering (CIRIA, 2010), concrete structures were of particular interest; a vertical concrete wall at Mylor Yacht Harbour and vertical concrete pylons at Newlyn Harbour in Cornwall were therefore chosen. Semi-horizontal limestone rock armor was monitored at a third site at Portland Port, Dorset, as a contrasting material type and surface orientation. Conditions at each of the sites varied to some degree with respect to the thickness of the algal canopy, and the aspect of the surfaces being monitored (Table 1). The importance of these factors for between-site variability and the relative influence of algae on temperature and humidity are considered in the Discussion (Section 4).

On each structure, microclimatic data were collected at two temporal scales in order to determine the influence of biological cover on thermal extremes (i.e., thermal maxima over daily tide cycles) and short-term (minutes–hours) variability when surfaces are exposed to the air (i.e., between tides). Mechanical decay processes associated with heat, drying and salt crystallization are deemed to be most important during those periods when surfaces are exposed to the sun (e.g., Stephenson and Kirk, 2001; Trenhaile, 2006; Gómez-Pujol et al., 2007). Freeze–thaw processes and potential buffering of low temperature extremes by biology may also operate in winter (e.g., Robinson and Jerwood, 1987; Sternberg et al., 2011), but this was not the focus of the present study.

### 2.2. Continuous temperature data (across tides)

In June 2011, iButton® temperature loggers (Maxim Integrated Products, DS1921G) were secured to the surface of each structure at the three monitoring sites in plastic waterproof capsules (DS9107) using marine epoxy (Fig. 2a). The iButtons® have an operating range of  $-30$  to  $+70$  °C, and were pre-programmed to log temperature continuously at 30-minute intervals at a resolution of 0.5 °C with an accuracy of  $\pm 1$  °C. The encased loggers were attached in paired 'colonized' (with algae) and 'cleared' (without algae) plots of  $10 \times 10$  cm approximately 30 cm apart (Fig. 2b), with one pair established on each structure. All loggers were positioned at Mean Tide Level for comparability. Before attachment, algae and all other macro-biology were removed from the 'cleared' plots using garden shears and a paint scraper; encased loggers in these plots were fully exposed to water and air during high and low tides, respectively. 'Colonized' plots were not manipulated, and loggers were secured beneath the existing algae canopy. Algae around all the cleared plots were trimmed to minimize 'whipping'

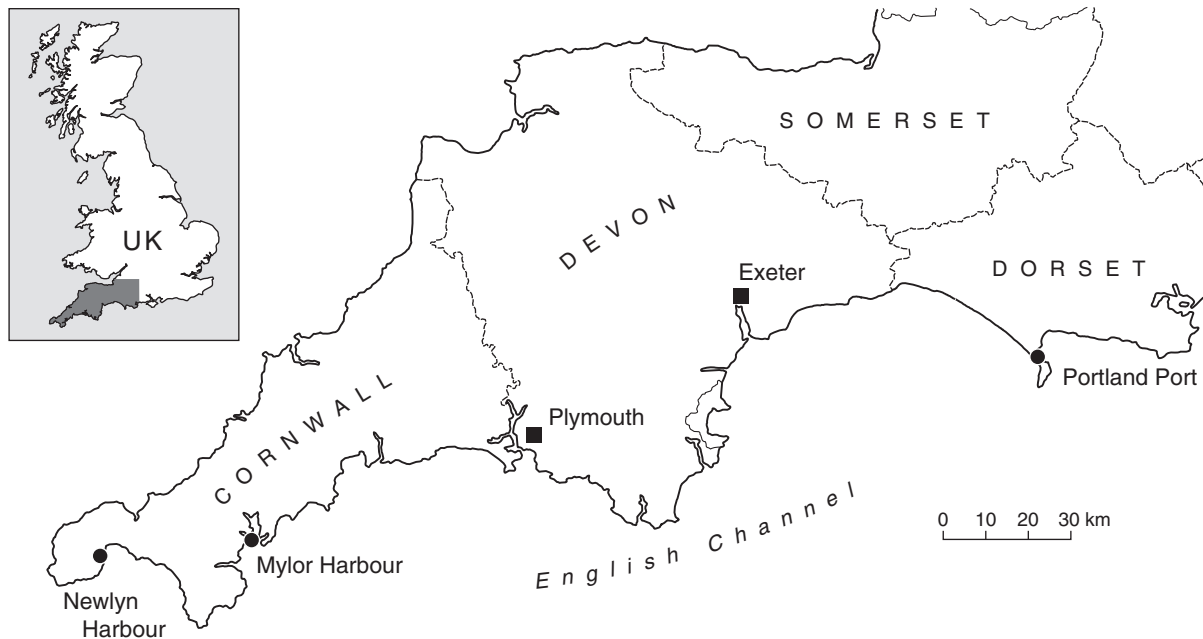


Fig. 1. Location of study sites in South West England, UK.

and the potential dislodgement of the loggers (e.g., [Trudgill, 1988](#)). Recolonizing algae were also removed from cleared plots during subsequent visits as necessary to maintain the treatments as described. Data were downloaded from each logger at roughly two-week intervals throughout the summer using a laptop computer, Blue-dot iButton® reader (DS1402D-DR8), and OneWireViewer software (Maxim Integrated Products). Data were subsequently collated for each plot into a continuous record.

### 2.3. Periodic temperature and humidity data (between tides)

Relative humidity loggers (Hygrochrons™, DS1923) could not be used underwater or placed in waterproof capsules as they must remain exposed to the air to function correctly. Humidity data were therefore collected during five different low-tide events at each site on dry, sunny days. On each day, loggers were temporarily attached to the structures with non-permanent adhesive putty during the receding tide and collected before the returning tide. Hygrochrons™ have an operating range of  $-20$  to  $+85$  °C, and were programmed to record relative humidity at 1-minute intervals with a resolution of 0.6%. Additional high resolution iButton® temperature loggers (DS1921H, operating range  $+15$  to  $+46$  °C, 0.125 °C resolution,  $\pm 1$  °C accuracy) were temporarily attached during the same low-tide

events to provide a higher resolution (1-minute) record of temperature for analysis of short-term variability. As with the permanently affixed loggers ([Section 2.2](#)), a paired plot design (i.e., cleared vs. colonized) was used during these low tides ([Fig. 2b](#)).

### 2.4. Data analysis

In order for statistical analysis to be performed on the continuous (across-tide) time-series data ([Section 2.2](#)), daily temperature maxima and range values were calculated for each plot for 30 consecutive days across July and August 2011. As each maximum and range value was derived from a different 24 h period (obtaining 30 values in each case), data were treated as independent replicate measurements and compared using ANOVA. This enabled comparisons to be made between treatments (two levels: colonized and cleared) and between sites (three levels: Mylor, Newlyn, Portland). For periodic (between-tide) temperature and humidity data ([Section 2.3](#)), variance was used as a simple statistical measure of short-term variability. This was done by calculating the variance of temperature and humidity data for a two hour period (i.e., 120 measurements) during each of the five low-tide events that were monitored at each site ([Section 2.3](#)). The period during which the loggers were acclimatizing to their surroundings, which was clearly visible at the start of each

**Table 1**  
Details of study sites.

Site name	Type of structure	Material type	Surface orientation	Aspect	Biological cover (at mean tide level)*	Algal canopy thickness
Mylor Harbour, Cornwall	Harbor wall	Concrete	Vertical	NNE	60% algae ( <i>F. vesiculosus</i> and <i>A. nodosum</i> ) 20% barnacles ( <i>Chthamalus</i> spp. and <i>S. balanoides</i> ) 20% bare space	<5 cm
Newlyn Harbour, Cornwall	Support pylons	Concrete	Vertical	NW	90% algae ( <i>F. vesiculosus</i> and <i>F. spiralis</i> ) 10% bare space	10 cm
Portland Port, Dorset	Rock armor revetment	Limestone	Semi-horizontal	NE	90% algae ( <i>F. vesiculosus</i> and <i>F. serratus</i> ) 10% bare space	10 cm

\* Biological cover denotes the community present in control plots (i.e., without manipulation). Cleared plots had all macro-organisms removed from the surface.



**Fig. 2.** Deployment of temperature loggers encased in waterproof capsules (a) on a concrete pylon in Newlyn Harbour and (b) limestone rock rubble at Portland Port.

dataset, was excluded from these calculations. These variance values were then compared between paired plots (cleared vs. colonized) at each site using two-sample t-tests.

### 3. Results

#### 3.1. Daily maximum temperatures

Fig. 3 shows a continuous record of near-surface temperature in cleared and colonized plots at the three study sites for July–August 2011. Fig. 4a shows average daily maximum temperatures at each site for the same period. These data are representative of mean daily summertime temperatures and extreme summertime maxima in South West England ([www.metoffice.gov.uk/climate/uk](http://www.metoffice.gov.uk/climate/uk), accessed January 2012).

In all cases, significantly higher temperatures were recorded in cleared plots than in those colonized by algae ( $p < 0.000$ , Table 2). Maximum temperatures were also significantly different between sites ( $p < 0.000$ , Table 2). Furthermore, interaction between 'site' and 'treatment' factors in the ANOVA ( $p = 0.001$ , Table 2) indicates that while the thermal dampening effect of algae was consistent across the sites (temperature maxima were on average 25% lower in colonized plots), the magnitude of the effect varied between locations; peak temperatures were 8%, 31% and 35% lower in colonized plots at Mylor, Portland, and Newlyn, respectively (a difference of 1.4–5.4 °C).

The greatest difference between cleared and colonized plots was 16.5 °C, which was recorded on the limestone rock armor at Portland on 13th August, and a difference of 10 °C or greater was recorded on several occasions both at Newlyn and Portland. In contrast, differences between the paired plots on the concrete wall at Mylor did not typically exceed 3.5 °C. At all sites, the greatest differences

occurred when low tide coincided with periods of peak insolation (i.e., around midday; Fig. 3).

#### 3.2. Daily temperature range

Fig. 4b shows the average daily temperature range in paired plots at each site. During any 24 hour period, the temperature range was significantly lower in colonized plots ( $p < 0.000$ , Table 3). Across all three sites the average temperature range in colonized plots (3.0 °C) was 56% lower than in cleared plots (7.3 °C), but the magnitude of this effect varied between sites ( $p < 0.000$ , Table 3); the daily temperature range was 35% lower in colonized plots at Mylor, 65% lower at Newlyn, and 67% lower at Portland, respectively. As with the maxima data, the greatest differences were measured at Portland on 13th August, when the thermal range below the algae canopy was more than 20 °C lower than the adjacent bare rock.

#### 3.3. Microclimatic variability at low tide

Fig. 5 shows a typical humidity/temperature dataset recorded at each site during low tide using temporarily attached loggers. Relative humidity was always higher in colonized plots (i.e., under the existing algae canopy), while temperature was always lower (Fig. 5; as discussed in Section 3.1). Fig. 6 summarizes the variance of microclimatic data from paired plots at each site during low tide. Both relative humidity and temperature were significantly less variable under the algae canopy over a temporal scale of minutes and hours ( $p < 0.05$  in all instances). This effect was again most pronounced when low tide coincided with sunny weather in the late morning and afternoon (Fig. 5). Across all three sites, temperature and relative humidity were on average 78% and 71% less variable in colonized plots, respectively.

## 4. Discussion

#### 4.1. The influence of seaweed on microclimate

At three different sites, seaweed was found to have a consistent and significant influence on microclimate at the surface of hard coastal structures built from concrete and limestone. Thermal maxima under algal canopies were reduced by an average of 25%, and the daily thermal range was reduced by 56% compared to adjacent areas cleared of growth. This is comparable with the 36% higher peak temperatures recorded on historic walls cleared of ivy, compared to within-canopy temperatures, and an associated dampening of thermal range (Sternberg et al., 2011). Ivy has also been found to significantly reduce the range of relative humidity on walls over a daily timescale, but this could not be determined for seaweed owing to the impracticalities of permanently deploying humidity loggers across tides. However, short-term (minutes–hours) variability of both humidity and temperature was found to be significantly lower (by more than 70%) under seaweed canopies during low-tide periods when the surfaces were exposed to the air and insolation.

This dampening effect on microclimate was clearly captured in the time series data, particularly for humidity where rapid fluctuations in cleared plots caused by wind and cloud were diminished in adjacent colonized plots (e.g., Fig. 5). This stabilizing effect of algae is significant with respect to salt weathering as the rate and extent of drying influence both the likely occurrence of crystallization and the depth within the material at which it occurs (Davison, 1986; Cardell et al., 2003). The depth of the 'wetting front' in hard materials, which has been linked to decay of terrestrial building stones, is also influenced by organic coverings and microclimatic regimes at the material–air interface (Smith et al., 2004, 2011). Less variable and higher (i.e., wetter) relative humidities below algal canopies (Fig. 6b) indicate that the

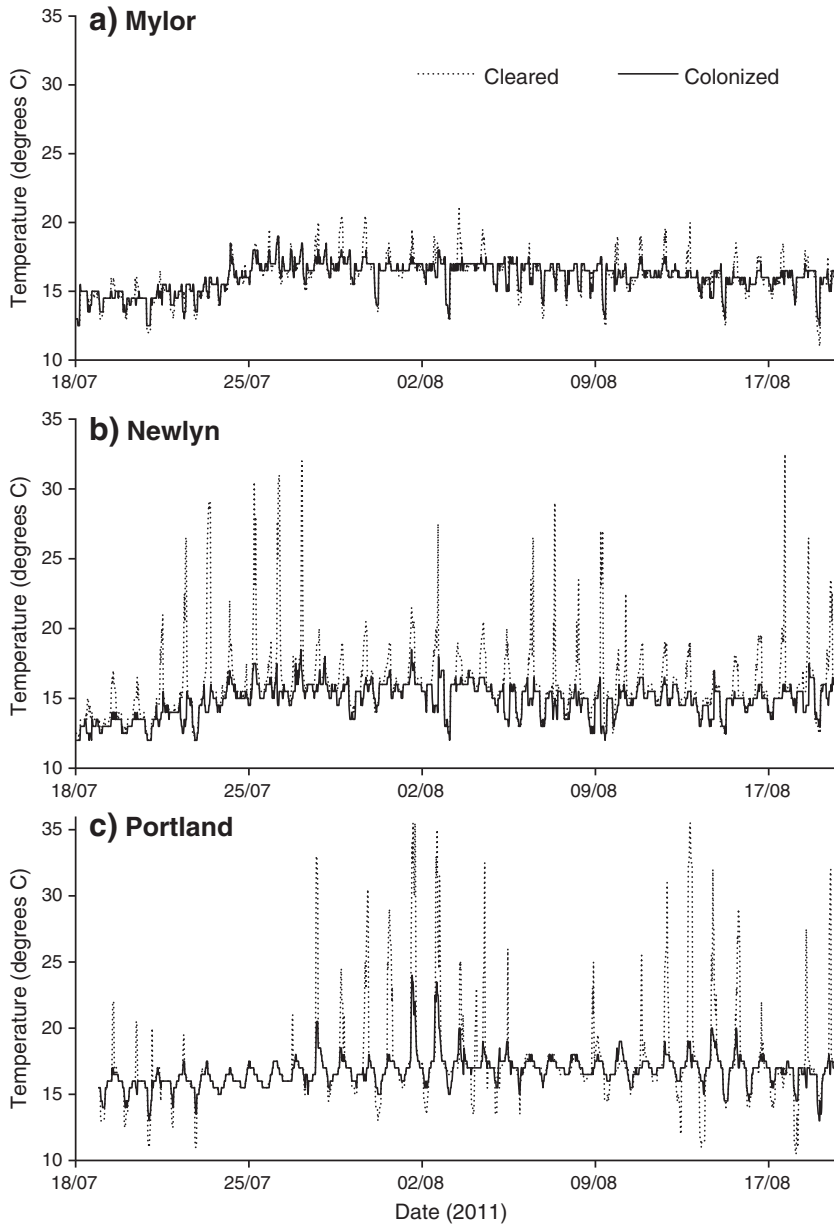


Fig. 3. Near-surface temperature records (30-minute data) in cleared and colonized plots at three sites during July and August 2011.

frequency at which a colonized surface will become sufficiently dry for salt crystallization to occur will be reduced relative to bare surfaces. At the same time, the efficiency of decay via short-term fluctuations in

moisture (i.e., wetting–drying) and temperature (i.e., warming–cooling) may be reduced (Camuffo, 1995; Goudie, 2000; Stephenson and Kirk, 2000, 2001). Shading of materials from direct solar radiation,

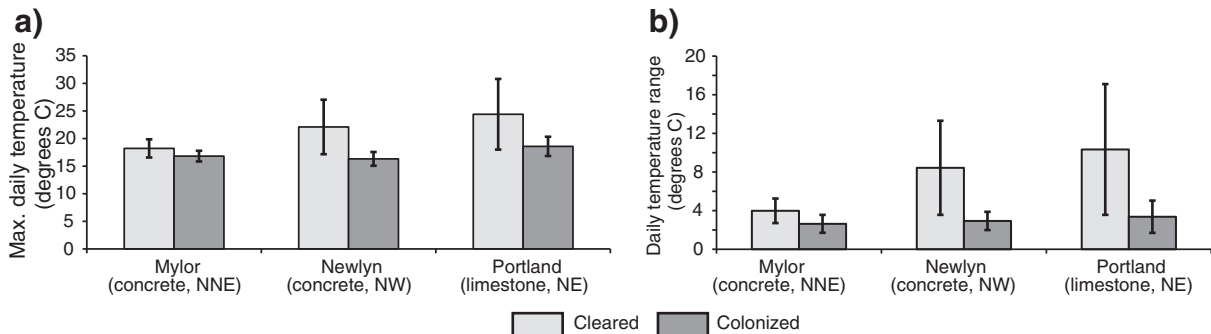


Fig. 4. (a) Average ( $\pm$ SD) daily maximum temperatures and (b) average ( $\pm$ SD) daily temperature range in cleared and colonized plots on artificial coastal structures (measurements taken over 30 consecutive days in July and August 2011).

**Table 2**

ANOVA for daily maximum temperatures ( $n=30$ ) in cleared and colonized plots at three sites during summer 2011.

ANOVA						
Source of variation	SS	df	MS	F	P-value	F crit
Site (Mylor, Newlyn, Portland)	477.519	2	238.760	19.461	<0.000	3.048
Treatment (cleared vs colonized)	845.000	1	845.000	68.874	<0.000	3.895
Interactions (site*treatment)	193.608	2	96.804	7.890	0.001	3.048
Residuals	2134.767	174	12.269			
Total	3650.894	179				

and reduced heat flux and evaporation can also limit the efficiency of mechanical decay and may thereby constitute indirect bioprotection of the underlying surface (Camuffo, 1995; Carter and Viles, 2005; Sternberg et al., 2011).

It is also clear that relative humidity below algal canopies is higher than on bare surfaces, and as such this may be indicative of enhanced chemical decay of certain substrates by processes such as hydrolysis, carbonation and solution (e.g., Jayakumar et al., 2010). The extent to which seaweeds moderate chemical weathering of hard materials in the coastal zone warrants further investigation. Such work should ultimately evaluate the relative importance of any such deteriorative influences over chemical bioprotective effects, which may include shielding rocks from acidic rainwater for example, alongside those mechanical bioprotective processes evaluated in this study.

Ecologically, established seaweed canopies reduce the frequency of potentially lethal thermal extremes, providing refuge for understory organisms like snails and limpets (e.g., Bertness et al., 1999). Such facilitation, or ecosystem engineering, is known to be important on natural rocky shores (e.g., Thompson et al., 1996; Harley, 2006; Thomsen et al., 2010), but the potential for microclimatic moderation by macroalgae on artificial (i.e., engineered) structures has not been previously recognized. Practices aimed at improving the ecological potential of coastal structures are increasingly being developed and tested in the coastal zone (Chapman and Blockley, 2009; Martins et al., 2010; Coombes, 2011a). Developing ways to increase the number of species able to colonize structures and, as this study suggests, those species that may offer additional ecosystem services such as bioprotection and facilitation, therefore require further investigation. The notion of bioprotection as an ecosystem service should help support efforts to maximize ecological potential in line with the European Water Framework Directive (e.g., Bolton et al., 2009), help developers meet stringent planning conditions, appease potential engineering concerns about the durability costs of colonization (Coombes et al., 2009), and help embed the notion of ecological enhancement in the broader design and build process (Naylor et al., 2011, 2012b).

#### 4.2. Spatial and temporal variability

The overall influence of algae on temperature and relative humidity – and by implication on surface habitat conditions and environmental

**Table 3**

ANOVA for daily temperature range ( $n=30$ ) in cleared and colonized plots at three sites during summer 2011.

ANOVA						
Source of variation	SS	df	MS	F	P-value	F crit
Site (Mylor, Newlyn, Portland)	390.903	2	195.451	15.490	<0.000	3.048
Treatment (cleared vs colonized)	954.501	1	954.501	75.645	<0.000	3.895
Interactions (site*treatment)	254.603	2	127.301	10.089	<0.000	3.048
Residuals	2195.575	174	12.618			
Total	3795.582	179				

regimes relevant to mechanical breakdown – was consistent between monitoring sites. However, the magnitude of the effect varied significantly between locations (Section 3). This suggests that site factors are important and warrant further discussion.

The three most critical between-site variables in this study were probably aspect, thickness of the algal canopy, and surface orientation. Aspect is known to be an important control on microclimate and weathering at the coast (e.g., Mottershead et al., 2003) and, while the structures at all three sites had a northern aspect (Table 1), there were differences in their positioning that gave rise to shading effects. The NNE facing concrete wall at Mylor, for example, was exposed to direct sunlight during the morning but became shaded by midday when the sun was obscured by an adjacent east-facing wall. This limited the period during which the wall was heated, and also prevented warming during the afternoon when insolation is most intense. The cover and thickness of the algal canopy at Mylor were also less than at the other two sites (Table 1), probably as a result of differences in wave exposure and because the structure was built most recently (Engelen et al., 2005; see Section 4.3). This, combined with the aspect and shading influences, likely explains the lower magnitude microclimatic differences between cleared and colonized plots at Mylor (e.g., Figs. 4 and 6). In contrast, the sub-horizontal limestone boulders at Portland received unobstructed insolation for most of the day, and this was where the greatest microclimatic differences were observed (Section 3). It should also be noted that the color of the materials at each site could not be controlled for, which may have influenced thermal regimes via albedo effects (Hall et al., 2005). However, the differences in temperatures recorded in cleared plots on the two concrete structures at Mylor and Newlyn – having comparable surface color – were also significant, which suggests that other variables such as aspect and canopy thickness contributed more to microclimatic differences between sites than material type alone.

Material type does, however, influence the relative importance of the observed differences for bioprotection. Larger-scale erosion events driven by waves are probably of more concern for engineers than fine-scale weathering on materials such as granite that are perceived to be more durable, for example (CIRIA, 2007). The potential importance of chemical deterioration of such materials cannot be ignored however, and the influences of seaweeds on conditions favoring or impeding thermoclasty may also be particularly relevant for crystalline rocks such as granite (e.g., Gómez-Heras et al., 2006, 2008). Where materials like limestone and concrete are used in maritime engineering, weathering can be especially important for durability (e.g., Thaulow and Sahu, 2004; Coombes et al., 2011). With respect to erosion, biology may have additional direct protective roles via wave energy dissipation (Mendez and Losada, 2004; Mangi et al., 2011) or by filling, stabilizing and binding potential areas of weakness such as joints in block-form coastal structures where growth is often favored. In general, microclimatic dampening is probably less geomorphologically relevant on shores and structures exposed to high energy waves, because disturbance in these settings will be broadly dominated by high-magnitude events. Fine-scale and low-magnitude decay processes can mediate erosion during storms (Naylor et al., 2012a), but in an engineering context at least, bioprotective effects are probably most important in sheltered locations such as harbors where weathering can be an issue with respect to the conservation of structures of social and heritage value (Brebba and Gambin, 2003).

Crucially, our observations demonstrate that the relative importance of algal influences on microclimate for geomorphology (and ecology) will not be consistent in time and space. Algal cover varies according to a number of factors including tidal height, biological disturbance (i.e., the presence or absence of grazers) and wave conditions (Menge and Sutherland, 1987). The potential for bioprotection via influences on microclimate is therefore predicted to be greatest where dense canopies are able to establish. Also, species able to colonize higher on the shore (e.g., *Fucus spiralis* in the UK) probably have more of an effect on the efficiency of breakdown processes because conditions are more variable at

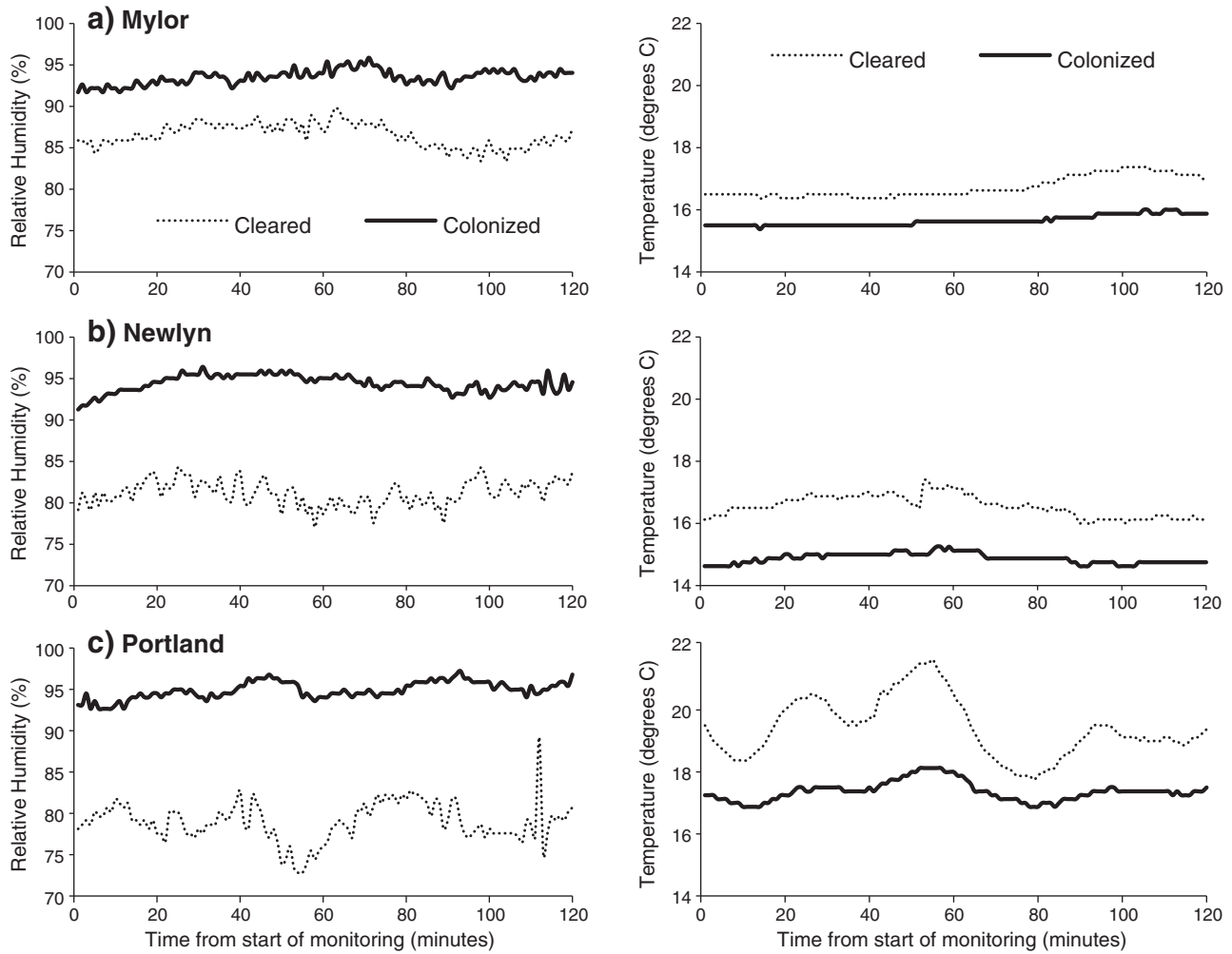


Fig. 5. Time series data of temperature and relative humidity at the surface of intertidal structures during low tide on selected dry/warm days at (a) Mylor, (b) Newlyn and (c) Portland.

higher tide levels owing to longer periods of emergence. Different species of algae also have varying morphologies, and form canopies of varying thickness and color, which must affect their microclimatic influence to some extent. The frequency and magnitude of disturbance events will also moderate biology–microclimate interactions by altering surface cover (Section 4.3). For example, stands of seaweed and mussels are often plucked from the surface by waves (Gaylord et al., 2008), which re-exposes surfaces to insolation. On rocky shores with abundant mobile sediment, abrasion may also limit growth (e.g., Airolidi, 1998), influencing the proportion of the surface that is colonized or exposed to subaerial decay.

More broadly, the strength and magnitude of these interactions are superimposed on regional climate regimes and seasonal influences. The blanketing effect of biological cover is expected to be greatest in summer and winter, and in very hot and very cold climates where thermal regimes are more critical for deterioration and biological mortality (e.g., Crisp, 1964; Helmuth et al., 2002). For example, Sternberg et al. (2011) and Viles et al. (2011) suggest that ivy canopies on historic walls in the UK can reduce the efficiency of frost weathering in winter. Research on the influence of intertidal macroalgae on winter microclimates is currently being undertaken, but it is reasonable to assume that a reduction in the frequency and efficiency of frost weathering

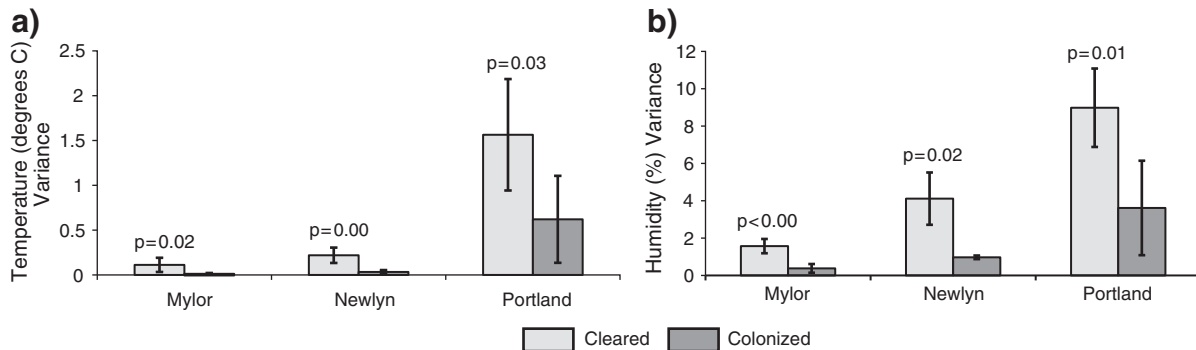


Fig. 6. Mean ( $\pm$ SD) variability of (a) temperature and (b) relative humidity data recorded in cleared and colonized plots during low-tide events ( $n=5$ ) at the three monitoring sites.

events via thermal blanketing also operates at the coast, and may be particularly relevant on some shores (e.g., [Trenhaile and Mercan, 1984](#); [Robinson and Jerwood, 1987](#)).

#### 4.3. A conceptual model

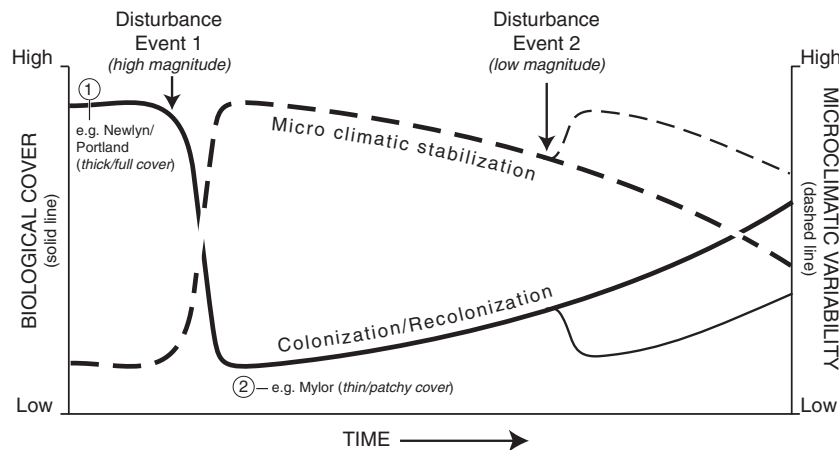
The data collected in the field show that algal canopies moderate microclimate on intertidal coastal structures, and illustrate how seaweed can have a bioprotective function via thermal blanketing. Disturbance events altering the distribution and cover of seaweed may therefore act to reduce or remove this bioprotective effect, while at the same time, seaweed canopies may reduce fine-scale physical disturbance by limiting mechanical decay of the substratum. More work is needed, however, to quantitatively relate these interactions to actual rates of rock breakdown. This is clearly a challenge owing to the numerous interacting variables operating at varying scales that influence the spatial and temporal efficiency of rock decay ([Viles, 2001](#); [Section 4.2](#)).

Developing conceptual models can support hypothesis generation about complex systems and inform new research questions (e.g., [Viles et al., 2008](#)). [Fig. 7](#) shows an idealized, temporal model of the interactions between biological cover and microclimate as supported by the data presented here, and the superimposed influence of disturbance events in the intertidal zone. The left vertical axis (solid line in the model) represents a continuum of biological cover from a completely bare or sparsely colonized surface (e.g., one that may result from an erosion event or the surface of a new/recently built artificial structure) to a surface completely covered by organisms (e.g., a thick algae canopy). The right vertical axis (dashed line in the model) represents microclimatic variability from low (i.e., a relatively stable temperature and humidity regime) to high (i.e., a relatively unstable/fluctuating temperature and humidity regime). The model suggests an overall inverse relationship between biological cover and near-surface microclimatic variability. This is supported by data presented above for algal canopies, which show a dampening effect on thermal extremes and ranges, and short-term temperature and humidity fluctuations compared to bare surfaces ([Section 4.1](#)). This general relationship is important for rock decay, as microclimate regimes influence the efficiency of breakdown processes involving fluctuations in temperature and moisture such as warming–cooling, wetting–drying and salt crystallization. In this way, the model suggests that the potential for bioprotection against mechanical decay (whether by direct stabilization of the surface or indirect microclimatic stabilization) is expected to be comparatively higher on a fully colonized surface than on a bare, uncolonized surface when exposed under the same environmental conditions.

The extreme left of the model [point (1)] represents conditions where biological cover is high and microclimatic variability is correspondingly low; the monitoring sites at Newlyn and Portland illustrate such conditions, where the surface cover of seaweed is relatively complete and thick (90% coverage in summer; [Fig. 7](#)). Conversely, point (2) in the model represents an opposite set of conditions, where biological cover is absent, thin or patchy, and microclimatic variability is comparatively high. Point (2) is also the effective starting point for new – or relatively young – materials arising from the construction of new coastal infrastructure, which have not yet become colonized. This is illustrated by the concrete wall at Mylor, which has a thin and patchy cover of algae, and showed the lowest magnitude differences between cleared and colonized plots with regards to microclimate.

Importantly, the model suggests that disturbance events acting to remove or reduce biological cover can mediate transitions between such relatively stable and unstable microclimatic states, at least at micro- to meso-scales most relevant to weathering and ecological stress. 'Disturbance Event 1', for example, denotes an event of sufficiently high magnitude to completely remove biological cover, or indeed the upper layer of the substratum itself, resulting in a step-change between point (1) and point (2) conditions ([Fig. 7](#)). This might include a large-scale erosion event during a storm (e.g., [Underwood, 1999](#)) or mass mortality following a period of hot weather (e.g., [Harley, 2008](#)). Parallel concepts of phase shifts and the development of alternative community states are important for ecological and biogeomorphological changes in a range of systems, including rocky shores ([Paine and Trimble, 2004](#); [King et al., in press](#)).

The model also recognizes that for bare surfaces, conditions may change via natural succession, as colonization (or recolonization) occurs through time ([Fig. 7](#)). Importantly, the rate of such 'recovery', denoted by 'colonization/recolonization' and 'microclimatic stabilization' in [Fig. 7](#), will depend on many factors such as tidal height, local larval/spore supply, and the geological and geomorphological properties of the substratum that influence biological settlement and survival (e.g., [Moschella et al., 2005](#); [Coombes et al., 2009](#); [Coombes, 2011a](#)). Indeed, a complete cover of biota may never occur, irrespective of time, where physical and biological conditions are limiting. Equally, lower-magnitude disturbance events (e.g., 'Disturbance Event 2' in [Fig. 7](#)) occurring during phases of colonization/recolonization may revert conditions back to an earlier state, when biological cover is lower and microclimatic variability assumed to be greater. Such events might include plucking of a seaweed clump from within a larger stand of algae, or a localized increase in grazing pressure ([Menge and Sutherland, 1987](#)). Where disturbance is frequent, such as on urban structures that require maintenance, biological recovery may be limited and the potential efficiency of bioprotection



**Fig. 7.** Conceptual model of interactions between biological cover (e.g., seaweed canopy coverage and thickness), disturbance events (that act to reduce or remove biological cover) and microclimatic stability in the intertidal zone: (1) denotes a heavily colonized surface (e.g., monitoring sites at Newlyn and Portland); (2) denotes an uncolonized or patchily-colonized surface (e.g., the monitoring site at Mylor).



can be assumed to be comparatively low. In this study, the occurrence of new algal sporlings in experimentally cleared patches over a period of weeks and months indicates that the dynamics represented in the model (i.e., colonization, disturbance, recolonization) can operate over relatively short periods of time, at least when conditions for regrowth are favorable. Finally, it is worth noting that while bioprotection is expected to be most important where disturbance is low and biological cover is correspondingly at its maximum, such conditions may not represent the most ecologically beneficial state. For example, a community dominated by a few macroalgae species may have high bioprotective potential but low biodiversity value (although this will certainly not always be the case). Such disparity between the geomorphological and ecological states that are perceived to be ideal, at least in terms of bioprotection and biodiversity, respectively, may be an inherent challenge in complex biogeomorphological systems that warrants much more theoretical and experimental attention.

## 5. Conclusions

In the first known study to quantitatively examine the influence of macrobiota on conditions for mechanical weathering in the intertidal zone, seaweed was found to significantly alter microclimate. Reduced thermal maxima and dampened short-term fluctuations in temperature and relative humidity were consistently measured beneath algal canopies at low tide, regardless of location. Via a stabilizing effect on microclimate, we suggest that canopy-forming macroalgae moderate the surface weathering environment, reducing the efficiency of mechanical breakdown associated with fluctuations of temperature and moisture. In addition to such bioprotective effects, seaweed canopies offer more favorable habitat conditions for other organisms compared to bare surfaces. The importance of these effects is predicted to vary in time and space as a function of regional and local factors including climate and seasonality, aspect, biological cover (including canopy thickness and plant density), and tidal height. Furthermore, the magnitude and frequency of ecological and physical disturbance may mediate shifts from relatively stable to unstable microclimates via changes in biological abundance and surface cover. At the same time, microclimate has feedbacks to disturbance, by reducing or enhancing temperature-related mortality for example, or the frequency of erosion events that are pre-conditioned by weathering.

Further work is now needed to examine how the complex interactions and feedbacks between biology, microclimate and geomorphology operate in different locations and under different environmental regimes. Effort must be made to evaluate the influence of epibiota on actual decay rates and to examine the potential bioprotective value of different types of biological growth. This includes encrusting species like barnacles that may directly protect surfaces as well as alter internal rock temperature and moisture regimes. It is also crucial to evaluate any bioprotective influences against biodeteriorative effects that may be operating concurrently. The implications of biotically-moderated microclimates for the efficiency of chemical decay processes, for example, remain to be evaluated. This is a particularly difficult challenge, but a combination of controlled laboratory experiments and field trials would prove useful here (e.g., Viles et al., 2011).

Considerable opportunity also exists for the integration of the respective geomorphological and ecological sub-disciplines of biogeomorphology and ecosystem engineering on rocky shores, as is increasingly being recognized in other environments (e.g., Francis et al., 2009; Corenblit et al., 2011; Osterkamp et al., 2012). Indeed, specific biogeomorphological interactions such as bioerosion, bioprotection, and bioconstruction may represent previously unrecognized ecosystem engineering linkages in the intertidal zone as well as in other environments. For example, microclimatic buffering by seaweed not only reduces ecological disturbance associated with climatic extremes (Thompson et al., 1996; Harley, 2006) but may also reduce the efficiency of physical disturbance associated with the decay and erosion of hard substrata. Furthermore, the direct involvement of organisms in the

decay and erosion of hard materials and the associated changes in geomorphological properties and behaviors resulting from biological activity (e.g., albedo, porosity, surface roughness etc.) can have linked consequences for landform evolution and ecological communities that warrant much more investigation (Corenblit et al., 2011; Jones, 2012).

In an applied context, using ecological enhancement methods to facilitate the colonization of hard coastal structures by species that moderate microclimate and limit rates of deterioration could offer potential engineering benefits alongside any associated biodiversity gains. In this way, bioprotection may represent a previously unrecognized ecosystem service in engineered coastal environments. Identifying and promoting how and to what extent the organisms colonizing engineered structures provide practical benefits or services to people, such as meeting planning requirements for ecological enhancement, or improving the durability of construction materials via bioprotection, should be a research priority if managers and engineers are to be expected to include habitat provision in the design of their structures. Recognizing that bioprotection is unlikely to be important in an engineering/durability context in all locations, further work is required to identify where these kinds of biogeomorphological interactions are most relevant for management, and which species offer the greatest potential to support wider engineering, social and conservation targets.

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