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The influence of engineering design considerations on species recruitment and succession on coastal defence structures

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The influence of engineering design considerations on species recruitment and succession on coastal defence structures

by

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AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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Relevant scientific seminars and conferences were regularly attended at which work was often presented; external institutions were visited to forge collaborations and a contribution to two collaborative papers made, which have been published. Further papers with the author of this thesis as first author are in preparation for publication.

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Collaborative work with the Environment Agency and the University of Exeter led to the development of new guidance for ecological enhancement of hard coastal structures, which was awarded with an 'Environment Agency Evidence award' for excellence in working externally. The panel was formed by the Chief Executive of the EA alongside representatives from Defra, the British Geological Society and Natural England.

Involvement with the design and testing of ecological habitat enhancements as part of the Environment Agency's Shaldon and Ringmore Tidal Defence Scheme has also been rewarded, with the overall scheme winning an Environment Agency Project Excellence Award for 'Exemplar Safety, Health and Environment Performance'. Four national awards of this level are awarded each year, and judges were particularly impressed with the work to create niche habitats in the flood walls. Both awards were in 2012.

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I, Juliette Elizabeth Jackson, hereby declare that the research presented in this thesis is my own original work, except where referenced otherwise.

…………………………………………………. ……………………..

Juliette Elizabeth Jackson Date

The influence of engineering design considerations on species recruitment and succession on coastal defence structures

Juliette Elizabeth Jackson

Abstract

Engineering design considerations of artificial coastal structures were tested to resemble as far as possible the nearest natural equivalent habitat, ecologically valuable rocky shores, as a potential management option. Coastal areas around the world attract urbanisation but these transitional areas between sea and land are inherently vulnerable to risk of flooding and erosion. Thus hard structures are often built in sensitive coastal environments to defend assets such as property and infrastructure (roads, railways, ports) against rising and stormy seas. The design, construction and maintenance of hard defences should wherever possible incorporate ecological considerations to enhance biodiversity, including maintaining or restoring natural habitats and wild species to ensure favourable conservation status.

Artificial habitats are less topographically complex than natural rocky shores, at millimetre scales in terms of surface roughness, centimetre to meter scales for crevices and pools to tens, hundreds and occasionally thousands of meters for variation in tidal height and wave action gradients. The habitat value of design features of an existing seawall and breakwater, such as areas of different slope and orientation, and the presence of crevices and pools, that are analogous to habitat created by topographical features on a natural shore, were demonstrated by their ability to support distinct assemblages of species.

Furthermore, evidence is provided that a greater variation in the type of design features led to a higher species diversity occupying the structure, and included species that would otherwise not be present on the structure. The long term succession on artificial structures and the biodiversity reached on intertidal coastal defence structures is described to inform understanding of timescales over which successional processes operate. As a consequence of succession, artificial structures of large extent eventually resemble natural rocky shores of the same exposure.

Increased surface heterogeneity of concrete armour units on Plymouth Breakwater by drilling holes was effective in adding habitat and increasing local species diversity. These can be added at the construction stage or post construction. In a real case study, added recessed pools, holes and surface texture during the construction of a tidal defence sea wall at Shaldon made heterogeneous surfaces to add habitat and influence species diversity, without compromising the engineering function or aesthetics of the structure.

This study provides coastal engineers and decision makers with well researched practical design options to inform future construction and maintenance of coastal defence structures that will encourage specific outcomes to mitigate the negative environmental impact of artificial structures and contribute to conservation priorities.

This thesis is dedicated to my mum, Jill Good, whose smile says so much even though she can no longer find the words; and to my mother-in-law, Gael Mitchell, whose wise words will stay with me forever.

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Chapter 1
General introduction

1.1.1 The Coastline

Anthropogenically driven global environmental change is accelerating (IPCC 2001, 2007, 2013), leading to a warmer world and a rising sea level. The coastal zone is particularly vulnerable, threatening an economically and ecologically important area. In this thesis I examine how an environmentally sensitive approach to design of coastal defences can play a role in adaptation to climate change. In the rest of this introductory chapter an overview is given of the coastal zone, its conservation and risks from flooding and erosion. Coastal defences are often considered as analogues of rocky shores, the main factors determining distribution patterns and community structure on both natural and artificial hard substrates are briefly summarised. Coastal areas are valuable to multiple sectors. They provide goods and services to society, including the provision of food, transport routes, medicines and employment for significant numbers of people (Rees *et al.*, 2010). Coastal areas also provide important functions such as flood control, storm protection and sedimentation. The cultural value of coastal areas includes the non-material benefits that people derive from the aesthetics of geomorphology and biodiversity, giving rise to recreation activity and the tourism industry (Beaumont *et al.* 2008). The ecological value of coastal areas thus underpins multiple sectors directly in the case of fisheries, particularly in their role as nursery areas for many commercial species, and indirectly for tourism and recreation. Some rare and sensitive coastal habitats exist alongside a diverse array of industrial activities such as fishing, tourism, agriculture, transport, construction and recreation. Maintaining or improving ecological value has multiple benefits for society as well as being of economic importance.

Mainland Britain has over 17,820 km of coastline (Frost *et al*. 2011) with an associated narrow transitional zone between land and sea that varies in width according to its slope and tidal range. Intertidal coastal areas are under increasing pressure from multiple factors, many of which reduce or squeeze the extent of the intertidal area and steepen the shore profile (Taylor, *et al.,* 2004). In addition to anthropogenic pressures, predicted rising sea levels and increased global sea temperatures threaten coastal areas (Gray, 1997; Hawkins *et al*. 2008; Hawkins *et al.* 2009; IPPC, 2007; Osborne and Hulme, 2002). Coastal areas are prone to erosion with flood and storm events and become inundated as a consequence of rising sea levels and stormier seas (Airoldi, *et al*. 2005; IPPC, 2007; Jackson and McIlvenny, 2011; Masselink and Russell, 2007). Although the increased frequency and intensity of storms is often reported, supporting evidence for this statement has not been widely documented. However, higher sea levels are widely accepted, and a consequence of higher sea levels is that the frequency and intensity that storm impacts are felt will increase.

Naturally occurring habitats, such as sand dunes, mudflats and salt marshes are increasingly being utilised to accommodate flood water and act as a buffer to storm waves (Angus *et al*. 2011). The option of using natural habitat for protection is not always available however, as appropriate space is restricted due to landward development. The use of artificial structures is often deemed necessary, especially when coastal property, industries and transport infrastructures require protection from flooding and erosion.

1.1.2 Conserving biodiversity and coastal habitat

Marine and coastal nature conservation measures are relatively recent, and of a small scale when compared to the conservation measures made on land despite their high ecological value. For example, Lundy became England's first statutory Marine Nature Reserve (MNR) in 1986 and England's first Marine Conservation Zone (MCZ) in 2010 (DEFRA, 2013). There are 81 marine Special Areas of Conservation (SACs) out of a total of 621 designated under the Habitats Directive, and very few marine Sites of Special Scientific Interest (SSSIs) (Frost *et al*. 2011). There are extensive coastal and estuarine Special Protection Areas designed primarily for bird conservation. Developments in terrestrial conservation have occurred at a quicker rate compared to marine and coastal conservation owing to legislation to influence landowners to conserve wildlife, habitats and landscapes. In contrast, marine conservation has lagged owing to an incompatibility of area based conservation measures with sector based management regimes (Cole-King, 1995). Historically conservation of land and marine environments has also differed owing to accessibility issues for the marine realm combined with differing conceptual attitudes and levels of interest (Cole-King, 1995). In recent years the most notable policy initiative in Europe is the Marine Strategy Framework Directive (MSFD), adopted by the EU in 2008. The MSFD uses an ecosystem based management approach in order to achieve *Good Environmental Status* (GES). Fenberg *et al.* (2012) present evidence that marine reserves may be an integral tool to the MSFD aim to ensure the long-term health of Europe's marine ecosystem.

Ecological value is often described using measures of biodiversity. Biodiversity is defined as the variability among living organisms from all sources, and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (Angel 1993). There are many different measures of diversity, in this thesis I use species richness, which refers to the number of species in an assemblage of species within a given area. Maintenance of biodiversity is the focus of many strategic policies, such as the United Nations' Convention on Biological Diversity, the European Community Biodiversity Strategy, the Habitats Directive and the Marine Bill.

Environmental policy both in the UK and Europe recognises the significant biodiversity value of coastal habitats, designating them as priority habitats for strategic protection through various policy initiatives, such as "*Biodiversity 2020: A strategy for England's wildlife and ecosystem services*" (DEFRA, 2011). Biodiversity 2020 takes into account 'Making space for nature' (Lawton *et al*., 2010), a major review of England's wildlife sites and ecological networks in the UK, and the National Ecosystem Assessment (Frost *et al*., 2011), a comprehensive study of the benefits nature provides to our society and economy. Coastal habitats are also protected under European legislation, such as Natura 2000 which has been implemented with an increased focus on Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) in the UK. Inshore sublittoral habitat and species are included in the UK Biodiversity Action Plan (BAP), the first national biodiversity action plan following the Convention on Biological Diversity (CBD), which the UK signed up to in 1992. In some instances, unique community structure may be of greater value than species diversity, for example very exposed rocky shores support several species that are restricted to areas of intense physical stress, such as areas of high wave exposure (Dayton, 1971).

1.1.3 The need for coastal defence and protection in urban areas

High wave exposure can exert a strong physical impact on urbanised coastal areas making them inherently vulnerable to damage. In the UK, Defra, the Environment Agency and other operating authorities manage flood and erosion risks through a range of policy, planning and operational activities. The potentially destructive forces of waves, often in combination with rising sea levels, tides and currents, can cause erosion and flooding. Coastal assets often need defending from destructive forces of high impact waves. To defend the shore against erosion and storm damage it is necessary to reduce the force with which waves, particularly storm waves, approach the shore by intercepting them to reduce the energy reaching the foreshore or by strengthening the portion of the shore where waves impact. In these cases hard structures such as detached nearshore breakwaters and seawalls are widely used. Breakwaters protect harbours, ports and marinas from wave energy and strong currents. Seawalls separate areas of land from the sea and are built to prevent coastal erosion and other damage due to wave action and storm surge, such as flooding (Firth *et al.,* 2012). Conventional breakwaters comprise raised reefs, and their crests are typically set above mean high water and permanently exposed throughout the tidal cycle. Low-crested and submerged breakwaters are (typically) shore-parallel structures that are not connected to the shore (Burcharth *et al.* 2007). They are raised reefs with crests that are submerged for part of the tidal cycle (Challinor and Hall 2008, Moschella *et al*. 2005).

The recent increased occurrence of flooding in many coastal areas has been explained by the impacts of climate change, including the predicted rise in sea level and a likely increase in intensity, severity and frequency of storms (Airoldi *et al*. 2005; Bulleri and Chapman, 2010; Chapman and Bulleri, 2003; Davis *et* *al.* 2002; IPPC, 2007; Moschella *et al.,* 2005) or storm damage. For this reason, there is increasing urgency for protective measures against flooding and erosion. Coastal protection may prevent shoreline inundation, which will reduce damage to or prevent destruction of coastal properties and cultural heritage; reduce saline intrusion to estuaries and groundwater aquifers; reduce sedimentation and restore or preserve habitats or recreational areas (Polomé *et al.* 2005). Seawalls are widely used to protect assets at risk of erosion and flooding. Other defence and protective measures include the placement of groynes, gabions, revetment, rock armour or piles or the retention of a natural sea defence, such as sand spits, salt marshes or sand dunes. Coastal protection is a multidisciplinary challenge for engineers, ecologists and socio-economists with political imperatives, owing to the continued physical pressures on the coastline, the fragile nature of complex habitats, and the wide range of stakeholder interest.

1.1.4 Introducing artificial defences to natural coastal habitats

A recent European study of coastal geomorphology and erosion (EUROSION, 2004) found that the coastline of England was most affected, with almost one third of its coastline suffering from erosion. Protective measures along the English coastline were also greatest, with almost half of its length lined with coastal defences or fronted with artificial beaches (Masselink and Russell, 2010). The extent of coastal protection is expected to rise (Connell and Glasby, 1999) with the predicted increase in flood risk. Building and maintaining hard infrastructure in sensitive coastal environments has positive and negative impacts on the environment, which can be temporary or prolonged. As with the construction and placement of any man-made structure, detrimental impacts on the environment are often a concern, and it is inevitable that damage to some marine life and habitats will occur at the time of construction (Airoldi *et al.*, 2005; Chapman and Bulleri, 2003; Connell and Glasby, 1999; Petersen and Malm 2006). Once in place, many structures will fragment large areas of relatively flat seabed of soft substrate with hard, protruding structures that may be suitable for colonisation by new species to the environment (Thompson *et al.* 2002, Moschella *et al.* 2005). The introduction of hard artificial structures onto natural rocky-bottom habitats may not affect the fundamental nature of the habitat, particularly when these structures are built of natural stone (Thompson *et al*. 2002).

In the majority of cases, hard structures are poor ecological surrogates for natural shores. The spatial extent of artificial habitats is generally much less than patches of natural habitat. Structures such as breakwaters and seawalls are also topographically less complex than natural rocky shores and thus habitat provision is much less at a variety of spatial scales (Chapman, 2006, Firth *et al.* 2013, Moschella, 2005). Suitable habitats need to meet the physical and biological requirements of a species to enable it to survive, grow and, ideally, reproduce (Firth and Crowe, 2010). In time, communities that increase the perceived value of an area may become established.

The use of artificial reefs for the purpose of enhanced fisheries, habitat protection and recreational activities such as angling, diving and surfing is increasing (Challinor and Hall 2008). The construction of artificial reefs include deployment of natural materials such as rock, manufactured materials such as concrete and materials of opportunity such as decommissioned vessels, oil platforms and tyres (Perkol-Finkel *et al.* 2006; Challinor and Hall, 2008). The presence of artificial reef structures will increase the environmental carrying capacity of an area (total biotic abundance and biomass) by providing additional habitable space to an area that was previously uninhabitable (Pickering and Whitmarsh, 1997). The importance of artificial reef design in maximising the production potential for exploitable species has been recognised (Pickering and Whitmarsh, 1997) and effective design of artificial reefs must consider structural aspects such as composition and arrangement of material type and location including depth, surrounding seabed and hydrodynamic environment (Challinor and Hall 2008).

Two hypothesis exist to describe the community dynamics of artificial structures: the production hypothesis and the attraction hypothesis (Pickering and Whitmarsh, 1997). The production hypothesis states that artificial reefs provide resources that increase the biomass and the abundance of mobile species of fish and crustaceans. These resources include increased availability of usable space, food, and refuges from predators together with suitable sites for reproduction and recruitment (Pickering and Whitmarsh 1997; Martin *et al.* 2005). In contrast, the attraction hypothesis states that artificial reefs attract fish from other habitats as a consequence of behaviour, but do not increase the total biomass (Svane and Petersen 2001). Martin *et al.* (2005) suggest that increased diversity of mobile fauna around low crested structures is local to the structure, particularly in coastal areas dominated by soft sediments, by attracting species typical of rocky shores.

The ecology of structures such as artificial reefs, seawalls and breakwaters are often compared to that of rocky shores as they are considered to be the nearest natural equivalent (Thompson *et al.* 2002). Rocky shores are valuable marine habitats as they form extensive feeding, resting, spawning and nursery areas for many marine species, and they provide unique habitats that support a unique community of species. Study of the rocky shore environment has developed our understanding of the physical challenges of this dynamic environment, species specific habitat requirements, essential resources for species survival and the initial supply of individuals (See Raffaelli and Hawkins, 1996; for review).

Changes in physical processes such as wave regime, hydrodynamics and depositional processes that occur in the vicinity of artificial structures that are deployed for coastal defence will influence the ecology of the wider geographical area (Airoldi *et al*., 2005; Martin *et al.* 2005), compared to the local scale of the structure itself (Moschella *et al*. 2005).

1.1.5 Environmental and physical factors influencing the distribution of organisms on natural rocky shores and artificial structures

The distribution and abundance of marine epibiota depends on interactions between species and the environment and each other (Airoldi *et al*., 2005; Benedetti-Cecchi *et al*. 2000; Raffaelli and Hawkins, 1996). Multiple environmental gradients influence the shore and the species living on it in different ways. Specific environmental characteristics of the coastal area, such as tides and waves, and characteristics of the coastal landform, such as particle size and surface heterogeneity, influence habitat attributes and the distribution of organisms (see Raffaelli and Hawkins, 1996). The influence on habitat and distribution of species of many environmental variables is similar to natural rocky shores because of the influence by the same environmental variables – namely tides and waves.

Recruitment of benthic organisms to a site occurs predominantly by migration from adjacent substrata and the settlement of spores and larvae. Successful recruitment to an area is influenced by currents, depth and distance to shore. Once a species has arrived, the presence of free space and the quality and heterogeneity of substrate will influence settlement success. Populations of most intertidal species are described as open, because outside sources recolonise the area in each new generation through planktonic dispersal (Hughes *et al*. 2000; Thompson *et al.* 2002). Several critical stages must be overcome before reaching adulthood: survival of larvae, settlement, recruitment and juvenile stages.

Initial colonisation of bare areas, the sequence of succession and the mature community reached are not always predictable and orderly (Connell and Slatyer, 1977; Raffaelli and Hawkins 1996). Most artificial reefs will eventually be covered dynamically by a mosaic of patches at different successional stages (Connell, 1972; Connell and Sousa, 1983); these reflect the heterogeneity observed on natural hard substrate but seldom of the same diversity (Svane and Petersen 2001). Most local assemblages change, either as a result of frequent disturbances or as a result of more gradual climatic changes (Connell, 1978). Changes in species assemblages maintain diversity by preventing the elimination of inferior competitors (Connell, 1978). Interspecies interactions are crucial in determining the course of succession. For example, keystone species, including grazers like *Patella*, are recognised for maintaining community composition and structure (Coleman *et al.* 2006; Hawkins 1981; Hawkins and Hartnoll, 1983; Jenkins *et al*. 2005; Jones, 1948; Raffaelli and Hawkins, 1996 Southward and Southward, 1978). In describing the physical challenges that intertidal species are exposed to, and the mechanisms used to cope with these challenges, we can begin to understand the potential benefits that specific structural features create, and the importance of specific features in channelling succession to achieve a particular type of assemblage.

The intertidal position of natural coastal habitats is a major governing factor creating similar habitats and physical challenges. The rise and fall of the tide over the shore can be referred to as the 'emersion- submersion' cycle (Little and Kitching 1996; Raffaelli and Hawkins, 1995), and causing a sharp change in environmental conditions along the vertical height on the shore (see Raffaelli and Hawkins 1996 for review). Many intertidal species will experience periods that are marine and periods that are essentially terrestrial, presenting a host of physical challenges such as extremes in temperature and humidity. The impact of the tide on the ecology of an area can be observed on all shorelines as clearly defined zones of species (McCarter and Thomas 1980; Raffaelli and Hawkins 1996). The majority of intertidal inhabitants are fundamentally marine and have developed mechanisms to cope with periodic intervals exposed to the air (See Connell, 1972; Raffaelli and Hawkins, 1996; Lewis, 1964; Little and Kitching 1996; Thompson *et al.* 2002 for reviews). Species, or assemblages of species, are distributed according to their different abilities to cope with physical factors and their variation in responses to the physical challenges (Lewis, 1964; Raffaelli and Hawkins 1996 for reviews) . The harsh physical environment of the high shore restricts the ability to survive (Hawkins and Hartnoll, 1985; Raffaelli and Hawkins 1996; Schonbeck and Norton, 1978; Southward 1958). In general physical factors set the upper limits of most intertidal species. This generalisation is based on factors such as the need for immersion which for example enables most algae to photosynthesise, and enables most aquatic animals to feed.

Lower limits are generally set by biological interactions such as predation, grazing and competition (Connell, 1972; Lubchenco, 1978). Lower shore species outcompete higher shore species (Hawkins and Hartnoll, 1985). There is, however, evidence that upper limits of some low shore species can be set by grazing algal turf and canopy (Southward and Southward, 1978; Boaventura *et al.* 2002). Competition can also set the upper limit of fucoids and kelps (Hawkins and Hartnol, 1985; Jenkins *et al*. 1999; Ingolfsson and Hawkins 2008). To date there are virtually no clear cut examples of physical factors setting lower limits of species on rocky shores.

Coastal habitats are susceptible to wave action. Waves can exert a destructive mechanical effect, including scour by sand and shingle, circulate water, and disturbance in some locations and deposit sediment in others (Ballantine 1961). The amount of wave action experienced by a shore depends primarily on the distance over the sea that the wind has travelled and the wind speed. The slope or vertical profile of the shore has an influence on the shape of waves and the point at which they break, thus affecting the force exerted on the shore by the breaking wave. On relatively flat shores, waves break far out from the shoreline, then 'spill' over the shore, while on steep shores the waves come close in before 'surging' up the rock face (Little and Kitching 1996). High species diversity can occur on disturbed shores because of the continuous reduction of predators and the renewal of the major resource of primary space (Connell, 1978). On rocky shores and artificial coastal structures, waves are therefore important in freeing space often through the dislodgment of larger older species (e.g. Jonsson *et al.* 2006).

For artificial structures, the area of the intertidal zone depends on the length and width of the structure, the width being determined by the slope of the structure. Artificial structures are often vertical or steeply sloping, creating a small vertical area, whereas the gradient of many rocky shores is relatively horizontal or gently sloping (Chapman, 2006). As well as dictating the extent of the intertidal area, the shore profile can also influence the conditions experienced by epibiota, for example steeper shores drain more quickly. Rocky shores are often heterogeneous in profile, with areas that can range from vertical cliff to shallow sloping shore platforms.

The timing of placing a new structure into the marine environment will affect the rate that species will arrive and settle (Svane and Petersen, 2001), and the rate that succession will take place. Ecological succession is the sequence of colonisation and species replacement of a site over time (Connell and Slatyer 1977. Three models of succession were first proposed by Connell and Slatyer (1977): facilitation, tolerance and inhibition. These models of succession consider the net effect of early successional or pioneer species on the establishment of later successional species. Understanding the mechanism of succession can facilitate predicting the sequence of succession, and subsequently modify this sequence to encourage a specific type of mature community development.

Whilst the influence of conditions on habitats and species distribution is similar for natural rocky shores and artificial structures, and the tide and wave regimes experienced are comparable; the landform or topographic characteristics of the shore or structure are equally important. Considerable differences in landform characteristics, however, exist between natural shores and artificial structures.

Rocky shores can comprise of large boulders on solid rock, providing large particle size that give conditions suited to accommodating a specific type of community. The large particle structure of rocky shores gives added biological richness when compared to coasts with boulder free bedrock and cliff habitats; owing to the increase in suitable habitats created by localised features such as overhangs, crevices, gullies, overhangs, caves, pools and damp areas (Garrity 1984; Johnson *et al.* 2003; Raffaelli and Hawkins 1996). The rock type and texture has an influence on water drainage, which will also affect the microhabitats available. These microhabitats give rise to microclimatic conditions that are considerably different to the conditions experienced on the open rock face (Southward, 1954), such as reduced period in air, less extremes in temperature and light, and reduced wave action.

Increased surface heterogeneity will improve the quality of a space by reducing extremes of local environment conditions, thus improving its suitability for inhabitancy, and increase the quantity of available space (Johnson *et al.* 2003). The primary space created by the surface of the rock is the resource that is in greatest demand (Raffaelli and Hawkins 1996), and the level of habitat complexity has a strong influence on the distribution and abundance of species (Helmuth and Hofmann, 2001; Firth *et al.* 2012; Martins, 2010; Menge *et al*., 1996, Naylor *et al.* 2011; Underwood, 2004). A diverse surface allows for the existence of different microhabitats that are considered essential to accommodate a diverse array of species (Jensen 1998; Chapman and Bulleri 2003) and the different life stages (Challinor and Hall 2008; Hawkins and Hartnoll, 1982). Microhabitats ameliorate environmental conditions by reducing thermal and desiccation stresses during low tide (Gray and Hodgson, 1998). Many species will settle in pits, holes or crevices as these provide shelter for avoiding the physical extremes caused by waves, tides and currents (Bracewell et al, 2012; Cartwright and Williams 1990; Little and Kitching 1996; Raffaelli and Hawkins 1996) and improve grip to avoid dislocation (Hawkins and Hartnoll 1983).

Surface diversity will also influence biological interactions such as competition and predation, and promote coexistence of species through niche segregation (Connell, 1978; Johnson *et al.*, 2003; Wahl and Hoppe 2002). At low tide, mobile animals such as snails will retreat to these protective refuges (Garrity 1984). Motile swarmers of green algae seek out crevices in which to settle (Little and Kitching 1996). Algae can also escape grazer action by settling in inaccessible crevices (Little and Kitching 1996), such as the gaps created between barnacles (Hawkins 1981).

In many situations the influence of environmental conditions and landform features on habitats and species distribution are likely to be similar between natural rocky shores and artificial structures, but the landform features are often different. Within the intertidal area, the vertical habitat of artificial structures is generally highly uniform, whereas the vertical habitat of rocky shores is highly variable.

Although more uniform than natural shores, artificial structures do have some landform features that influence habitats and species distribution. Chapman and Blockley (2009) found that small crevices present on the surface of seawalls increased the diversity of sessile animals and algae, but the increase in diversity is limited by the amount of habitat created by crevices. Lemire and Bourget (1996) identified that substratum heterogeneity had an impact on the distribution of species, however, in contrast to others they found that substrate heterogeneity and complexity had little effect on early colonisation or the overall density of sessile invertebrates. Surfaces that are complex on different spatial scales provide an increased surface area, thus providing increased habitat and food availability to support a larger total biomass (Challinor and Hall 2008; Chapman and Blockley 2009).

The age of a structure is likely to affect the condition of the surface, especially with materials such as concrete. Weathering and aging of construction materials typically creates greater surface texture/complexity (pers. obs.). Connell (2001) recognised age as a determinant of the identity and abundances of epibiotic organisms within a habitat.

Blockley and Chapman (2006) studied areas of seawalls that were shaded by wharves, or unshaded. They found that for many species the response to shade on an artificial structure were similar to the responses observed to shade in natural habitats. For adult populations, most sessile invertebrates had greater cover on shaded seawalls, while algae and mobile invertebrates were more abundant on sunlit seawalls. From the studies of Blockley and Chapman (2006) it is evident that when comparing natural rocky shores and artificial structures it is important to consider the extent to which sheltered conditions are made available. For example, the area of shade created by a structure will influence species assemblages and interactions. Conditions during the retreat of the tide when organisms are exposed to the air are different according to the direction in which the shore faces (the aspect). A northerly aspect (in the northern hemisphere) on a shore with high cliffs, means that the sun will seldom cause much desiccation, while on a southerly aspect the cliffs may trap the heat so that the drying and overheating may become limiting (Little and Kitching 1996).

Many benthic organisms actively select the substrate on which they settle. Hence the development of divergent communities could be produced by using different substrate materials in the construction of artificial structures. Position within the tidal frame strongly influences the development of communities and the abundance of epibiota on artificial structures. The highest rate of development is expected just below low water springs, where primary producers have the light resource that is needed for growth (Hawkins and Hartnoll, 1983). As the depth increases, the light resource and subsequently the community growth rate is reduced (Connell 2001; Svane and Petersen 2001; Petersen and Malm 2006). The depth in which the artificial structure is placed will also influence whether an artificial structure will support the same or a distinct assemblage of species to that of nearby natural reefs; thus influencing local habitat and species diversity (Chapman and Bulleri 2003). Also, coastal defence structures that are placed on the interface with sedimentary environments will be prone to scouring from waterborne cobbles, gravel and sand.

1.1 Overview of thesis

Coastal areas around the world provide a plethora of direct and indirect resources of high economic value, and encompass areas of high environmental value. However, these transitional areas between the land and sea are prone to flooding and storm damage. The construction of artificial defence structures is often necessary as a method of protecting valuable coastal areas from potentially devastating effects. The need for coastal protection is likely to increase as a rise in sea level is predicted and the frequency and intensity of storm damage is expected to increase (Airoldi *et al*. 2005; Bulleri and Chapman, 2010; Chapman and Bulleri, 2003; Davis *et al.* 2002; IPPC, 2007; Moschella *et al.,* 2005). Marine conservation is a priority for sensitive coastal areas and is an important consideration when planning the construction of structures in the marine realm. Various conservation targets are addressed in national and international policy, including maintaining or restoring natural habitats and wild species at a favourable conservation status.

The overall goal of this thesis is to provide coastal engineers and decision makers with a selection of practical design options that can be incorporated into the construction and maintenance plans of coastal defence structures, to encourage specific outcomes that will reduce the negative environmental impact of artificial structures and may contribute to conservation priorities.

Factors that are common to both natural and artificial intertidal areas include the tide, waves and sediment regime. The specific influences of factors that differ between shores have been discussed above. These site specific factors include surface features, crevices, age, slope, shade, material, aspect, angle of exterior surface and the presence of water retaining features. This knowledge combined with an outline of basic ecological principles surrounding species recruitment, succession and community dynamics has been used to shape the observational and experimental chapters of the thesis. Surface complexity is recognised as an important feature in the success of species recruitment and succession. Chapters 2, 3 and 4 of the thesis gather observational and experimental evidence to inform design concepts which are trialled in Chapter 5 of the thesis.

In chapter 2, features of existing coastal defence design that would be expected to influence marine biodiversity are examined to develop an increased knowledge and understanding of influential features of coastal defence design on the diversity and abundance of marine epibiota. Observations of species diversity and abundance on a detached breakwater at Plymouth and a seawall at Starcross, in Devon, are described.

In chapter 3, succession and biodiversity of existing coastal defence design structures are investigated to develop an increased knowledge and understanding of the ecological processes of species succession and the biodiversity reached on intertidal coastal defence structures. Observations of species communities of different age on wavebreaker units at Plymouth

Breakwater, Devon are described in order to understand long term succession on artificial structures.

The influence of surface manipulations of concrete armour units on diversity and abundance of marine epibiota via experimental modifications of habitat are examined in chapter 4. Experimental modifications of the concrete armour units used to strengthen Plymouth Breakwater and a new seawall at Shaldon, Devon, are described. The aim of this chapter is to examine the influence of design modifications on species abundance and diversity.

Chapter 5 is a demonstration of how scale modification of surfaces on coastal defence structures can work. Modification at the design phase of a new coastal defence development at Shaldon, Devon occurred in 2011 and has been monitored.

Chapter 6 highlights and integrates the main findings of the thesis focusing on the difference between natural and artificial structures. Some brief recommendations for future schemes are made as well as suggestions for future research.

Chapter 2

The influence of design features of existing coastal defence structures on habitats and biodiversity

2.1. Introduction

2.1.1: An outline of the need for artificial structures as coastal defences

The coastline provides important resources for humans, and with the projected growth in human population predicted to exceed 9 million people by 2050 (UN report, 2009), coastal areas are increasingly susceptible to urbanisation. Traditionally coastal areas attracted urbanisation; however population growth has led to urban expansion, resulting in many of the world's largest cities located on the coast (Diez *et al*. 2011 and Timmerman and White, 1997).

The threat of sea level rise, flooding and erosion has led to a growing need to defend our coasts, often with the placement of hard defence structures (Airoldi *et al.,* 2005; Bulleri and Chapman, 2010; Chapman and Bulleri, 2003; Davis *et al.* 2002; Moschella et al., 2005). 'Coastal squeeze' occurs in conjunction with land reclamation and development, the construction of sea wall defences, jetties and marinas (Masselink and Russell, 2007); these hard structures act as static barriers and prevent a system from responding naturally to environmental change (Taylor *et al.,* 2004). Thus, physical processes and anthropogenic factors contribute to reduced extent and steepening of the intertidal zone. More than 50% of the coast in England and Wales is suffering from erosion

(Masselink and Russell, 2007) and 60% of the intertidal zone is recognised to have steepened over recent decades (Taylor *et al*., 2004).

Coastal defences are essential for defending coastal assets against the impacts of flooding and erosion, in addition to stabilising and retaining beaches and reclaimed land, and are consequently prevalent in areas of high economic value with commensurate levels of coastal squeeze.

2.1.2: Coastal defences as incidental habitable space to intertidal marine epibiota analogous to natural rocky shore as habitable space to intertidal marine epibiota.

Construction has a destructive effect on the immediate environment, by removing natural habitats which are generally already limited in extent. However artificial structures often develop species assemblages that are similar in many ways to nearby natural rocky shore environments (Chapman, 2003; Chapman and Blockley, 2009; Chapman and Bulleri, 2003; Firth *et al.*, 2013; Moschella *et al*., 2005; Thompson *et al*., 2002). Irrespective of the similarities between natural rocky shores and artificial structures outlined in section 1.1.5 of this thesis, artificial structures are poor surrogates for natural rocky shores (Southward and Orton, 1954, and, Thompson *et al*., 2002), and seemed lower in ecological value (Firth *et al*. 2014). Rocky shores are ecologically valuable marine habitats as they form extensive feeding, resting, spawning and nursery areas for many marine species; they provide unique habitats that support a diverse assemblage of species.

To encourage a secondary function of coastal defences as habitable space to intertidal marine epbiota I identify factors and design features of existing defence structures that I expect to influence habitat diversity and biodiversity by considering the type of features that are known to influence habitat diversity and biodiversity on rocky shores. These include the extent of intertidal area, properties of the rock or beach material and levels of disturbance.

2.1.3: The availability of habitable space owing to the design of artificial structures

On an artificial structure, the extent of the intertidal area depends on the vertical placement together with the length and width of the structure; the width being determined partly by the gradient or slope of inclination of the structure. Artificial structures are generally small in extent, especially compared to natural rocky shore habitats. Artificial structures are generally vertical or near vertical, creating less intertidal area than a shallow slope; whereas natural rocky shores can range from vertical cliff to resemble extensive gently sloping platforms.

The materials used for artificial structures rarely resemble the rock of natural rocky shores in properties such as size, shape and positioning. Although a range of materials such as granite, limestone and concrete are used to build artificial structures; they are usually constructed of one type of material, cut to a consistent shape and size to form the building bricks of a relatively uniform structure. This uniformity reduces surface heterogeneity and gives few areas of shelter from exposure. Artificial structures are not abundant in biologically rich microhabitats created by overhangs, crevices, gullies and pools, which are known to add to the ecological value of natural shores. Natural shores demonstrate that these habitats give rise to climatic conditions that are considerably different to the conditions experienced on the open rock face (Little and Kitching, 1996), such as fewer extremes in temperature and light, and attenuated wave action. Uniformity in shape and material type used in artificial structures restricts the variability in rock type, and texture, and water drainage;

creating uniform habitats with the associated low levels of protection from shade, shelter and retention of moisture.

This lack of suitable habitat in combination with high levels of natural disturbance, particularly on structures designed to attenuate wave energy, or where there are high levels of anthropogenic disturbance, such as harbour walls, purpose built promenade or a pedestrian accessible frontage; interrupt colonisation and successional processes, and tend to favour the establishment of species with opportunistic traits (Airoldi *et al.* 2005).

On a rocky shore the access to space on the surface of rock, or the primary space created by the surface of the rock is the resource that is in greatest demand (Connell, 1972; Raffaelli and Hawkins, 1996). The uniform surfaces of artificial structures lack the topographic variability of many natural rocky shores that provide increased primary space and a heterogeneous surface consequently has a strong influence on the distribution and abundance of species (Challinor and Hall, 2008; Chapman and Blockley, 2009; Little and Kitching, 1996; Raffaelli and Hawkins, 1996).

2.1.4 Conditions experienced on artificial structures and natural shores owing to environmental gradients and landform features

Artificial coastal structures and natural rocky shores are often exposed to common environmental gradients due to their position within the intertidal (see section 1.1.5). Continuously varying and intersecting environmental gradients give shape to the shore through physical processes; small scale (*e.g.* topographic) and large scale (*e.g.* regional, geographical) factors modify shore patterns and processes (Raffaelli and Hawkins, 1996). Environmental factors that are known to be of importance to marine epibiota on rocky shores, and that are considered important to marine epibiota on coastal defences include tide, and waves. Particle size and other landform features are factors that influence distribution of species influencing biological factors such as settlement, recruitment, competition and predation. In describing the environmental pressures, the associated challenges to which intertidal species are exposed, and the mechanisms related to habitat used to cope with these challenges, it is possible to explore the potential influence that specific features could create in order to enhance the intertidal epibiotic community on, and ecological value of, artificial coastal structures. The factors outlined in section 1.1.5 as most influential to habitats and the distributions of species on artificial structures are considered in more detail below.

Seawalls are positioned at the coastline at the foot of possible cliffs, dunes or urban habitats, usually emergent to the sea surface (Firth *et al.* 2012). Breakwaters are not connected to the shore and can be positioned emergent to the sea surface, low crested or submerged. Structures built with the primary function to defend the coast against tidal flooding are often built to a height where the crest is above extreme high water; above extreme wave and surge conditions and their height takes into account the predicted rise in sea level. On flood defence structures the vertical gradient from fully exposed to submerged is often steep as structures are usually vertical or near vertical. Thus, presuming the base of the structure is within the intertidal, epibiota on the structure will experience the influence of the tidal range. On natural rocky shores the vertical gradient from land to sea is one of the most influential to marine animals (see section 1.1.5), with the rise and fall of the tide creating dramatic changes in physical conditions, where marine animals often become increasingly stressed further up the shore where they are at greater risk of desiccation (Raffaelli and

Hawkins, 1996). On the natural shore many species seek refuge in microhabitats. It is expected that areas of shade on coastal defences will provide valuable refuge against desiccation. Southward (1958) compared temperature in a variety of microhabitats in Plymouth and found open rock to be up to 10°C warmer than shade; and temperatures on the shore were considerably different to Met Office recordings of air temperature. Shade is provided by heterogeneous surfaces, where areas of different orientation to the sun exist, or by cracks, crevices and pits, some of which may retain water and create a microhabitat with different conditions to areas that dry out during low tide.

Artificial structures built to defend against storm damage are constructed to attenuate the prevalent wave force, thus many artificial structures are predominantly exposed with few sheltered areas. On a natural shore, wave exposure is the predominant influential feature of the horizontal gradient, ranging from sheltered bays to exposed headlands (Raffaelli and Hawkins, 1996). The slope or vertical profile of an artificial structure will direct the force exerted on a structure in the same way as a slope on the shore. Thus, slope will influence the environment and consequently the intertidal marine epibiota colonising structures.

The effects of wave exposure are experienced evenly in space on a uniform structure, and relatively evenly in time with structures often built to interrupt the prevailing wave force. Natural rocky shore environments are generally more heterogeneous, providing a range of areas from those that take the full direct force of the wave to areas of increased shelter. Localised features on artificial structures and rocky shores give suitable habitable space and influence species assemblage. Localised features are less prevalent on artificial structures than natural shores owing to their uniformity; however they are not completely featureless. Some topographic features on artificial structures are built in to give strength, such as buttresses; others result from the construction process, such as holes in units necessary for manoeuvrability; others develop over time, owing to erosion, weathering and ecological processes; and, features can also occur when different materials are used. These features create areas of complexity such as areas of differing slope and orientation where shelter from physical factors such as waves, through attenuation of wave action and protection from wave induced dislodgement, or through the provision of shade and protecting species from the effects of direct sunlight.

2.1.5: Biological interactions on artificial structures and natural shores

In order to cope with the physical and biological environment, animals and plants have adapted both morphologically and behaviourally. For intertidal organisms, biological interactions include competition for resources such as food; nutrients; light and space; grazing; predation; and facilitation (Hawkins and Hartnoll, 1983; Southward, 1964). See Little and Kitching (1996); and, Raffaelli and Hawkins (1996) for reviews of physical and biological interactions. One of the key challenges is to find a suitable place to live, particularly for plants and sessile animals (Raffaelli and Hawkins, 1996). On artificial structures the uniformity of structures will influence availability of resources such as suitable places to live where shade, shelter and water retention are needed. Precise cues for species settlement can include the texture of the substratum, such as the presence of pits, crevices and concavities, which afford protection to larvae and metamorphosed juveniles (Raffaelli and Hawkins, 1996).

Biological factors are also highly spatially and temporally sensitive; and on artificial structures, biological factors are likely to be influenced by factors such as time of placement or construction; intertidal position of the structure and surrounding depths; distance from a source of species, and currents to carry a supply of species.

There are several comparative studies of artificial structures and natural rocky shore (Airoldi *et al.* 2005, Bulleri and Chapman 2004, Challinor and Hall 2008, Firth *et al*. 2013). However there are considerably less studies of the influence of specific design features of existing coastal defence structures. Blockley and Chapman (2006) compared species assemblages on shaded and unshaded seawalls in Sydney Australia.

2.1.6: Design features of existing coastal defence structures

In the Southwest of England, hard engineered structures such as breakwaters and seawalls are particularly widespread and are built to defend ports against storm damage and to defend coastal infrastructure against flood and erosion damage. Hard engineered structures are designed to receive high energy impacts from the physical pressures of waves, tides and currents. A protective structure is usually placed so that the whole structure is at a consistent height above chart datum, and at a specific orientation to the dominant wave direction of the area being defended. Replicate design features, including buttresses, are commonplace to add strength to the structure.

Two sites were selected to assess the influence of design features of existing coastal defence structures upon habitat and diversity, in South Devon. The study sites include a section of seawall at Starcross and a detached breakwater in Plymouth. These existing defence structures are relatively uniform in design over the scale of hundreds of metres, with regular replicate design features, including buttresses and pools. The general uniformity in structure design and position in the intertidal area relative to the shore minimises environmental influence external to the experimental design. The occurrence of design features, such as buttresses and water-retaining depressions, occur regularly, with multiple replicate features of the same dimensions. These design features provide surfaces with different conditions, which can provide different habitats, for example areas of shade, slope and retention of moisture. The design features also provide convenient sampling units for accurate experimental replication and comparison of habitat.

In this chapter, the different habitat types available to intertidal marine epibiota on existing coastal defences as a consequence of the construction process and design were examined. The overall aim was to compare the intertidal marine assemblage established within the different habitats provided by different structural characteristics. Specific hypotheses to be tested on existing coastal defence structures were:

1) Slope will influence diversity and abundance of intertidal marine epibiota
2) Orientation to the sun will influence diversity and abundance of intertidal marine epibiota
3) The presence of pools will influence diversity and abundance of intertidal marine epibiota
4) The presence of crevices will influence diversity and abundance of intertidal marine epibiota
5) Any influences that may exist owing to slope, orientation, pools and crevices on diversity and abundance of intertidal marine epibiota will be different from each other

2.2. Method

2.2.1. Areas of study

Starcross (50° 37′ N, 3° 26′ W) is a relatively sheltered, tidal location situated on the Exe Estuary between Exmouth and Dawlish (Figure 2.1). The Seawall at Starcross protects the railway line from the open sea, and extends along the coast for six kilometres. The seawall (Figure 2.2) was designed by Isambard Kingdom Brunel and constructed using Devonian limestone. Regularly placed buttresses provide strength. These buttresses make a convenient replicate sampling unit on which to study species distribution and abundance on sloping and vertical sections of seawall; and on areas with different orientation to the sun, since they provide areas of both shade and sunlit seawall.

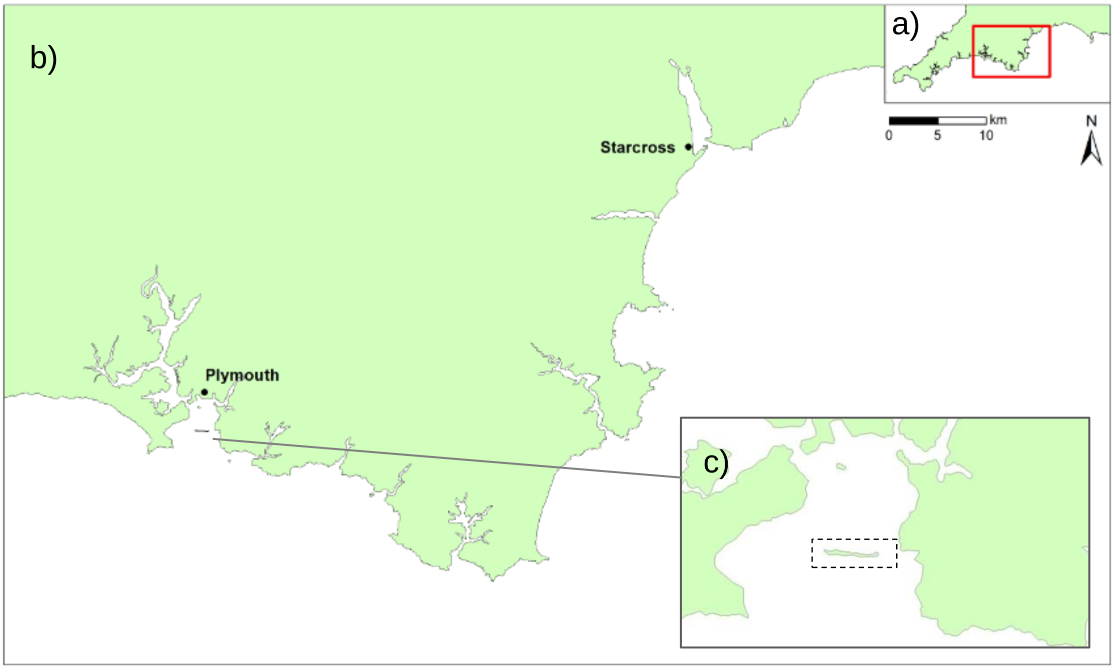


Figure 2.1 a) and b): Location of the Starcross and Plymouth study sites in SW Devon, UK, c) Location of the Plymouth Breakwater, within the dashed box.

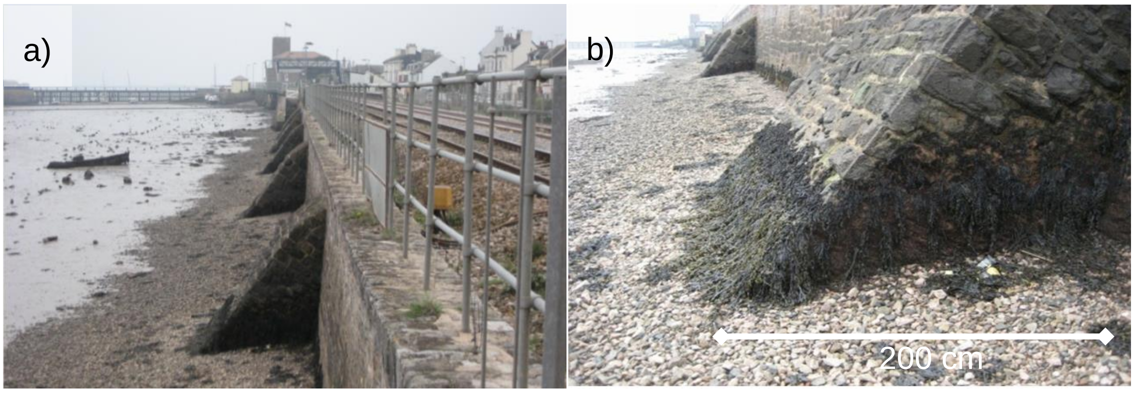


Figure 2.2 a) General view of the seawall at Starcross, and b): detail of regularly placed buttresses on the seawall.

Site elevations were estimated using Lidar data obtained from the Plymouth Coastal Observatory. This provides elevation data correct to the nearest 15 cm. The survey sites at Starcross were positioned at 4.2 m ± 15 cm above chart datum (C.D.), 1.8m above the Mean Tide Level (MTL) = 2.4 m. The Starcross seawall is high in the tidal frame, with submersion only occurring on high water springs. The seawall is sheltered from wave exposure and has moderate tidal currents.

Plymouth Breakwater (50° 19′ N, 4° 08′ W) is a 1.56 km long structure, situated four kilometres from Plymouth Hoe (Figure 2.1). The detached breakwater is a solid wall of predominantly limestone, with some granite paving, and is protected on the seaward side by regular addition of cast concrete wavebreaker armour units (Figure 2.3a and b).

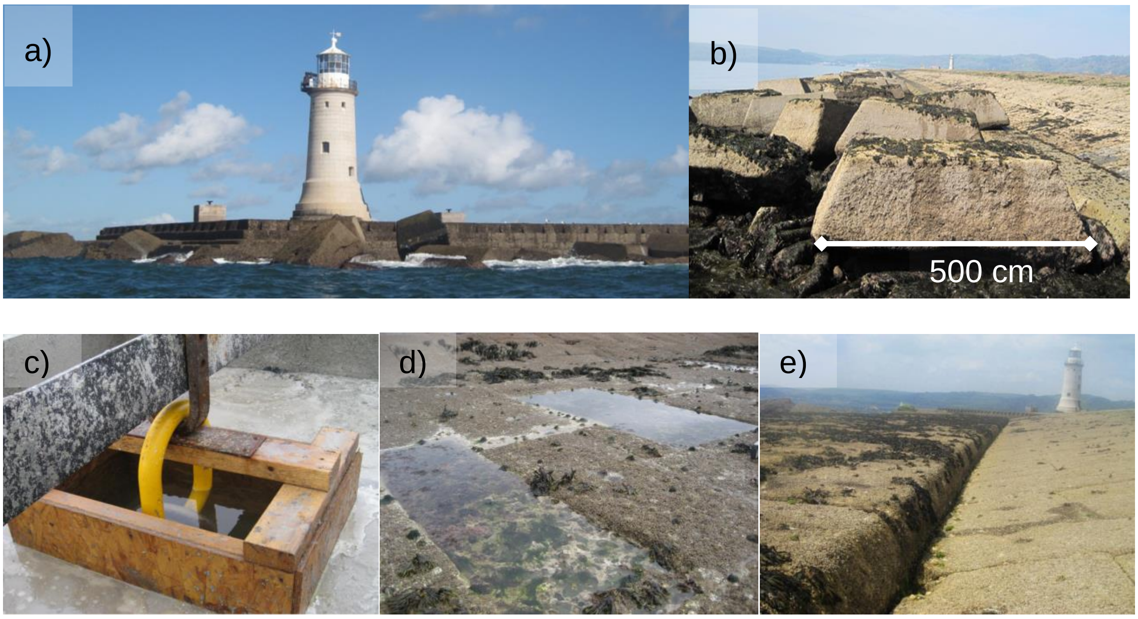


Figure 2.3: a) General view of Plymouth Breakwater, b) Armour units protecting the main structure of Plymouth Breakwater; c) incorporation of a lifting davit during construction; d) formation of limestone pool; and e) crevice between two sections of Plymouth Breakwater main structure.

Recesses form at the top of the armour units during the incorporation of lifting davits (Figure 2.3c). Each recess is created by pressing and temporarily securing wooden boxes into the wet concrete surface, which were broken out once the concrete had set (Figure 2.3c). When units are placed within the intertidal zone the recesses retain water and develop the character of a rock pool. The dimensions of these artificial concrete pools are:- 34 × 71 cm, 41 cm deep, hereafter referred to as concrete pools. In addition, the main breakwater has several shallow water-retaining features (Figure 2.3d), approximately 118 × 85 cm, 3 – 8 cm deep. These shallow pools were created when retained water influenced local erosion of limestone blocks, hereafter referred to as limestone pools. Furthermore, along the main breakwater, a crevice is present at the interface of two levels of structure, and extends for approximately 80 m (Figure 2.3e).

Established intertidal marine epibiota within different habitat types on the seawall and breakwater were compared in order to examine the influence of design features on marine life. Design features on the seawall provided habitats that owing to their position on the shore experience similar conditions and are constructed using similar material, but have areas that differ in slope and orientation (See 2.2.2). Features on the breakwater provided habitats that allowed a comparison between the presence of pools and crevices.

The average heights of survey locations on the Breakwater were 3.4 m ± 20 cm above C.D., which is approximately MTL, and is rarely emersed at high tide. The wave exposure at Plymouth Breakwater is generally greater than at Starcross; however, the survey location at Plymouth Breakwater is sheltered to a limited extent by further wavebreaker units seaward.

2.2.2. Comparisons of established marine epibiota between areas where structural features providing differing slope and orientation

In order to understand the influence that slope and orientation to the sun have on the diversity and abundance of intertidal epibiota, established intertidal marine epibiota were surveyed on replicate buttresses on the seawall (Figure 2.2) at Starcross (Figure 2.1). Sloping and vertical areas were surveyed on the easterly aspect; vertical areas of three aspects of different orientation to the sun were surveyed on the north (N), south (S) and east (E) surfaces. Each slope and orientation was assumed to provide different environmental conditions that are likely to influence diversity and abundance.

Sloping and vertical areas were surveyed during 2007 and 2008. Randomly placed 50 × 50 cm quadrats were sampled on four buttresses. Data were collected at low tide. Species abundance was estimated as the percentage cover of maroalga canopy; percentage cover of ephemeral green algae and sessile fauna. The number of mobile species within the survey area were recorded as individual counts. Where mobile species were low in numbers the percentage cover and individual count data were included in the same analysis. Identification to species level was achieved for the majority of species. Species not identified *in situ* were described, photographed and subsequently identified to the lowest possible taxonomic rank. For some species, covers were recorded as aggregated taxa and the approximate relative proportions of each species were recorded, thus accurately recording cover without sacrificing individuals, which reduced the impact of the survey. The term “sp(p).” denotes organisms of either one or several unidentified species, and groups of organisms are referred to as “taxa”. The World Register for Marine species (WoRMs, 2014) has been used as a reference for up to date taxonomy. The lists of species displays the current accepted name followed by the name of the discoverer of the basionym, the original name on which the accepted name is based, and the date of the basionym discovery. Analysis has been performed at the species level, although for uncluttered presentation some results are displayed at a higher taxonomic rank.

Prior to further analysis, a Cochran’s C tests were performed to assess the homogeneity of variance to determine whether the data needed transforming. Two-factor Analysis of Variance (ANOVA) were performed using the statistical package GMAV (Underwood and Chapman, 1998). The factor Slope had two fixed levels (slope and vertical surfaces). A separate ANOVA were performed for the factor ‘Orientation’, this had three levels (north, south and east). To achieve balanced design where the sample number were equal for each treatment, random data were selected for analysis, thus sample number (n) for each treatment matched that of the treatment with the lowest number of replicates recorded. The lowest sample numbers per data set for slope and orientation were considered sufficient to provide analysis using ANOVA. Multivariate analyses were performed on species abundance data so as to compare assemblages between different slopes and orientations. A one-way ANOSIM permutation test was performed using the PRIMER 6 computer program (Clarke and Gorley, 2006) to test for differences in species assemblages according to the same factors examined in the ANOVA test. The Similarities Percentage procedure (SIMPER) (Clarke, 1993) were performed on total species cover to identify discriminating features. SIMPER calculates the average Bray-Curtis dissimilarity between all pairs of inter-group samples, i.e. the cover of each species found on one feature/ treatment being compared with the cover of each species found on the other features/ treatments in the comparason. Because the Bray-Curtis dissimilarity measure incorporates the contribution of each species, the average dissimilarity between features such as different slope or orientation can be expressed in terms of the average contribution from each species. The standard deviation provides a measure of how consistently a given species will contribute to the dissimilarity between each treatment. A 'good' discriminating species contributes heavily to inter treatment dissimilarity and has a small standard deviation. In a similar way, characteristic features can be identified where average similarity is calculated between the cover of all species of each treatment. Species which consistently contributed greatly to the average similarity between treatments are considered characteristic of the treatment.

The ordination of species were performed on the species abundance data recorded on each treatment, which were square root transformed, characterized numerically and displayed graphically as non multidimensional scaling (nMDS) and as a cluster diagram. The distance between each sample represents similarity and dissimilarity, whereby the samples close to each other were more similar. To complement the ordination plot the grouping of assemblages of species is also displayed in a cluster diagram.

ANOSIM were used to complement the SIMPER and nMDS analysis, which were performed on the complete unbalanced design set as these analysis do not require a balanced design set. Biological data were square root transformed to allow for less abundant species to be taken into account and the Bray Curtis measure of similarity were used. The Bray Curtis similarity measure reflects the differences between two samples owing both to differing assemblage composition and/or differing total abundance.

2.2.3. Comparisons of established marine epibiota on areas where structural features provide areas of different habitat type, such as pools and crevices, on Plymouth Breakwater

In order to determine whether features such as pools and crevices will influence the diversity and abundance of intertidal epibiota the established intertidal marine epibiota were surveyed on areas of pool and crevice habitat, and the adjacent emergent rock habitat. Each feature was assumed to provide different habitat types and to influence local biodiversity.

On Plymouth Breakwater, the established intertidal marine epibiota were studied during late spring and early summer of 2010. Each habitat, described as concrete pool, limestone pool and crevice, were compared to the adjacent emergent substrata. Eight concrete pool habitats situated on armour units;

twelve limestone pool habitats; and four sections of granite crevice habitat were surveyed. The substrate adjacent to the limestone pools was granite; the substrate emergent to the concrete pools were concrete; and the substrate adjacent to the crevice were granite. Randomly selected areas with a surface area of 0.25 of a square meter were surveyed in each habitat type and on the adjacent substrata.

The elevation of the limestone pool and crevice were measured with a RTK-GPS system to standardise height between samples. The RTK measures the elevation in relation to a conventional level, which were converted to C.D. to match the local tidal information.

Species abundance within limestone and concrete pools and the emergent area adjacent to pools were estimated and analysed as described in section 2.2.2. Balanced designs were tested using Cochran's C test, ANOVA, ANOSIM permutation test, SIMPER and nMDS analysis. Analysis were performed on the complete data where a balanced design were not required.

2.3. Results

A total of 15 species across 6 taxonomic classes were recorded on the seawall at Starcross. The highest diversity were attributed to the classes Florideophyceae (5 species) and Phaeophyceae (3 species) (Table 2.1). Analysis has been performed at the species level but for uncluttered presentation some of the results are grouped and displayed at the taxonomic rank of 'class'. The species authority for each recorded species is given in table 2.1.

Table 2.1: List of species identified at the Starcross study site. Key to the position of species on the seawall; N = north, S = south, V = vertical (east), Sl = Slope.

Class	Species / taxa	Position			
		N	S	V	Sl
Ulvophyceae	*Ulva* spp.	X	X	X	X
Phaeophyceae	*Fucus spiralis* (Linnaeus, 1753)	X	X	X	X
	Fucus vesiculosus (Linnaeus, 1753)	X	X		
	Ascophyllum nodosum (Stackhouse 1809)	X	X	X	X
Florideophyceae	*Catenella caespitosa* (Withering, 1776)	X	X	X	X
	Corallina officinalis (Linnaeus, 1758)			X	
	Plumaria plumosa (Hudson, 1762)	X			
	Halurus flosculosus (J.Ellis,1768)	X	X		
	Vertebrata lanosa (Linnaeus, 1767)	X	X		
Maxillopoda	*Chthamalus montagui* (Southward, 1976)	X	X	X	X
	Chthamalus stellatus (Poli, 1791)	X	X	X	X
Gastropoda	*Littorina littorea* (Linnaeus, 1758)	X	X	X	X
	Littorina fabalis (Turton, 1825)	X			
	Patella vulgata (Linnaeus, 1758)	X	X	X	
Decapoda	*Carcinus maenas* (Linnaeus, 1758)		X		

2.3.1. The influence of the slope of a seawall on intertidal epibiota

To address hypothesis 1, that slope will influence diversity and abundance of intertidal marine epibiota, the established intertidal epibiota on sloping and vertical areas of seawall were examined.

Comparison of vertical and sloping substrata revealed that the vertical aspect had the highest diversity of species across classes, with 9 species across 5 classes, with the highest diversity attributed to the classes of Phaeophyceae (*A. nodosum* and *F. spiralis*), Gastropoda (*L. littorea* and *P. vulgata*) and Florideophyceae (*C. caespitosa* and *E. elongata*). The sloping aspect had 7 species across 5 classes, with the highest diversity attributed to the class Phaeophyceae (*A. nodosum* and *F. spiralis*).

The number of species in assemblages found on vertical and sloping surfaces were not significantly different ($F_{1,14} = 1.77$, $p = 0.21$) (Table 2.2). Intertidal species assemblages found on vertical surfaces had a significantly higher total species abundance than sloping surfaces ($F_{1,14} = 79$, $P < 0.001$) (Table 2.2). ANOVA was performed for the most common taxonomic groups, Ulvophyceae, Phaeophyceae, Florideophyceae and Maxillopoda; the cover of each was influenced by slope and the significances are displayed on figure 2.4. Areas of wall with a vertical aspect had significantly higher cover of *Ulva* spp. and *C. caespitosa* than sloping walls, and significantly lower cover of *A. nodosum* (Table 2.2).

*Table 2.2: Species assemblages on surfaces of different slope on a seawall at Starcross, Devon. A series of one-way ANOVA comparisons of species richness, total species cover and combined species to taxonomic 'class' between areas of seawall with different slope. Where needed, data has been √ transformed (√) to obtain heterogeneity of variances. Slope (n = 8); Vertical (n = 8). Significant P values in bold script. Post hoc Student-Newman-Kuels (SNK) comparisons, where * p < 0.05 and ** p < 0.01. Not significant (NS).*

	C	***Df***	***Ms***	***F***	***P***	***SNK***
Species Richness	0.72, NS	1	1.56	1.77	0.209	
Res		14	0.88			
Species cover (√)	0.80, NS	1	42	78.87	**<0.001**	V > Sl **
Res		14	0.54			
Ulvophyceae (√)	0.73, NS	1	45.56	31.31	**<0.001**	Sl > V **
Res		14	1.455			
Phaeophyceae	0.73, NS	1	430.56	5.44	**0.035**	V > Sl *
Res		14	79.1			
Florideophyceae	0.73, NS	1	1225	18.46	**<0.001**	Sl >V **
Res		14	66.36			
Maxillopoda (√)	0.71, NS	1	30.25	5.61	**0.033**	Sl >V *
Res		14	5.39			

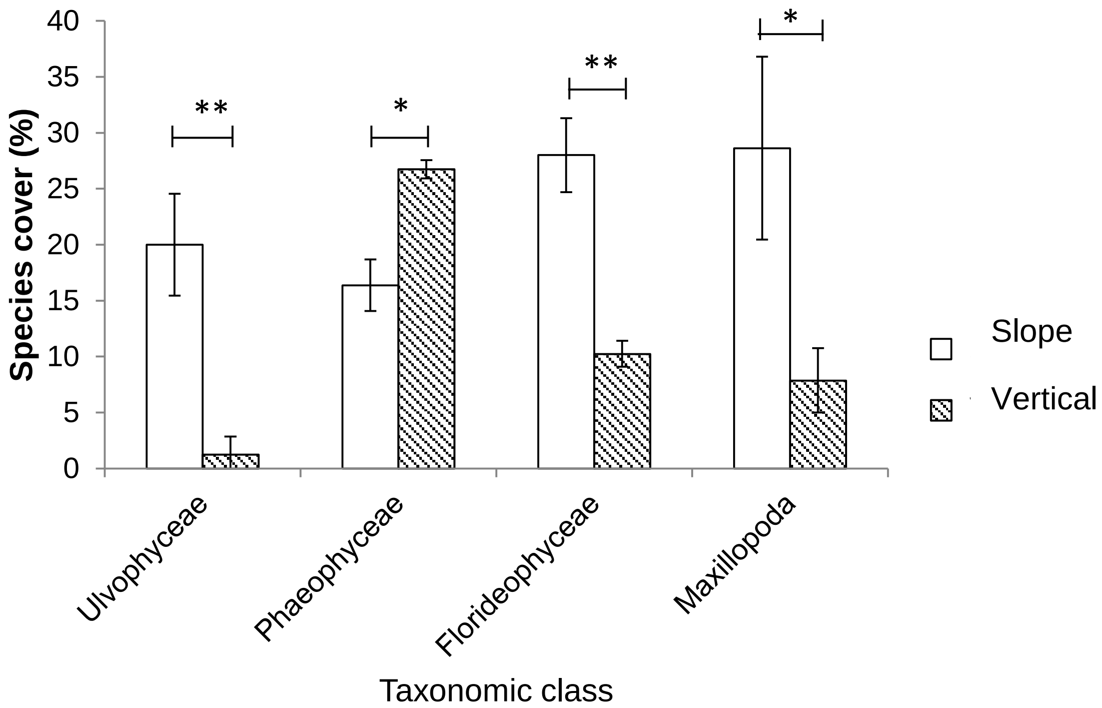
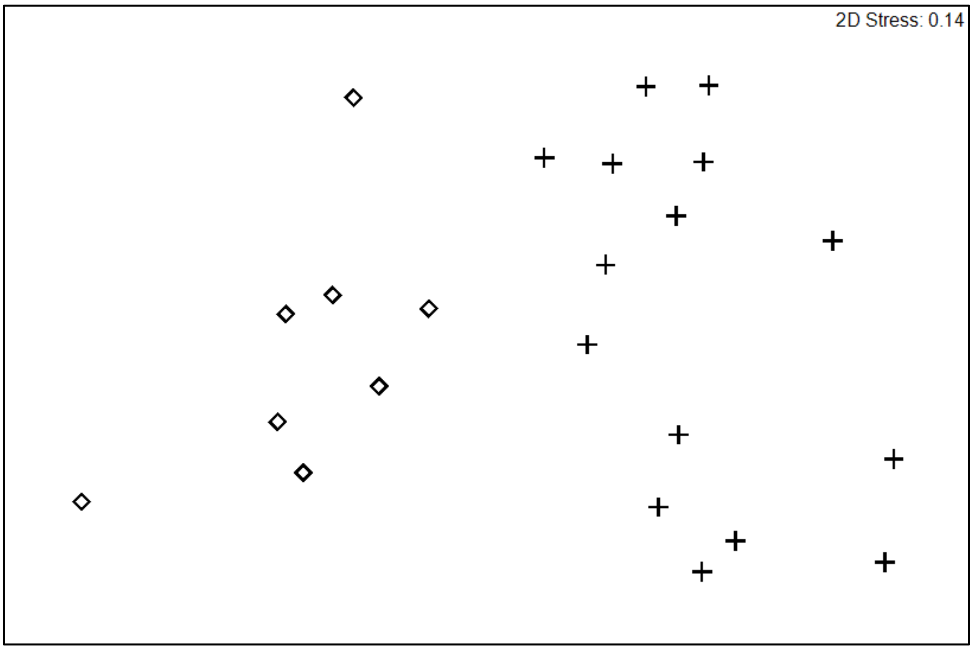


*Figure 2.4: Mean percentage cover of epibiota from different taxonomic classes on surfaces of seawall that was sloping or vertical. Slope (n = 8), vertical (n = 8), ANOVA * p < 0.05 and ** p < 0.01 ($\bar{x}$ ± standard error).*

Ordination indicated that there was no overlap in the samples of species assemblages on slope and vertical surfaces (Figure 2.5a). At the 75 % level of similarity assemblages on vertical surfaces had 2 clusters, whereas sloping surfaces had 8 clusters (Figure 2.5b).

a)



b)

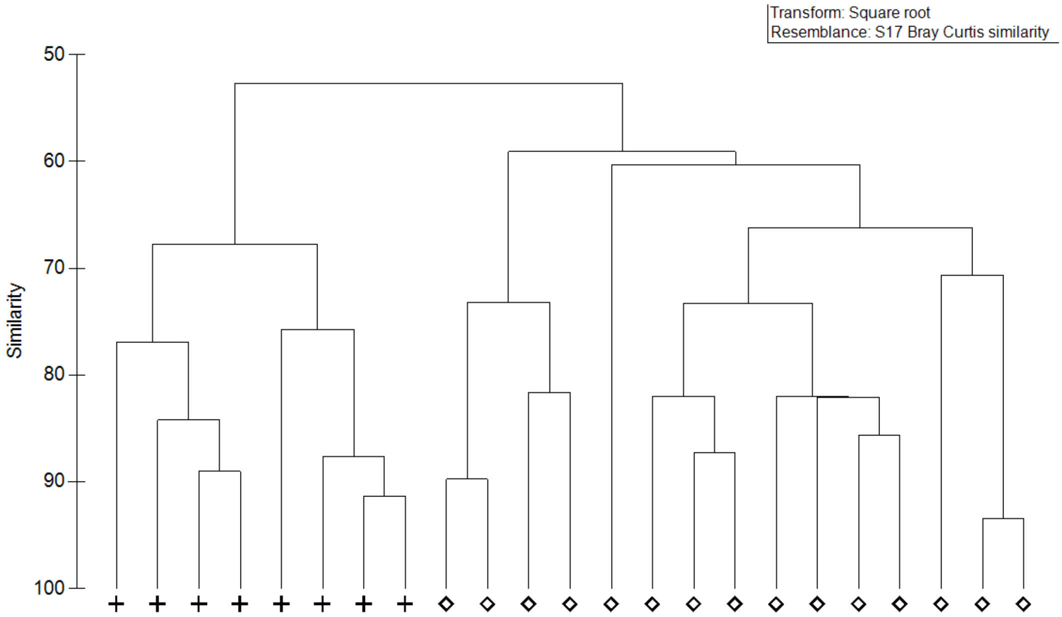


Figure 2.5: Intertidal epibiota at Starcross. a) MDS ordination and b) cluster analysis of Bray-Curtis similarities from √-transformed species abundance data for sloping (diamond, n = 8) and vertical (cross, n = 15) samples along the same stretch of seawall.

Each species were considered important if its contribution to percentage similarity/ dissimilarity exceeded the arbitrary value of 3%. The abundance of six species, *A. nodosum,* total barnacle spp. (predominantly *C. montagui), C. caespitosa* and *Ulva* spp*., F. spiralis* and *L. littorea,* each contributed over 3% to the average disimilarity of 47% between slope and vertical aspects. The abundance of four species contributed over 10% to the total dissimilarity between aspects (Table 2.3); *A. nodosum* contributed 27% to the dissimilarity, being more abundant on sloping aspect; whilst total barnacle spp.*, C. caespitosa* and *Ulva* spp*.* were more abundant on vertical substrate, contributing 19%, 18% and 17%, respectively, to the total dissimilarity between aspects. Species assemblages on vertical aspects had a higher within group similarity (74%) compared to species assemblages on sloping aspects (66%) (Table 2.3).

Table 2.3: SIMPER of average species cover (√ transformed) on sloping and vertical surfaces of a seawall at Starcross a) similarity within vertical surfaces (V) (n=14), b) similarity within sloping surface (S) (n=8), and c) dissimilarity between V and S. Sim: similarity; Diss: dissimilarity; Sim/SD and Diss/SD: a measure in the contribution of the species to similarities/ dissimilarities between pairs of samples; Contrib%: percentage contribution of the species to the average overall similarity between groups of treatments; Values of Sim/SD ≥ 1 (in bold font) indicated that the contribution of a given species to the percentage dissimilarity were consistent among pairwise comparisons between S and V.

		Cover	Sim	Sim/SD	Contrib%
a) S similarity Average sim 66%					
Catenella caespitosa		5.3	31.6	3.6	47.1
Fucus spiralis		3.1	15.0	1.9	22.4
Ulva spp.		2.9	11.4	1.5	16.9
Total barnacle spp.		2.9	7.7	**0.9**	11.5
b) V similarity Average sim74%					
Ascophyllum nodosum		3.8	24.2	3.8	32.8
Fucus spiralis		3.3	21.1	3.4	28.6
Catenella caespitosa		3.1	17.3	3.0	23.4
Total barnacle spp.		2.2	7.0	**0.9**	9.5
c) V & S dissimilarity Average diss 47 %					
	V	S	Diss	Diss/ SD	Contrib. %
Ascophyllum nodosum	0.19	3.8	13	2.8	27
Total barnacle spp.	2.94	2.2	9	1.4	19
Catenella caespitosa	5.31	3.1	8	1.6	18
Ulva spp.	2.92	0.8	8	1.4	16
Fucus spiralis	3.10	3.3	4	1.2	90
Littorina littorea	0.20	0.7	2	1.1	95

2.3.2. The influence of the different orientations of a seawall, facing north, south and east, on intertidal epibiota.

To address hypothesis 2, that orientation to the sun will influence diversity and abundance of marine epibiota, the established intertidal epibiota on north (N), south (S) and east (E) facing vertical areas of seawall were examined.

This comparison of orientation revealed that diversity were highest in N and S orientations with 12 species across 5 classes recorded on the N surface; the highest diversity were attributed to the classes Florideophyceae (4 species), Phaeophyceae (3 species) and Gastropoda (3 species); and 11 species across 6 classes recorded on the S surface, with the highest diversity attributed to the classes of Phaeophyceae (3 species) and Florideophyceae (3 species) (Table 2.1). Significant differences in species richness and the abundance/ cover of some species (Table 2.4) among orientations were found.

*Table 2.4: Intertidal epibiota on surfaces of different orientation on a seawall at Starcross, Devon. A series of one-way ANOVA comparisons of the number of species, cover of the most abundant species and combined species to taxonomic 'class' between areas of seawall with different orientation. Where needed, data has been √ transformed (√) to obtain heterogeneity of variances. North (N), south (S), and east (E), where n = 15 for each orientation. Post hoc Student-Newman-Kuels (SNK) comparisons, where * p < 0.05 and ** p < 0.01. Not significant (NS). Significant P values in bold script.*

	C	***Df***	***Ms***	***F***	***P***	***SNK***
Number of	0.5, NS	2	5.49	3.51	**0.038**	N > E *
Species		42	1.56			
F. spiralis (√)	0.5, NS	2	12	2.63	0.08	
Res		42	4.6			
A. nodosum	0.5, NS	2	1084	3.44	**0.04**	S > E *
Res		42	315			
C. caespitosa	0.4, NS	2	1073	7.11	**0.002**	E > S **; E > N **
Res		42	151			
L. littorea	0.5, NS	2	2	1.9	0.16	
Res		42	1.06			
Ulvophyceae (√)	0.5, NS	2	2	7.67	**0.001**	E > N **; E > S **
Res		42	0.26			
Phaeophyceae	0.6, NS	2	100	1.6	0.21	
Res		42				
Florideophyceae	0.5, NS	2	523	2	0.15	
Res		42	261			
Maxillopoda	0.5, NS	2	184	0.88	0.55	
Res		42	308			
Gastropoda	0.5, NS	2	3.46	3.17	**0.05**	N > E *
Res		43	1.09			

Species richness was greater on north facing surfaces, which were shaded, than on south and east facing surfaces ($F_{2,42}$ = 3.51, p = 0.038) (Table 2.4 and Figure 2.6). *C. Caespitosa* ($F_{2,42}$ = 7.11, p = 0.002) and ulva spp. ($F_{2,42}$ = 7.67, p = 0.001) had the highest cover on the east surface. *A. nodosum* had the highest cover on the south surface ($F_{2,42}$ = 3.44, p = 0.04) (Table 2.4). Differences in species cover were greatest between the north and east; and, south and east facing surfaces (R = 0.413, R = 0.423; P <0.001, Table 2.5).

Table 2.5: Global ANOSIM and pair-wise comparisons of epibiota on different orientation of a sea wall. S = south (n = 18), N = north (n = 18), E = east (n = 15).

Comparisons (orientation)	
Global *R*	0.271
S *vs*. N	*R* = 0.031
S *vs*. E	*R* = 0.413
N *vs*. E	*R* = 0.423

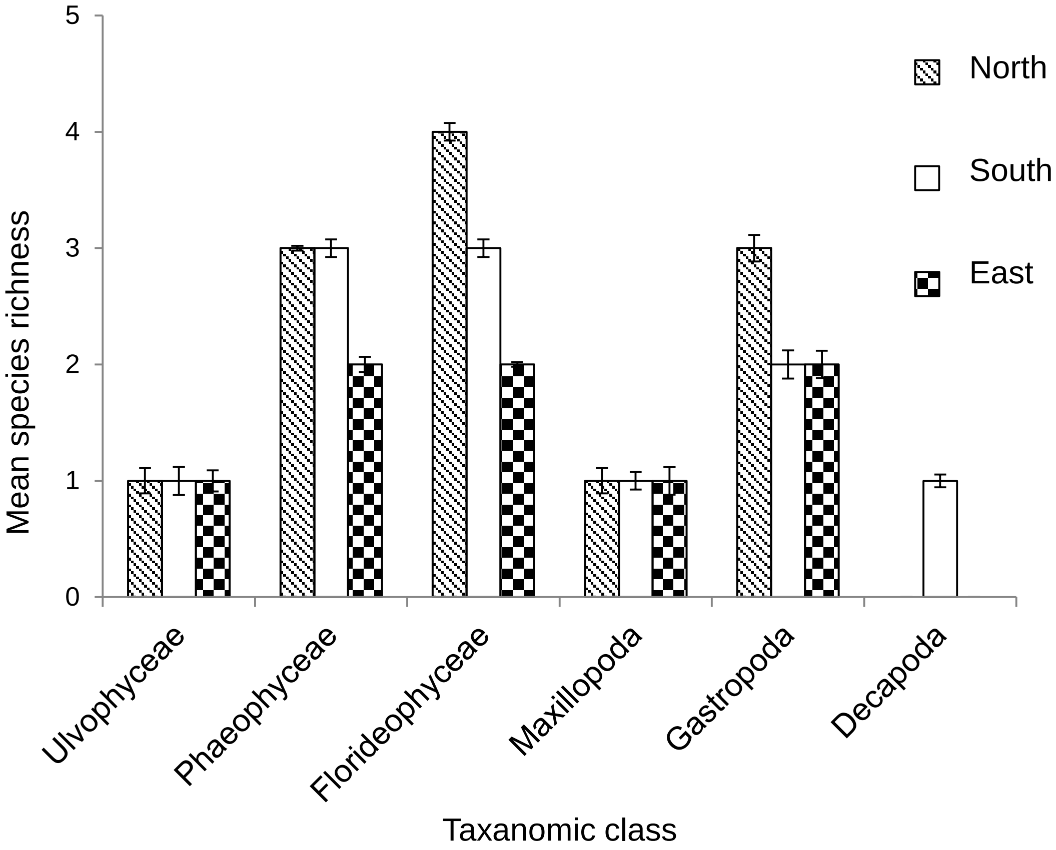


Figure 2.6: Number of species on different orientations on a seawall. N = north (n = 18), S = south (n = 18) and E = east (n = 15) ($\bar{x}$ ± standard error).

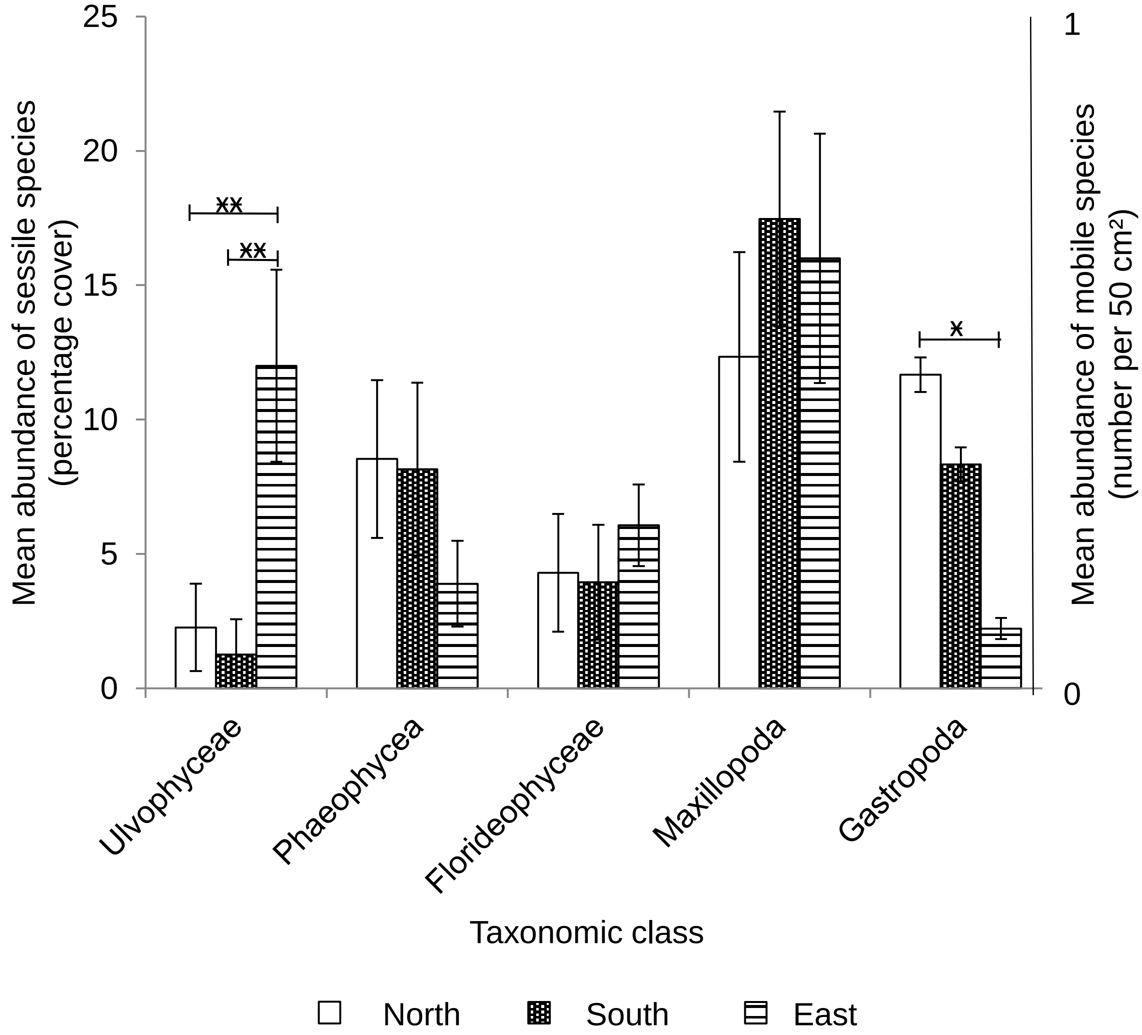
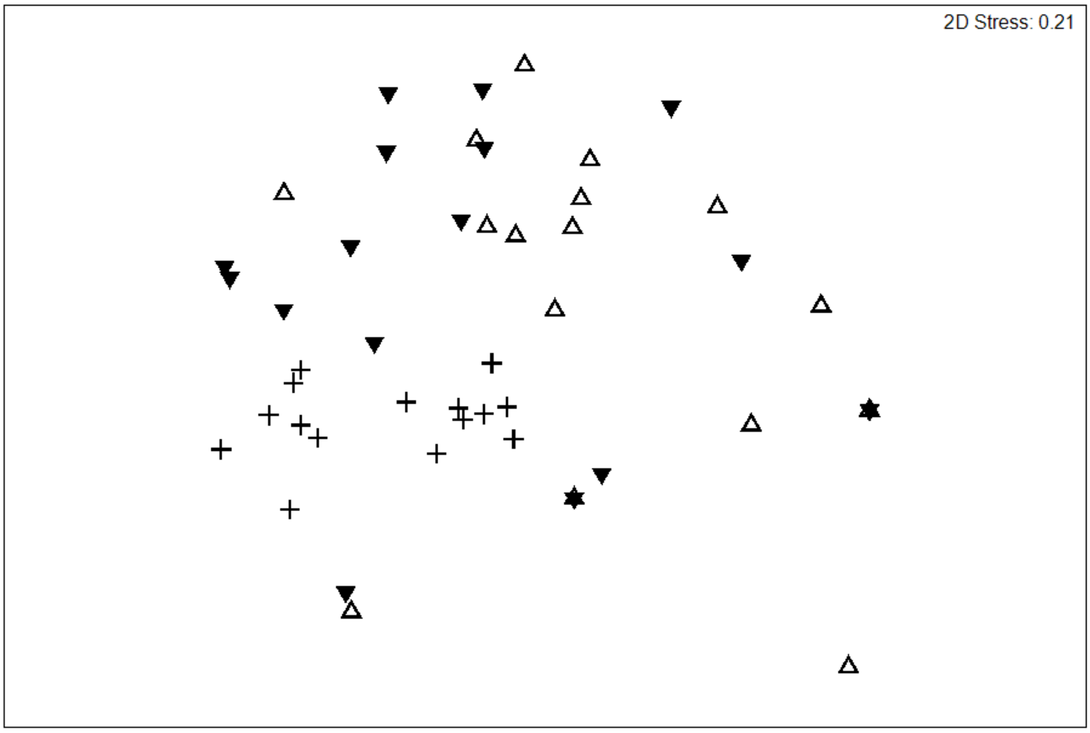


Figure 2.7: Total species abundance on different orientations on a seawall. N = north (n = 15), S = south (n = 18), E = east (n = 15). SNK results for significance between species within the taxonomic rank of 'class' for each orientation N, S and E; ӿ $p < 0.05$, ӿӿ $p < 0.01$ ($\bar{x}$ ± standard error).

The nMDS ordination plots of species composition of the epibiotic assemblages on areas of different orientation indicated that the assemblages were similar in location and dispersion (Figure 2.8). Fewer dissimilarities between E and S samples were found (46% dissimilarity, Table 2.6). There was one outlier in the N samples, which was a considerable distance from the remaining cluster of N samples, with less than 20 % similarity to the rest of the samples. At 60 % similarity 9 clusters were present, 2 of these clusters of species assemblages were from N and S orientations; 1 cluster had samples from the N, S and E orientation; 4 clusters were predominantly N oriented, and 2 clusters were predominantly S oriented (Figure 2.8b). The groups of samples representing N and S were clustered with a greater distance between the samples than the groups of samples representing East (the percentage similarities within groups were 44, 51, 73 respectively, table 2.6). This indicates that the E surface may create conditions that were suited to a more specific assemblage of species than the N and S surfaces.

a)



b)

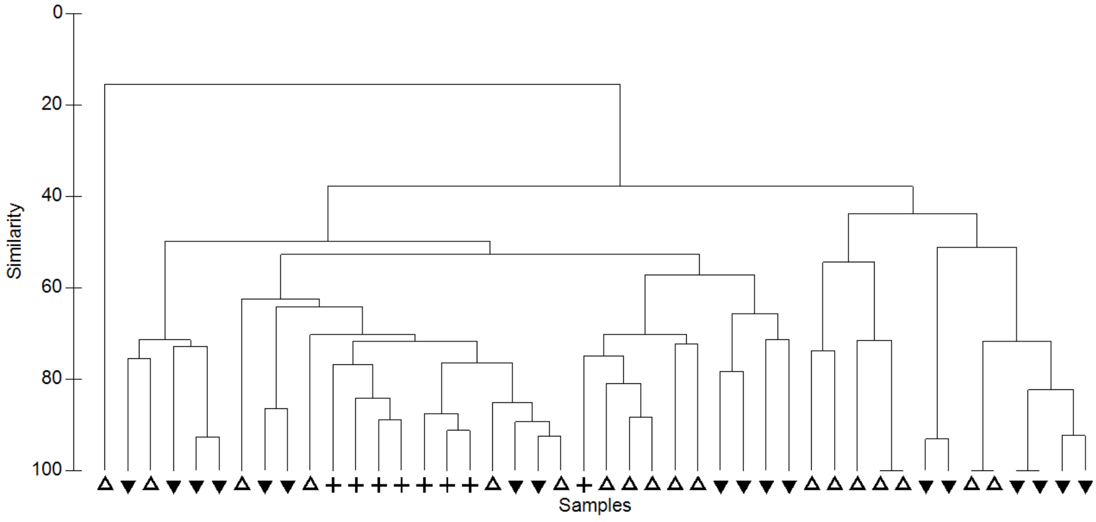


Figure 2.8: Starcross epibiota. a) MDS ordination and b) cluster analysis of Bray-Curtis similarities from √-transformed species abundance data for different orientation positions along the same stretch of seawall. Shaded diamond = south (n = 18), unshaded diamond = north (n = 18), and cross = east (n = 15).

The total barnacle spp., *C. Caespitosa* and *A. nodosum* each contributed more than 10% to the within group similarity for surfaces with a N and S orientation;

whereas C. caespitosa, F.spiralis, Ulva spp. and total barnacle cover each contributed more than 10% to the within group similarity for surfaces with an E orientation.

When N and S orientations were compared, 8 species contributed more than 3% each to the total dissimilarity of 55%, and 4 species contributed more than 10% each. When S and E orientations were compared, 8 species contributed more than 3% each to the total dissimilarity of 54%, and 5 species contributed more than 10% each. When N and E orientations were compared, 5 species contributed more than 3% each to the total dissimilarity of 56%, and 4 species contributed more than 10% each. The 4 reaccurant greatest contributing species to the dissimilarity between orientations were total barnacle spp., which had the greatest cover on the N orientation; *A. nodosum,* which had greatest cover on the S orientation; *and, F. spiralis* and *C. caespitosa* which had the greatest cover on the E orientation. Ulva spp. contributed more than 10% to the dissimilarities between N and E; and, S and E orientations.

Table 2.6: SIMPER comparison of species on different orientation of a sea wall. S = south (n = 18), N = north (n = 18), E = east (n = 15).

Within group	Similarity	Between group	Dissimilarity
N	43	N & S	55
S	48	N & E	56
E	67	S & E	53

2.3.3. The influence on intertidal epibiota of pool habitat on a breakwater.

To address hypothesis 3, that pools will influence diversity and abundance of intertidal marine epibiota, the established intertidal epibiota within two different pool habitats and emergent rock habitats were compared. These were limestone and concrete pools. Crevice habitats were also studied and their results are included here. The elevations measured at the pool habitats were within a 18 cm range, which were considered insufficient to compromise comparisons between pools when likened to the overall tidal range of 4.5 m at Plymouth.

A total of 23 species across 10 classes were recorded at Plymouth Breakwater, with the highest diversity attributed to the classes Florideophyceae (6 species), Phaeophyceae (5 species) and Gastropoda (3 species) (Table 2.7).

Table 2.7: List of species identified within pool and crevice habitats; and the adjacent emergent area, at the Plymouth Breakwater study site. LP = Limestone pool; CP = Concrete pool, and C = Crevice (section 2.3.5.).

Class	Species	Habitat			Adjacent emergent substrate		
		LP	CP	C	LP	CP	C
Ulvophyceae	*Ulva* spp.	X	X	X	X	X	
Florideophyceae	*Ceramium* sp.	X	X				
	Corallina officinalis (Linnaeus, 1758)	X					
	Laurencia sp.1	X					
	Laurencia sp.2	X					
	Lithophyllum sp*.*	X	X	X			
	Mastocarpus stellatus (Stackhouse, 1797)				X		
Bangiophyceae	*Porphyra* sp.	X		X	X		
Algae	Unknown A	X	X				
	Unknown B	X					
Phaeophyceae	*Arthrocladia villosa* (Duby, 1830)	X					
	Fucus spiralis (Linnaeus, 1753)	X			X		
	Fucus vesiculosus (Linnaeus, 1753)		X		X	X	X
	Himanthalia elongata (Linnaeus, 1753)		X				
	Leathesia marina (Lyngbye, 1819)	X		X			
Anthozoa	*Actinia equina* (Linnaeus, 1758)	X	X	X			
	Anemone viridis (Forskål, 1775)	X					
Ochrophyta	*Scytosiphon lomentaria* (Lyngbye, 1819)	X					
Maxillopoda	Barnacle spp.	X		X	X	X	X
Gastropoda	*Gibbula umbilicalis* (da Costa, 1778)			X			
	Nassarius incrassatus (Strøm, 1768)			X			
	Patella vulgata (Linnaeus, 1758)	X	X	X	X	X	X
Bivalvia	*Mytilus edulis* (Linnaeus, 1758)	X		X			

Comparison of limestone pool and concrete pool habitats and the emergent substrate adjacent to sheltered pool habitats indicated that the limestone pool habitat had the highest diversity with 18 species across 8 classes recorded. Highest diversity were attributed to the classes Florideophyceae (6 species) and Phaeophyceae (5 species) (Figure 2.6). Nine species across 6 classes were recorded on the emergent substrate adjacent to the limestone pool habitat, with the highest diversity attributed to the classes of Phaeophyceae (predominantly

F. spiralis and *F. vesiculosus*) and Florideophyceae (predominantly *M. stellatus).*

In the concrete pool habitat 11 species across 6 classes were recorded, with the highest diversity attributed to the classes Phaeophyceae (*F. vesiculosus*, *H. elongata*, and *L. marina*) and Florideophyceae (*E. elongata* and *Lithophyllum* sp.) Five species across 5 classes were recorded on the emergent substrate adjacent to the concrete pool habitat.

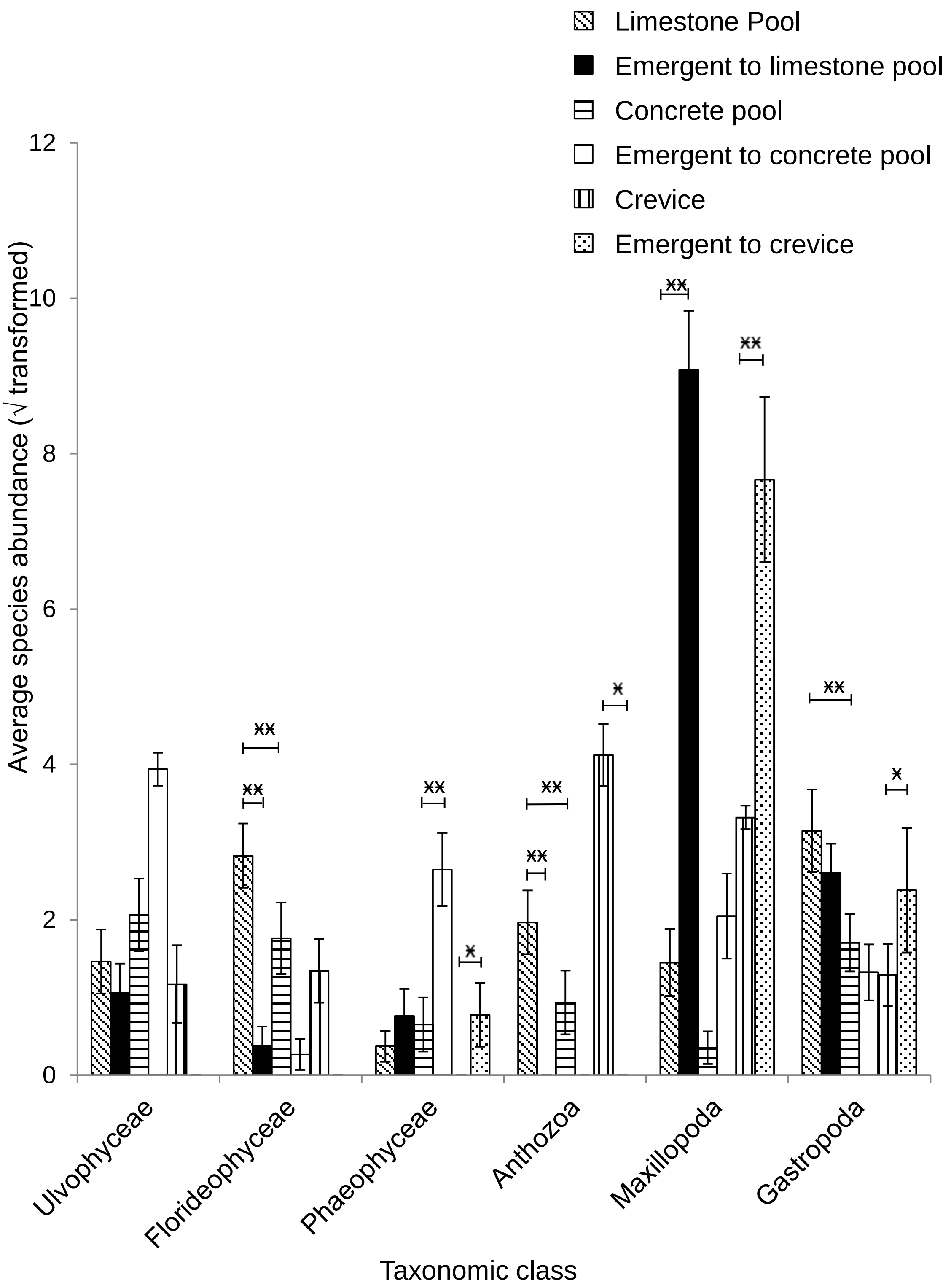


Figure 2.9: Abundance of species (√ transformed % cover of sessile species; √ tranformed number of individual mobile species per 0.25 of a square meter) in different habitat types on Plymouth Breakwater ($\bar{x}$ ± standard error). Limestone pool (n = 12); Emergent limestone pool (n = 9); Concrete pool (n = 8), Emergent concrete pool (n = 8); Crevice (n = 4), and Emergent crevice (n = 4). ANOVA SNK among pool and crevice habitats and adjacent substrate emergent to pool and crevice habitats, ⁎ P < 0.05 and ⁎⁎ P < 0.01.

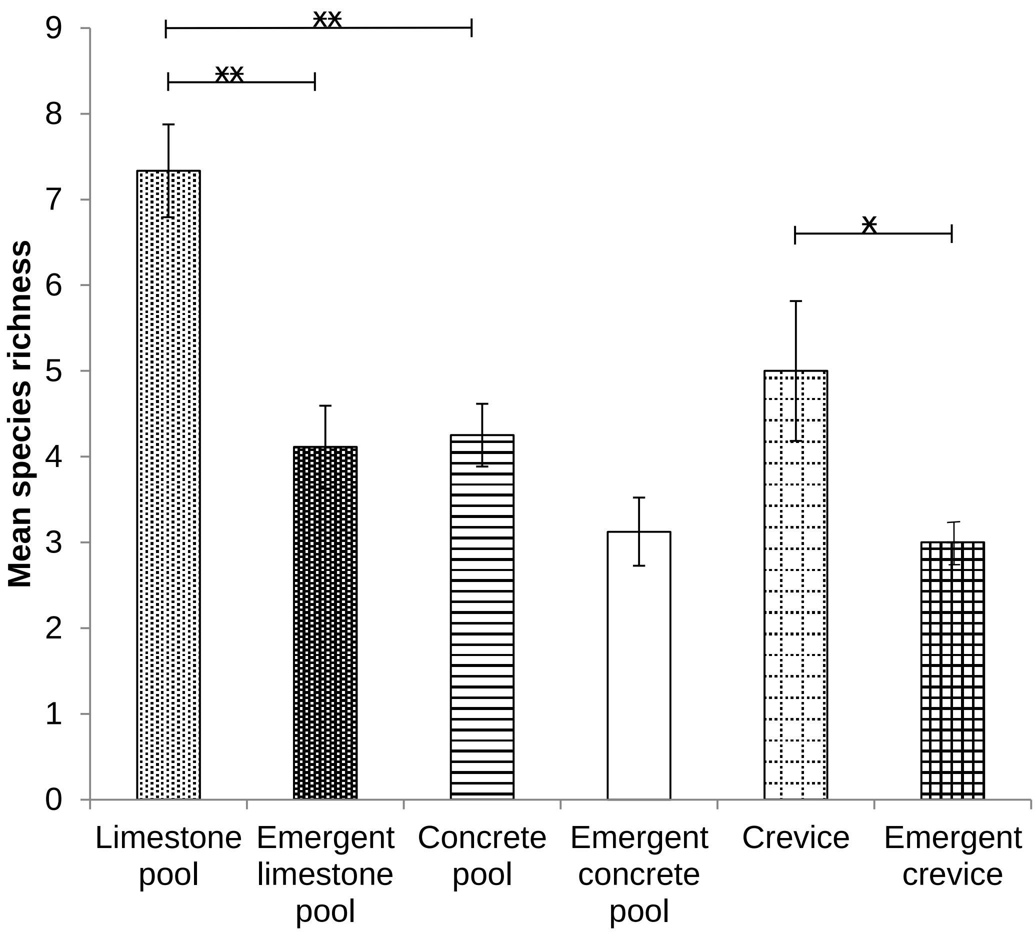


Figure 2.10: Species richness in different habitat types on Plymouth Breakwater ($\bar{x}$ ± standard error). Limestone pool (n = 12); Emergent limestone pool (n = 9); Concrete pool (n = 8), Emergent concrete pool (n = 8); Crevice (n = 4), and Emergent crevice (n = 4). ANOVA SNK among pool and crevice habitats and adjacent substrate emergent to pool and crevice habitats. ⁎ $P < 0.05$, ⁎⁎ $P < 0.01$, ⁎⁎⁎ $P < 0.001$.

*Table 2.8: Species assemblages on different habitats and adjacent emergent substrate on Plymouth Breakwater. A series of one-way ANOVA comparisons between different habitats of the number of species, combined species to taxonomic 'class' and average covers of the species identified by SIMPER as contributing most dissimilarity between habitats. Where needed, data has been transformed (√ or log + 1) to obtain heterogeneity of variances. Limestone pool (LP), emergent to limestone pools (ELP), concrete pools (CP) and emergent to concrete pools (ECP), where n = 8 for each habitat. Post hoc Student-Newman-Kuels (SNK) comparisons, where * p < 0.05 and ** p < 0.01. Not significant (NS). Significant P values in bold script.*

	C	***Df***	***Ms***	***F***	***P***	***SNK***
Number of species	0.45, NS	3	69.11	31.66	**< 0.001**	LP > ELP **;
4 level		28	2.1			LP > CP **
Ulvophyceae	0.92	3	351.3	3.13	**0.04**	
4 level	*P* < 0.01	28	112.2			
Florideophyceae	0.66,	3	110.3	14.66	**< 0.001**	LP > ELP **;
4 level	*P* < 0.01	28	7.5			LP > CP **
Phaeophyceae	0.34, NS	3	3.4	16.04	**< 0.001**	ECP >CP**
4 level, log(x+1)		28	0.21			
Anthozoa (√)	0.53,	3	2.73	11.37	**< 0.001**	LP > ELP **;
	NS	28	0.23			LP > CP **
4 level						
Maxillopoda	0.91	3	12895	42.25	**< 0.001**	ELP > LP **
	P < 0.01	28	305			
Gastropoda (√)	0.35	3,	6.47	14.96	**<0.001**	LP > CP **
4 level		28	0.43			
Lithophylum sp.	0.6	1	2675	5.6	**0.03**	LP > CP *
2 level: LP and CP		14	475.9			
C.Officinalis	0.6	1	217.6	1.9	0.19	
2 level: LP and CP		14	116.8			

*Table 2.9: Species assemblages on crevice habitat and adjacent emergent substrate on Plymouth Breakwater. A series of one-way ANOVA comparisons between different habitats of the number of species, combined species to taxonomic 'class' and average covers of the species identified by SIMPER as contributing most dissimilarity between crevice habitat (C) and Emergent to crevice habitat (EC), n = 4. Heterogeneity of variances was not achieved for some tests, but a balanced design makes ANOVA viable. Significant P values in bold script. * p < 0.05 and ** p < 0.01.*

	C	Df	Ms	F	**P**	SNK
Number of	1	1	8	6	**0.049**	C > EC *
species	P < 0.01	6	1.3			
Ulvophyceae	1	1	3.78	1.28	0.3	
	P < 0.01	6	2.95			
Florideophyceae	1	1	6.48	3.67	0.1	
	P < 0.01	6	1.76			
Phaeophyceae	1	1	0.72	54	**< 0.001**	EC > C **
	P < 0.01	6	0.01			
Anthozoa	1	1	144.5	102	**< 0.001**	C > EC **
	P < 0.01	6	1.4			
Maxillopoda	0.85, NS	1	4560	21.98	**0.003**	EC > C **
		6	207			
Gastropoda	0.58, NS	1	32.4	7.11	**0.037**	EC > C *
		6	4.5			

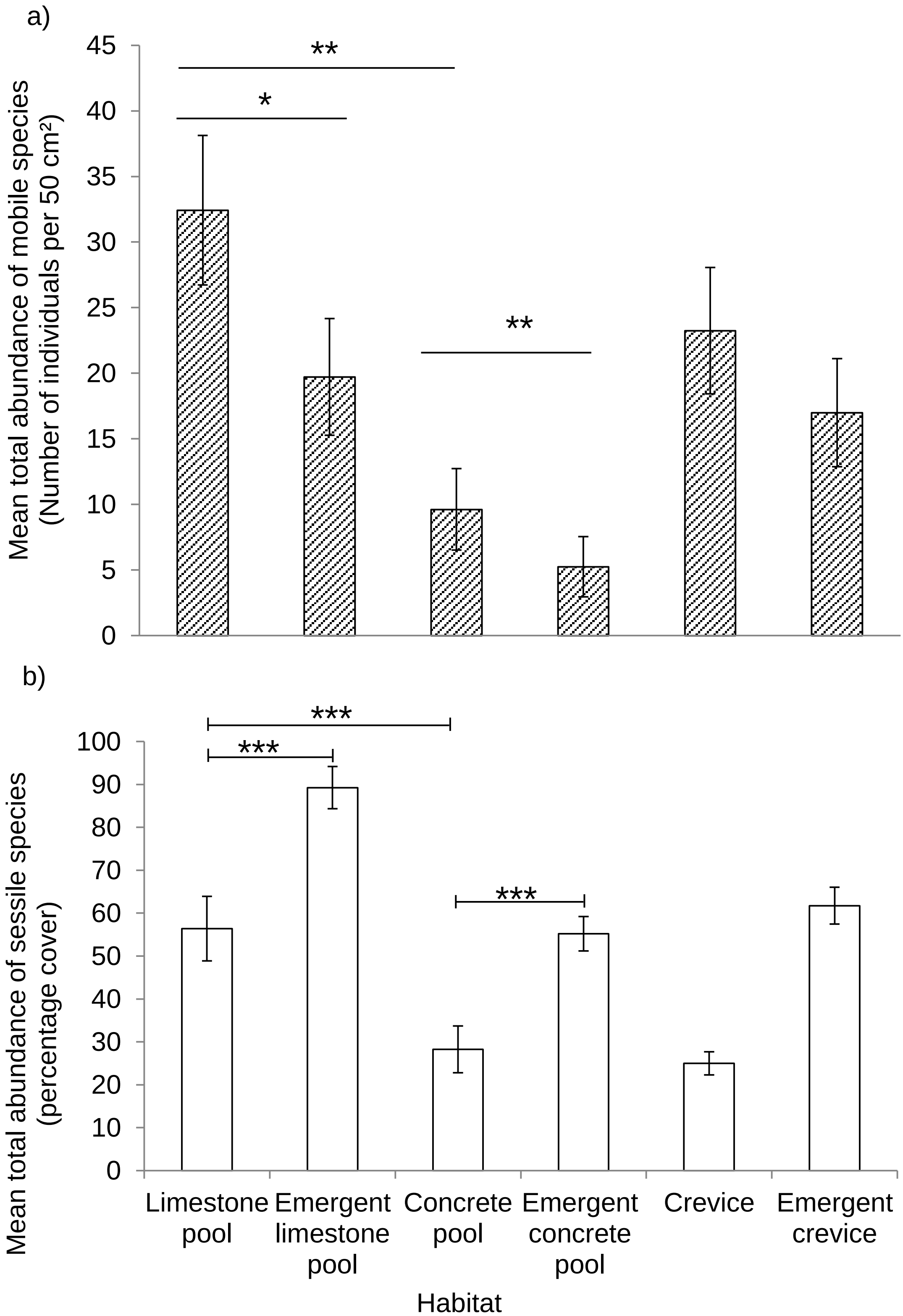
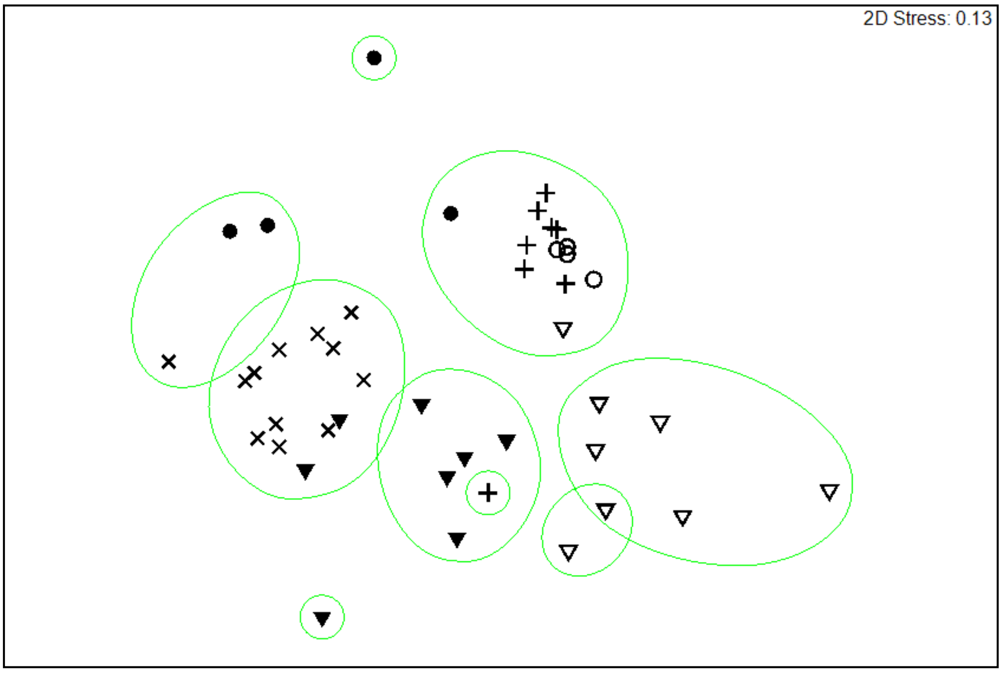


*Figure 2.11: Abundance of a) mobile species, and, b) sessile species in different habitat types on a detached Breakwater ($\bar{x}$ ± standard error). ANOVA SNK among pool and crevice habitats and adjacent substrate emergent to pool and crevice habitats, * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.*

Ordination by nMDS (Figure 2.12) of species samples in the different habitat types showed distinct clusters; with differences in species assemblages between habitats and similarities in species assemblages between samples within each habitat.



b)

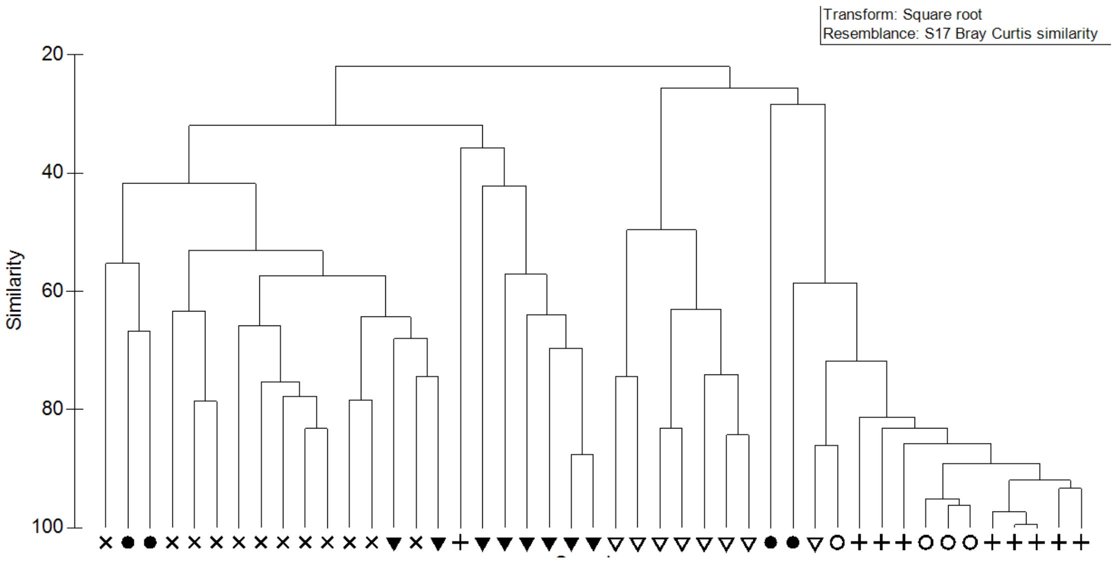


Figure 2.12: Plymouth Breakwater epibiota. a) MDS ordination b) cluster analysis of Bray-Curtis similarities of species abundance (√- transformed) for the habitats crevice (filled circle, n = 4), emergent substrate adjacent to crevice (open circle, n = 4), limestone pool (X, n = 12), emergent substrate adjacent to limestone pool (cross, n = 12), concrete pool (filled triangle, n = 8) and emergent substrate adjacent to concrete pool (open triangle, n = 8). Shaded line outlines clusters with 50% similarity.

Lithophyllum sp. cover was high (Figure 2.13) in pools and crevices, but absent from emergent substrate. Extensive cover of *E. elongata* was found within pools but not on the emergent substrate. Cover of barnacle spp. was high on the emergent substrate and the crevice habitat, and very low within pools (Figure 2.13 and table 2.7).

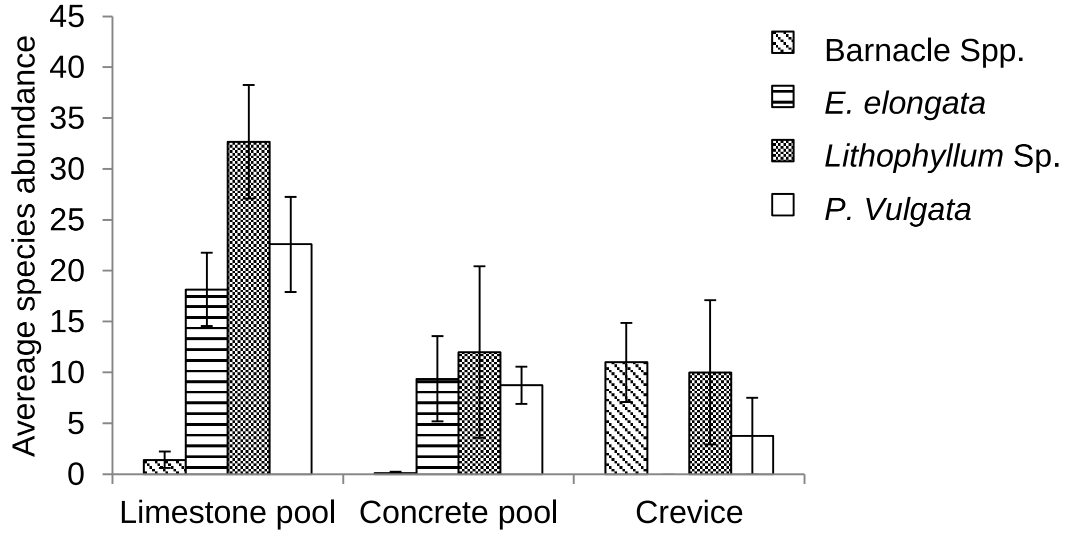


Figure 2.13: Abundance of species in different habitat types that contributed >10% to the total dissimilarity ($\bar{x}$ ± standard error).

The global ANOSIM pair-wise comparisons between all habitat types revealed significant differences (Global R = 0.8, P < 0.001). Significant differences in species assemblages were found between the pool habitat types and the emergent structure, and between each of the pool habitat types (*Table 2.8*). Global ANOSIM pairwise comparisons revealed highly significant differences between limestone pool and emergent next to limestone pool (Table 2.8 and Figure 2.11). Pairwise comparisons revealed highly significant differences between concrete pool and emergent to concrete pool (Table 2.8).

*Table 2.10: Global ANOSIM pair-wise comparison of epibiota on areas of different habitat and the emergent area to that habitat, * $p < 0.05$ and ** $p < 0.01$.*

Comparisons (habitat)	Global $R = 0.8$	**
LP *vs*. ELP	$R = 0.963$	**
CP *vs*. ECP	$R = 0.744$	**
C *vs*. EC	$R = 0.792$	*
LP *vs*. CP	$R = 0.613$	**
LP *vs*. C	$R = 0.894$	**
CP *vs*. C	$R = 0.928$	*

Species assemblages were consistently less similar within the pools than the adjacent emergent area (Table 2.8). Ten species each contributed over 3% to the total dissimilarity between the two pool types of 60% (Table 2.11). Three species each contributed over 10% to the total dissimilarity: *Lithophyllum sp., C. officinalis* and *P. vulgata;* these species were more abundant in the limestone pool than in the concrete pool, contributing to 23, 11 and 10% of the total dissimilarity. The sheltered habitats were highly dissimilar in species assemblage than the emergent area to each of these habitats (Table 2.11). Nine species each contributed over 3% to the total dissimilarity between limestone pool and emergent to limestone pool of 77% (Table 2.11). Total barnacle spp. cover were greatest of the emergent area and contributed 27% to the total dissimilarity*; Lithophyllum sp.* and *C. officinalis* cover were greatest within the limestone pool and contributed, 18 and 13%, respectively, of the total dissimilarity. Seven species each contributed over 3% to the total dissimilarity between concrete pool and emergent to concrete pool of 71% (Table 2.11). *F. vesiculosus* and *Ulva* spp. were most abundant on the emergent area and contributed *35*% and 15%, respectively, to the total dissimilarity. *C. officinalis* were most abundant within pool habitat and contributed 15% to the total dissimilarity.

Table 2.11: SIMPER comparison of species on areas of different habitat and areas emergent to that habitat. Limestone pool (LP), concrete pool (CP), crevice (C), emergent to limestone pool (ELP), emergent to concrete pool (ECP), emergent to crevice (EC).

Within group	% Similarity	Between group	% Dissimilarity
LP	57.69	LP & ELP	76.77
CP	51.59	CP & ECP	71.29
C	49.94	C & EC	70.22
ELP	75.44	LP & CP	59.94
ECP	57.49	LP & C	69.53
EC	89.23	CP & C	81.74
		ECP & EC	62.97
		ELP & EC	23.87
		ESP & EDP	71.45

2.3.5. The influence on intertidal epibiota of crevice habitat on a breakwater.

To address hypothesis 4, that crevices will influence diversity and abundance of intertidal marine epibiota, the established intertidal epibiota within the habitat and the emergent rock habitat were examined. The elevations measured at the crevice habitats were within a 7 cm range, which did not compromise comparisons in relation to its tidal range of 4.7 m (UK Hydrographic Office, 2013).

Comparison of crevices and adjacent areas emergent of substratum showed that the crevice had the highest diversity representation across classes. 10 species across 8 classes were recorded within the crevice habitat, with the highest diversity attributed to the class Gastropoda (*G. umbilicalis*, *N. incrassatus* and *P. vulgata*); 3 species across 3 classes were recorded within the emergent crevice habitat table 2.7).

Significantly more species were present in the crevice than the emergent area (Figure 2.10 and table 2.9). The total species cover were higher on the emergent area to the crevice than in the crevice, although this was not significant (Figure 2.11 and table 2.9). In the crevice the assemblages were dominated by a high cover of *A. equina,* and had a lower cover of barnacle spp. and *P. vulgata* than the adjacent emergent structure.

Ordination by MDS (Figure 2.12) on species composition of the epibiotic assemblages in the different habitat types indicated that the assemblage were scattered within the crevice group, with greater distances between samples indicating greater differences between assemblages, compared to the tight samples of the assemblages within crevices.

The level of similarity of species assemblages within crevice, and within the emergent area were very different (50 and 89% respectively, table 2.10). Eight species each contributed over 3% to the total dissimilarity between the crevice and emergent to crevice area of 70% (Table 2.11). Four species each contributed over 10% to the total dissimilarity between crevice and the emergent substrate adjacent to crevice habitats; barnacle spp. were more abundant on the emergent substrate adjacent to the crevice (23%), *A. equina* were most abundant within crevices (21%), *P. vulgata* were most abundant on the emergent substrate adjacent to the crevice (21%) and *Lithophyllum* sp. were most abundant within crevices (11%) (Table 2.11).

2.4. Discussion

Artificial structures such as seawalls and breakwaters are often uniform in design and consequently low in species richness when compared to many natural rocky shores. On the natural shore it is known that many species will settle in pits, holes or crevices, as these provide shelter for avoiding the physical extremes caused by waves, tides and currents (Little and Kitching, 1996; Raffaelli and Hawkins, 1996), and improve grip to avoid dislocation (Hawkins and Hartnoll, 1983). Similarly on intertidal artificial structures that are regularly exposed to the air or periodically exposed to high wave energy, refuges are important for species to survive extreme environmental conditions associated with emersion or wave energy. At low tide, mobile animals, such as snails, will retreat to these protective refuges (Little and Kitching, 1996). Features on artificial defence structures create habitat heterogeneity which will often increase the local biodiversity. There is a need to recognise the potential for specific types of features to create habitat heterogeneity on structures so that their influence can be assessed for incorporation into new designs, or created on appropriate existing artificial structures.

Existing features of artificial structures that have been incidentally created during construction or maintenance gave species shelter from extreme physical conditions. Features provided species with areas of shade, dampness or retained water (pools); or areas that deflected or dampened the direct physical impact of detrimental forces of tidal currents or wave force. This chapter showed that incidental features on existing structures influenced species assemblages by generating habitat heterogeneity which in turn increased species richness and local diversity. Detailed comparisons of species assemblages on areas with different surfaces were carried out to advance current concepts to increase habitat and species diversity on artificial structures.

Where methods to increase habitat and species diversity are to be considered, an initial assessment of the local area where a structure is to be placed or modified should be performed to assess its general suitability to support marine epibiota. The suitability of a site to increase habitat and species diversity is likely to be principally governed by its position in the intertidal but other possible influential factors such as wave impact and salinity should also be assessed and their impact on marine epibiota predicted before specific design features are considered for a specific desired outcome.

The area in which the marine epibiota on surfaces of differing slope and aspect were studied here is within the intertidal supporting an assemblage of species from multiple taxonomic 'classes', demonstrating the suitability of the artificial structure to support a diverse assemblage of marine epibiota.

2.4.1. *The influence of the slope of a seawall on intertidal epibiota*

Vertical and sloping surfaces did not significantly influence the number of species (Table 2.2, $F_{1,\ 14}$ =1.77, p = 0.21). However, a significantly higher abundance of species within assemblages was found on vertical surfaces than sloping surfaces ($F_{1,14}$ = 78.9, P < 0.001) (Table 2.2 and Figure 2.4). Phaeophyceae cover was high on vertical surfaces ($F_{1,\ 14}$ =18.46, p = < 0.001), predominantly A. nodosum, which can dominate and inhibit the growth of other species whilst providing shade and habitat for epiphytic species of plants and animals (Jenkins *et al*., 1999). The percentage covers of Ulvophyceae, Florideophyceae and Maxillopoda on vertical surfaces were significantly greater than the percentage cover of these species on sloping surfaces. Sloping surfaces seem to be occupied by slow growing species that are perhaps less tolerant to water currents and wave splash but more tolerant to increased direct sunlight. Sloping surfaces had a high abundance of littorinids, possibly owing to an improved ability to grip. *C. officinalis* and *P. vulgata* were unique to vertical surfaces. No species were found to be unique to sloping surfaces. Assemblages of species were generally more uniform on vertical surfaces than sloping surfaces (Fig 2.5b and Table 2.3). Indicating that slope may create conditions suited to a wider and patchier assemblage of species than vertical surfaces (Hartnoll and Hawkins, 1985). Structures with variation in slope will support different assemblages, thus where variation in slope exists an overall higher diversity is likely to be supported, compared to structures that are uniform in slope.

Chapman and Underwood (2011) expected seawalls with areas of slope to have increased diversity; they devised and tested a method to modify seawalls to change the slope in an attempt to increase habitat availability and promote biodiversity on coastal structures. On two seawalls in White Bay, Sydney Chapman and Underwood (2011) created a wall of small blocks stepped up a slope to replace a vertical seawall, giving an increase in total surface area and adding a new horizontal aspect to the habitat. However, the anticipated increase in density or cover of species on the modified surface did not occur during the 26 months of monitoring and they conclude that the two sites were likely to be too sheltered for the effects of slope to be observed (Chapman and Underwood, 2011). Thus emphasising the importance that when a modification or design feature is to be considered, as many as possible of the existing external influences need to be assessed to demonstrate the general suitability of the local area or artificial structure to support epibiotic marine species.

At Starcross, although clear differences between surfaces were identified, the relatively sheltered and mid intertidal position of the study site meant that the influence of some features were not as significant as anticipated. As there is 60% (Table 2.1) of the total species recorded at this site on the sloping and vertical surfaces it is considered that an additional factor is influencing the species present, such as orientation.

2.4.2. The influence of orientation of a seawalls on intertidal epibiota.

The orientation of the seawall influenced species diversity and abundance. Conditions while the tide is out, when organisms are exposed to the air, are different according to the orientation of the shore. In the northern hemisphere, a northerly aspect shore with high cliffs seldom experiences desiccation owing to the sun; while on a southerly aspect, the cliffs may trap the heat so that drying and overheating may become critical factors for limiting colonisation (Little and Kitching, 1996). Between these two extremes there is a spectrum of orientations, creating a variety of conditions to which specific species will differ in their levels of tolerance.

The orientation of seawall influenced the species richness ($F_{2,42} = 3.51$, $p < 0.05$) and the cover / abundance of some species of intertidal marine epibiota (Table 2.4). Typically the north facing surface of the buttresses were the most diverse (with 86% of the total species present, table 2.1) compared to the south facing surfaces (with 80% of the total species present) and east facing surfaces (with 60% of the total species present). The north facing surface generally had a higher cover and abundance of species (Figure 2.6), with the exception of the high cover of barnacle species on the south and east facing surfaces of the buttresses. The south and the east facing surfaces are presumably less favourable to many species due to an increased exposure to the sun, with barnacles making use of the available space because of their ability to resist desiccation.

The within group species assemblages on the easterly facing surface were more similar than within group species assemblages on the north and south surfaces, as revealed by the greater distance between samples on the ordination plot on the N and S surfaces and within group SIMPER (Figure 2.8 and table 2.6). It is likely that the easterly facing surface may create conditions suited to a more specific assemblage of species than the N or S orientations. The east sloping surface provided unique conditions, possibly owing to its position parallel to the rising tide; therefore the water current and wave splash may be of stronger influence than the amount of sunlight.

Species assemblages on surfaces of different orientation to the sun were different; therefore structures with surfaces that vary in orientation will support different assemblages of species and support overall higher species diversity than structures with uniform orientation.

2.4.3. *The influence on intertidal epibiota of pool habitat on a breakwater.*

Pools provide habitat that give different environmental conditions to the emergent rock surface. Organisms within rock pools are often continually submerged and, therefore, do not experience the same stresses caused by the emersion-submersion conditions of the open rock face. Although rock pools can create a refuge from some types of physical stress such as desiccation; other stresses are associated with rock pool such as large fluctuations in temperature, salinity, carbon dioxide and dissolved oxygen and hence pH (Metaxas & Scheibling 1994).

The site at which the marine epibiota in pools of differing material were studied here is within the intertidal supporting of an assemblage of species from multiple taxonomic ‘classes’, demonstrating the suitability of the artificial structure to support a diverse assemblage of marine epibiota.

The presence of pools influenced diversity and abundance of intertidal marine epibiota. Species assemblage differed among pool habitats and the adjacent emergent substrata. Limestone pool and concrete pool habitats (which were shallow and deep, respectively) influenced the number of species, cover of some sessile species and abundance of mobile intertidal marine epibiota when compared to each other and the adjacent emergent substrate. More than twice the numbers of species were found in the pool habitats compared to the emergent area, although, for both pool types, there was one additional new class found. Limestone pools had a significantly higher number of species ($F_{3,28} = 17.4$, $p < 0.001$) than the emergent area and the concrete pool (Table 2.8), and was the habitat with representative species from the highest number of taxonomic ‘classes’ (table 2.7). The assemblages within the limestone pools and concrete pools were less similar (58% and 52%, respectively), than the adjacent emergent areas (75% and 57%, respectively). The greatest differences were between the limestone pool and its emergent area, indicating that the limestone pools supported a varied assemblage of species, whereas the adjacent emergent area supported a more uniform assemblage of species. It was assumed that the high numbers of species found in limestone pools were largely due to the depth as well as material type.

Unique species to the limestone pool were *C. officinalis*, Laurencia spp., *A. viridis* and *S. lomentaria*. *H. elongata* was the only species that was unique to the concrete pool. Typically the concrete pool had more species than the emergent area, with 34% and 21% of the total species present (Table 2.7). Thus the concrete pool seemed to add habitat for some additional species to the area. *P. vulgata* and *Ulva* Sp had a high percentage cover in all concrete pools, typically with a low abundance of few other species, although a high cover of *C. officinalis* and *Lithophylum sp*. were recorded in a few concrete pools. The high covers of total species recorded in areas of emergent substrate were attributed to the high cover of barnacle species and *F. vesiculosus* on the emergent open rock surface.

The assemblages of species found on the adjacent emergent area to limestone pools were similar (table 2.11) to the assemblage found on the adjacent emergent area to crevice, probably because the areas are the same material; whereas, the assemblage of species on the adjacent emergent area to the limestone and concrete pools are highly dissimilar (71%, table 2.11), probably because the areas are of different material.

Species assemblages within pool habitats of different material and depth, and the adjacent emergent area to the pools were different; therefore structures with pool habitats of different material and depth will support different assemblages of species and support overall higher species diversity than structures without pools.

In section 2.3.3 of this study the pools were described, labelled and treated separately according to the different materials; however the depth were also different. Depth was likely to have contributed to the differences recorded in species diversity and abundance. The concrete pools were the same depth as each other and were deeper than the limestone pools, which were also the same depth as each other. Pool depth might have been a stronger influential factor than the material type, through effects on physicochemical conditions within the pool during low water (Martins *et al.*, 2007). The identification of additional pools that would allow replicate testing of depth and material type separate to one another would provide confirmation.

As with the present study, Firth *et al*. (2013) found evidence in experimentally created rock pools of two depths on a new breakwater at Tywyn, Wales, that shallow pools supported significantly greater richness than emergent substrata, whilst deep pools supported similar numbers of species as the emergent substrata. The pools were described, labelled and treated separately according to the different materials; however the depth were also different. The concrete pools were the same depth as each other and were deeper than the limestone pools, which were also the same depth as each other.

2.4.4. The influence on intertidal epibiota of crevice habitat on a breakwater.

The presence of crevice habitat to influence species diversity and abundance. Crevices provide areas of shade and dampness that will shelter against the desiccating effect of the sun on many species, and provides protection against the potentially destructive mechanical forces of waves, splash and currents. The site at which the marine epibiota in crevices and the adjacent emergent area were studied here is within the intertidal supporting of an assemblage of species from multiple taxonomic ‘classes’, demonstrating the suitability of the artificial structure to support a diverse assemblage of marine epibiota. As expected, the number of species is high within the crevice with 43% of the total number of species found at the site, and species from 8 out of the 9 classes found at the site. More than three times the number of species, across twice the number of classes, were found within the crevice compared to the adjacent rock surface. Two species *G. umbilicalis, N. incrassatus* were unique to the crevice habitat. *A. equina* and *Lithophyllum* sp. were found within the crevice habitat. Mobile species are likely to have taken refuge during low tide, and are expected to emerge and forage or predate over a wider area when submerged by the incoming tide. The assemblages of species within the crevice samples were varied (50% similarity, Table 2.11), whereas the assemblages in the emergent area adjacent to the crevice were more uniform (90% similarity, Table 2.11). The total abundance of species is higher on the emergent area adjacent to the crevice habitat, which is caused by a high percentage cover of barnacle species.

Species assemblages within crevice habitats and on the adjacent emergent rock surface were different; therefore structures with crevices will support different assemblages of species and support overall higher species diversity than structures without crevices.

On natural rocky shores, crevices provide refuges for many species (Gray and Hodgson, 1998, Johnson *et al*. 2003). Chapman and Underwood (2011) investigated the effects of adding crevices to an existing seawall in Kirribilli, Sydney Harbour. Taking advantage of the maintenance regime of the seawall, the authors modified crevices that were being filled with mortar between blocks – some were filled as normal (flush with the blocks) and others were indented by 20 mm to create crevices. As with the findings of my study, Chapman and Underwood (2011) found that epibiotic diversity were greater within the crevice than the adjacent area without crevice. Chapman and Blockley (2009) found that small crevices present on the surface of seawalls increased the diversity of sessile animals and algae, but the increase in diversity were restricted by the limited size of crevices.

2.4.5. Implications for design

The dynamic coastal environment is created by multiple interactions between environmental gradients and biological processes. It is considered that different assemblages of species require different levels of protection from multiple stress gradients and disturbance regimes. Protection can be provided on structures through the provision of different areas of slope and orientation, and the availability of different habitat types. The structural features of coastal defences create diverse habitats, analogous to the features that are known to create habitable space on rocky shores, such as pools and crevices.

This study found that established intertidal marine epibiota colonising structures were influenced by features such as different slope and orientation of surface, and the presence of different habitat types, such as pools and crevices. These features provide refuge from extreme conditions caused by tidal currents, wave action or periods in the air. The features created different forms of shelter, which broadened the potential habitat type available on the structures. A variety of available habitats suited a greater number and diversity of species.

It is also likely that when the tide rises and the feature is submerged these habitats support species such as fish and crustaceans, which may not reside in the pool whilst the tide falls and will therefore not be recorded in a survey carried out during low tide. Therefore, structures with variation in habitat type such as pools and crevices will support different assemblages and support an overall higher local diversity than structures are uniform in habitat type.

Heterogeneity in design can be achieved by combining features such as sloping areas at different orientations, or pools with overhangs to create shade. Blockley and Chapman (2006) studied areas of seawalls that were shaded by wharves, or unshaded. They found that for many species the response to shade on artificial structures were similar to the responses observed to shade in natural habitats. For adult populations, most sessile invertebrates had greater cover on shaded seawalls. Algae had a greater cover and mobile invertebrates a greater abundance on unshaded seawalls. Combinations of features will provide a host of habitats affording different conditions and degrees of protection against the elements, which in turn influences the composition of assemblages and consequently increases the overall diversity.

There are few studies of the influence of existing design features of coastal structures on epibiota. The study presented in this chapter investigated the influences of features that create habitat variability owing to different orientation and the slope of surface of the structure, and the presence of sheltered habitats in pools and crevices. By design, coastal structures provide practical experimental units often with ideal replicate sampling units, where physical impacts are relatively uniform along the length of the structure, particularly in respect of intertidal position and wave direction. Also, where features do exist, they are often present in multiple with replicate dimensions, and positioned in a regular manner, which were highly suited for experimental replication.

Shelter and water-retaining features enable many species to survive the conditions of the intertidal environment. Structural features create a different set of conditions to that of an even surface. Some features provide a habitable space which were more species rich; others support a different community to that of the surrounding emergent rock, thus increasing the overall diversity of an area.

The present study found that different habitat types exist on coastal defences as a consequence of the construction design and process. Structural features on coastal defences provide areas of diverse surface that creates different habitat. Structural features that provide areas of sloping surface at different angles; areas of surface that face a different orientation to the sun; water-retaining features (pools); and, crevices influence intertidal marine epibiota by providing different habitats. A diverse surface allows for the existence of different habitats that are considered essential to accommodate a diverse array of species (Chapman and Bulleri, 2003; Jensen, 1998) and the different life stages (Challinor and Hall, 2008).

From the studies of Blockley and Chapman (2006), it is evident that, when comparing natural rocky shores and artificial structures, it is important to consider the extent to which the conditions are made available, for example, the area of shade offered by a structure, which will result in different species assemblages or interactions. The extent and interval that uniform structures are interspersed with areas of shelter and shade is likely to influence the overall ability of a structure to support intertidal marine epibiota.

Wave exposure was a major factor influencing the horizontal patterns of distribution on Plymouth Breakwater (Southward and Orton 1954), as expected, given the reason of need for the Breakwater. Swells and refracted waves are important in Plymouth, and were particularly noticeable influences on the ability to collect data. Thus on this exposed site, protection from waves through the provision of sheltered habitats were likely to be particularly significant.

The influence of features on intertidal epibiota is likely to be site specific, as multiple factors, such as geographic location, species recruitment and even season of construction, will interact. For this reason, to strengthen the findings of this study, further example sites should be identified and tested in a similar manner. Further research of this topic is necessary to inform stakeholders of the possible ecological outcomes of specific design features, to allow for careful provision of additional habitat to enhance ecological value without losing its function.

Chapter 3
long-term colonisation of wavebreaker units added to Plymouth Breakwater

3.1. Introduction

Coastal defences are needed to protect property, agricultural land and infrastructure (Jackson and McIlvenny, 2011, Masselink and Russell, 2007; Taylor *et al*., 2004). They do, however, have an impact on the environment (Airoldi *et al*. 2005; Chapman, 2003; Chapman and Blockley, 2009; Chapman and Bulleri, 2003; Firth *et al.*, 2013; Martins *et al*. 2005; Moschella *et al*., 2005; Thompson *et al*., 2002. See section 2.1.2 of this thesis). Any hard substrate placed in the sea will be rapidly colonised or fouled by marine biota (Wahl, 1989). Understanding the patterns of and processes involved in succession are crucial for better predictive capability about the biota colonising artificial substrata (Connell and Slatyer, 1978; Benedetti-Cecchi, 2000).

Primary succession occurs when new hard substrate is placed in the sea or natural processes lead to exposure of a new rock surface (See Connell and Slatyer, 1977 for review of terms and concepts). Secondary succession is when disturbance opens up space for colonization, but some elements of the community remain (Dayton, 1971; Sousa, 1979a). This occurs when space on rocky shores becomes released owing to the removal of sessile organisms such as algal canopies or turfs or relaxation of grazing pressure (Hawkins, 1981; Hawkins and Harkin, 1985; Jenkin *et al*., 1999; Jones, 1975; see Hawkins and Hartnoll, 1985 for a review of early literature; Sousa and Connell, 1992). There can be multiple phases of succession occurring simultaneously on a shore at any one time, as physical or biological disturbance spatially re-sets the successional sequence (Connell, 2001). There can also be multiple different end points (or climaxes) to succession owing to the influence of multiple factors.

Various models of succession have been proposed (Connell and Slatyer, 1977; see Benedetti-Cecchi, 2000 for commentary). “Facilitation” is when an early stage, such as the presence of a biofilm, is required for the success of later arriving species. “Inhibition” is when an intermediate stage suppresses or slows replacement of later arriving species; this has often been observed when early successional green algae dominate an area. Grazing is required to enable procession to later stages (Sousa, 1979). Tolerance is when neither positive nor negative interactions occur, but, owing to life history traits, early- and mid-successional species die off and are replaced by longer lived mid- or late-successional species. This is a neutral model of succession. As a community reaches late succession, the community structure can stabilise about an equilibrium or climax, with high levels of similarity in species abundance and diversity. Generally, species diversity is higher in mid succession than at early and later stages (Connell and Sousa, 1983).

Construction of Plymouth Breakwater (see Figures 2.1, 2.3a and b; and Section 2.2.1) commenced in 1812 to protect Plymouth Sound from south westerly storms, thereby improving conditions for anchorage. The wave action on the exposed seaward face is often greater than 3 m, up to ten times the amplitude of the landward face (Southward and Orton, 1954). This indicates the effectiveness of the defence structure in its primary role of reducing wave energy. Southward and Orton (1954) showed that distribution patterns were primarily influenced by tidal inundation on the vertical gradient, and wave exposure on horizontal gradient. The main section is 914 m in length. At each end of the main section there are two arms of 320 m length, which extend at an angle of 120 degrees to the main section. The structure is 13 m wide at the top and 65 m wide at the base. The breakwater is of sufficient extent that it resembles the scale of many natural rocky shores (Southward and Orton, 1954).

Additional date-stamped concrete wave breaking units were regularly added to the seaward facing slope of the breakwater to create protection to the main structure by dispersing the wave energy (Figures 2.3 and 3.1). With a few exceptions, as a consequence of the 2^{nd} World War and problems with the transportation barge, this maintenance has been annual over the last 85 years. The date stamps dating from the 1970s (Hawkins, pers. comm.) provides a reliable indication of the duration of succession on each unit. Hence, the wave breaking units provide excellent test systems for long-term successional studies (Hawkins *et al.,* 1983).

Concrete wavebreaker armour units (Figure 2.3 and 3.1) continue to be cast and deployed as part of the ongoing maintenance (Figure 3.1). The units are frustums (truncated pyramids), 2.5 m high, 2.4 × 4.8 m at the top and 3.5 × 6.8 m at the base. They are cast at Oreston, a sheltered tidal area at the mouth of the River Plym, and stamped with the year of placement using numerical inserts, which are placed within the mould at the time of casting. After being released from the mould, the concrete units are cured in a sheltered location for some time (typically at least one year) before deployment on the breakwater; thus succession is not primary. The armour units provide isolated sites in a chronosequence, which are spatially independent; multiple units have several common attributes, but are of different ages (Griffin, 2008).

Irregular surfaces with a greater surface texture and complexity of features can occur on hard defences as a consequence of weathering and erosion over time; this is particularly evident with concrete structures (Figure 3.2, pers. obs.).

Hawkins *et al*., (1983) used the units on the breakwater to understand succession and stabilisation of *Patella* populations over time. Unfortunately, during this study (Hawkins *et al.,* 1983) there was a gap in unit deployment enabling only early and late stage succession to be examined. Fortunately for my work, the regular deployment of units of known age enabled the study of the long-term colonisation sequence on artificial concrete structures. My overall aim was to describe sequences of colonisation of the units on the outside of Plymouth Breakwater. This should aid understanding of timescales over which interventions to enhance biodiversity can operate. The work also provides basic knowledge of successional processes on rocky shores, as studies over 20 year timescales are rare. This longitudinal study also allowed assessment of the influence of the weathering of the concrete units over time and the consequences of this for biodiversity. The aims of this chapter were to quantify the diversity and abundance of species on the artificial structure, and to observe successional sequences. In particular, the study provided insights into the ecological processes and timescales to reach community equilibrium on intertidal coastal defence structures.

Thus, the specific objectives were to record the assemblage of marine epibiota on artificial structures in order to:

1) Describe the colonisation sequence of the units over at least 20 years.
2) Estimate whether as a consequence of succession the units eventually resemble natural rocky shore of the same exposure.

3) Understand the weathering processes of the units themselves and its influence on biodiversity.

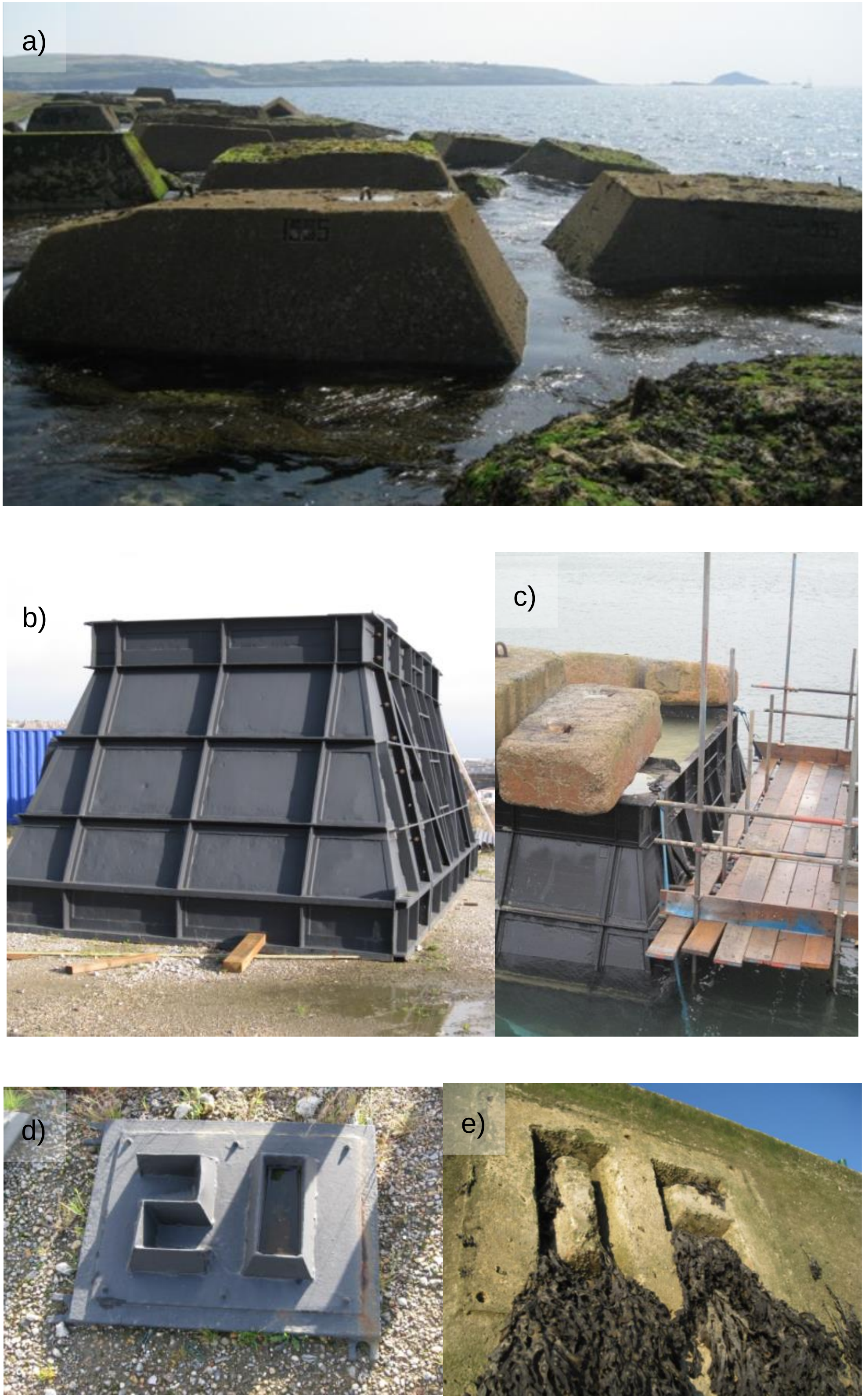


Figure 3.1 *a) Concrete armour units on the seaward side of Plymouth Breakwater; b) the mould; c) the casting process during the production of the armour units; d) the numerical inserts, and, e) the date stamp on the armour units, with associated species*.

3.2. Methods

3.2.1. Area of study

Oreston is an estuarial area on the River Plym where the concrete armour units are cast and left to cure on the foreshore, where they are submersed with each high tide.

Plymouth Breakwater is described in section 2.2.1 of this thesis. The tops of the armoured units (Figure 3.1) placed on the seaward side of Plymouth Breakwater (Figure 2.3 and 3.1) were the focus of this study in order to examine succession. The tops of units were located at approximately the same tidal height (3.4 m ± 40 cm above chart datum), which is approximately Mean Tide Level (MTL).

3.2.2. *Comparisons of marine epibiota on established wave armour units of known age.*

The species established on the tops of the units at Oreston were recorded after the blocks had been curing on the foreshore for approximately one year. Four randomly placed 50 × 50 cm quadrats were sampled on the tops of five blocks at low tide. Abundances were recorded as the percentage cover, and for mobile species as number of individuals.

In order to describe the colonisation sequence of the units, intertidal marine epibiota were surveyed on wave armour units of known age (Figure 3.1) on the seaward side of Plymouth Breakwater. The community composition on the tops of units that were horizontal and within ± 40 cm of MTL were surveyed on four occasions during mid-summer in 2006, 2007 and 2009. The age of older units, from the 1980s, that were either not date stamped or whose dates were not legible were grouped as mature (16 – 20 years) units, where the condition and weathering was very similar to units of known age, or as weathered (21+ years) units. Slight changes in the design of the lifting ring also helped to age the older blocks. A range of units of different ages were selected on each sampling occasion to reduce the potential for seasonal variability to affect comparisons. The age of the units surveyed were: 2 years (n = 15), 5 years (n = 10), 6 years (n = 15), 7 years (n = 25), 9 years (n = 20), 10 years (n = 5), 12 years (n = 5), 14 years (n = 20), 20 years (n = 10), 21 years (n = 5), and 26 years (n = 15) of age.

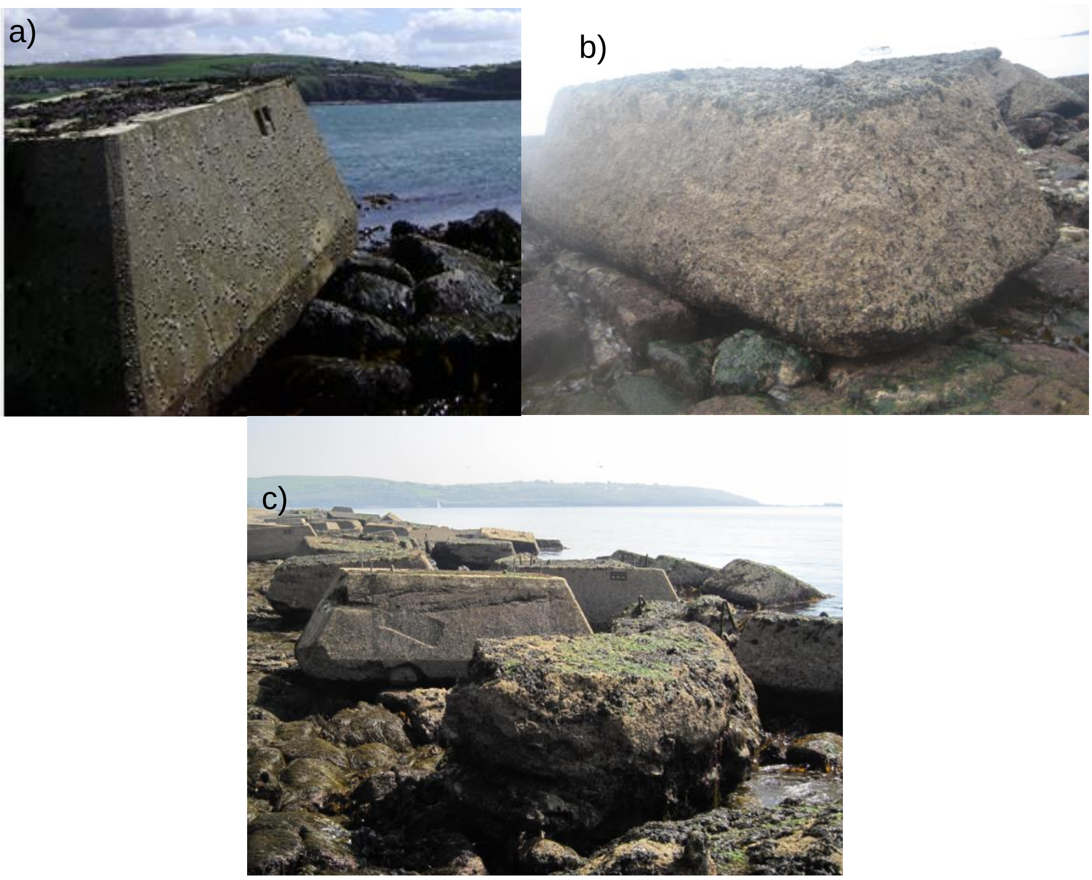


Figure 3.2: a), b) and c): Evidence of weathering and increased surface roughness as a consequence of age.

To improve continuity for data analysis, the units were grouped and described as different phases of succession where units < 3 years of age were classified: as "recently deployed" (as described in the introduction of this chapter, n = 15), units of 4 – 6 years were described as "early", n = 35, 7 – 10 years were labelled "mid", n = 40; 11 – 15 years were labelled "late", n = 25; 16 – 20 years are "mature", n = 10; and, 21 + years were called "weathered", n = 20.

Data were collected at low-tide when the units were exposed to the air and could be accessed using a ladder from the main structure. A minimum of five randomly placed 50 × 50 cm quadrats were sampled on a selection of units within each age range. Abundances were recorded as the percentage cover, and for mobile species as number of individuals. *Patella* spp. sizes were measured for and used to calculate the percentage cover. For some species, cover were recorded as taxa and the approximate relative proportions of each species were recorded, thus recording cover at a high level of accuracy without sacrificing individuals, thus reducing the impact of the survey. The term "sp(p)." denotes organisms of either one or several unidentified species, and all groups of organisms are referred to as "taxa". The World Register for Marine species (WoRMs, 2014) has been used as a reference for up to date taxonomy, and the species name is shown with the discoverer name and date in the list of species. Analysis has been performed at the species level, although for uncluttered presentation some results are displayed at a higher taxonomic rank.

Barnacle spp. were recorded as percentage cover in the 50 × 50 cm quadrats. The accurate identification to species level for each individual were not possible. The size of Patellid species were recorded to assess whether inter size competition were occurring irrespective of species. Algal abundance was assessed as percentage cover of substrate or as canopy cover.

Statistical analyses were performed using PRIMER 6 (Clarke and Gorley, 2006) and GMAV (Underwood and Chapman, 1998). Assemblages on units of different age were compared using a one-way ANOVA (using GMAV) and MDS ordination (using PRIMER) for the abundance of dominant taxa at the different ages, or phases, of succession. Multivariate analyses were performed on species assemblage data. The Similarities Percentage procedure (SIMPER) (Clarke, 1993) were performed on total species cover to identify discriminating features of species abundance within assemblages, as described in section 2.2.2.

3.3. Results

3.3.1. Intertidal epibiota on units of different age

To describe the colonisation sequence of the units, including reduction of algae that had pre-colonised during the curing process, the established intertidal epibiota on units prior to deployment to the breakwater, and a chronosequence at the breakwater were examined.

A total of 11 taxa across 5 taxonomic classes were recorded on the top of the units at Plymouth Breakwater, with the highest diversity attributed to the class Florideophyceae (Table 3.1). The species authority for each recorded species is given in table 3.1.

Table 3.1: List of species identified on the top of units on Plymouth Breakwater.

Class	**Species**
Ulvophyceae	*Ulva* spp.
Phaeophyceae	*Fucus vesiculosus* (Linnaeus, 1753)
Florideophyceae	*Vertebrata lanosa* (Linnaeus,1767)
	Laurencia sp.
	Corallina officinalis (Linnaeus, 1758)
Maxillopoda	*Chthamalus spp.*
	Perforatus perforatus (Bruguière, 1789)
	Semibalanus balanoides (Linnaeus, 1767)
	Austrominius modestus (Darwin, 1854)
Gastropoda	*Patella vulgata* (Linnaeus, 1758)
	Patella depressa (Pennant, 1777)

Considerable spatial variation in abundance were observed for all species across the chronosequence. For example, cover of *F. vesiculosus* ranged from 0 – 86%, Patellid (predominantly *P. vulgata*) abundance ranged from 0 – 25 individuals per 0.25 of a square meter survey area, *Ulva* spp. cover ranged from 0 – 51% and barnacle cover ranged from 0 – 94%.

Four taxa were identified on the tops of blocks at Orestone. *Fucus* cover dominated, and on some units there was a high cover of *Ulva* spp.. *Littorina littorea* and *Carcinus maenus* were present in very low numbers.

The sequence of succession of species over time is shown in Figure 3.3. Ephemeral algae (*Ulva* spp.) and *F. vesiculosus* dominated units of less than four years old. The *Fucus* cover initially present on recently deployed units resulting from colonisation whilst curing at Oreston, reduced to a low cover within 4 – 6 years (Figure 3.3). Barnacles rarely occur on recently deployed succession units. Total barnacle spp. cover and *Patella* spp. numbers were higher and the fucoid cover were much lower on units between 4 to 14 years old. When fucoid species cover were low, the cover of *Ulva* spp. increased.

The cover of fucoid species were greater on recently deployed, mature and weathered units (Figure 3.3 and 3.7). The abundance of *Patella* spp. were greater on old and mid-stage units. *Patella* spp. were present on all successional phases, although not on all units and with no easily recognisable pattern of abundance across the successional phases (Figure 3.6 and 3.7). *Patella* spp. were abundant on some units of a specific phase, but were absent from some units of the same successional phase. Dominant species were absent from the mid-age units. *Ulva* spp*.* occurred on units of all ages throughout the successional sequence.

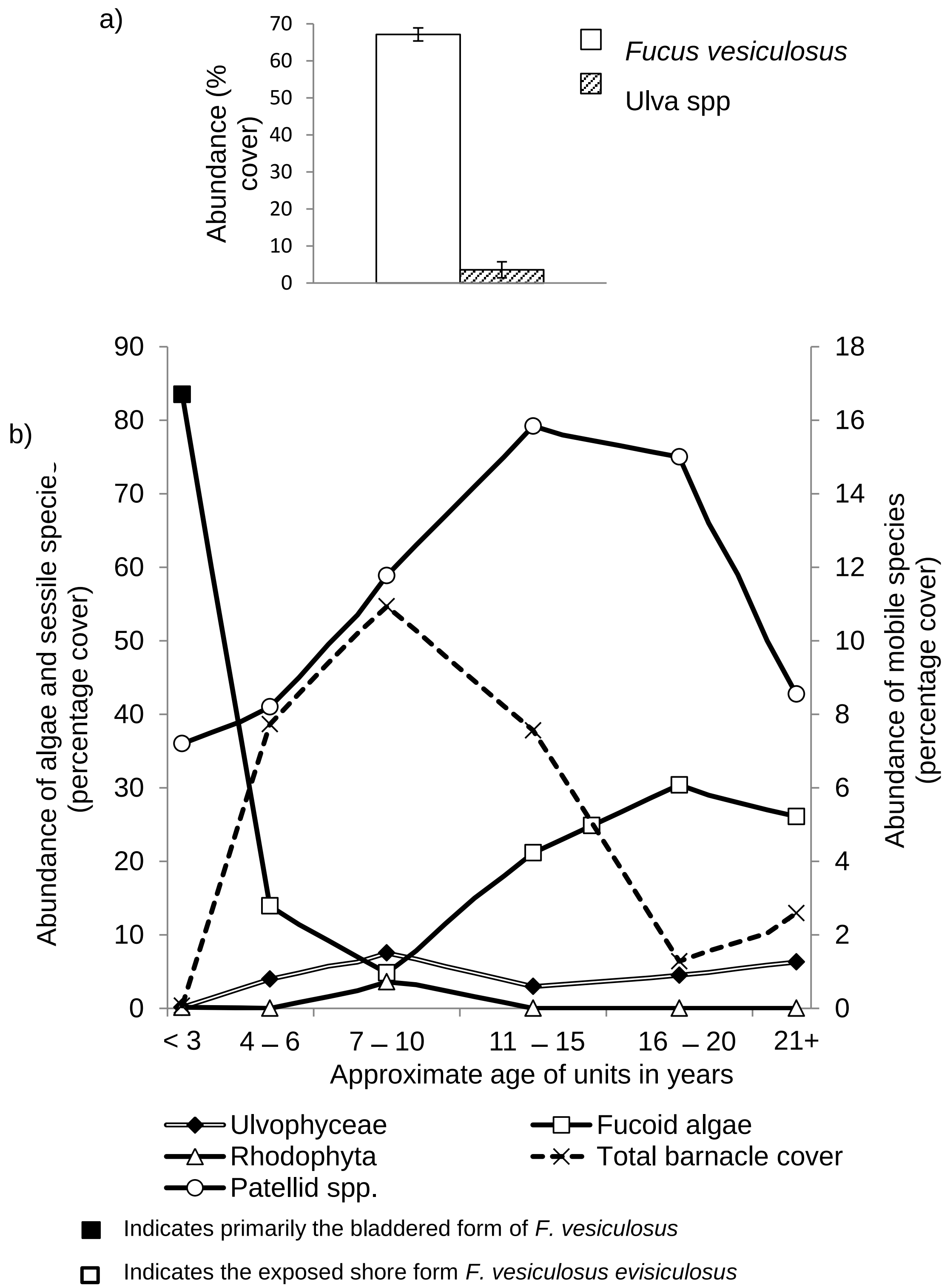


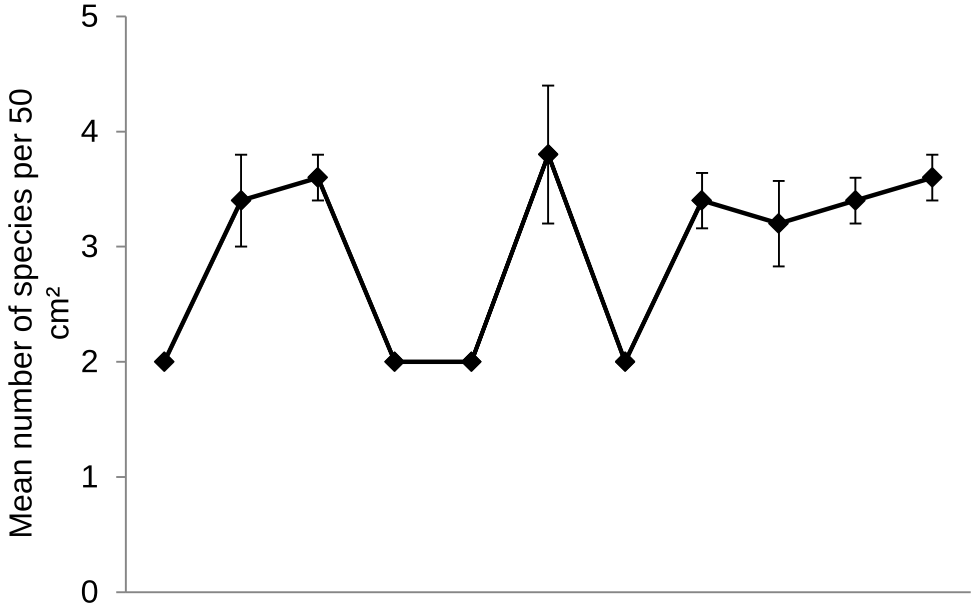
Figure 3.3: a) Species established on the units at Oreston, prior to deployment to Plymouth Breawater. b) Species abundance on different phases of succession, as a function of unit age. $\bar{x}$ ± standard error. Units "recently deployed" <3 years, n = 15; "early" 4 – 6 years, n = 35; "mid" 7 – 10 years, n = 40; "late" 11 – 15 years, n = 25; "mature" 16 – 20 years, n = 10; and, "weathered" 21+ years, n = 20.

Table 3.2: a) Species assemblages on armour units of increasing age at Plymouth Breakwater. A series of one-way ANOVA comparisons of species richness and abundance on units of 11 different ages (ages in years were 2, 5, 6, 7, 9, 10, 12, 14, 20, 21, 26; for each age n = 5); b) Student-Newman-Kuels comparisons. See graphs 3.4a and b for direction. Two symbols denotes significance P < 0.01 and one symbol denotes P < 0.05. Number of species denoted by ◊, diversity denoted by ♦, and, total species abundance denoted by •.

a)	**Cochrans *C***	**MS**	***F***	***P***
Number of species (◊)	0.38	2.9	*7.31*	***<0.001***
Total abundance of sessile species (●)	*0.22*	*2598*	*7.22*	***<0.001***

b) Age	2	5	6	7	9	10	12	14	20	21	26
2		◊●	◊◊♦			◊◊♦		◊♦♦	◊♦●●	◊♦♦●	◊◊♦●●
5	♦		●	◊	◊◊♦ ●●		◊◊♦●●				
6				◊◊♦	◊◊♦		◊◊♦		●		●
7		♦			●	◊◊♦	●	◊◊♦	◊♦	◊♦	◊◊♦
9						◊◊♦●		◊◊♦	◊♦●●	◊♦●●	◊◊♦●●
10							◊◊♦●				
12								◊◊♦	◊◊♦●●	◊◊♦●●	◊◊♦●●

a)



b)

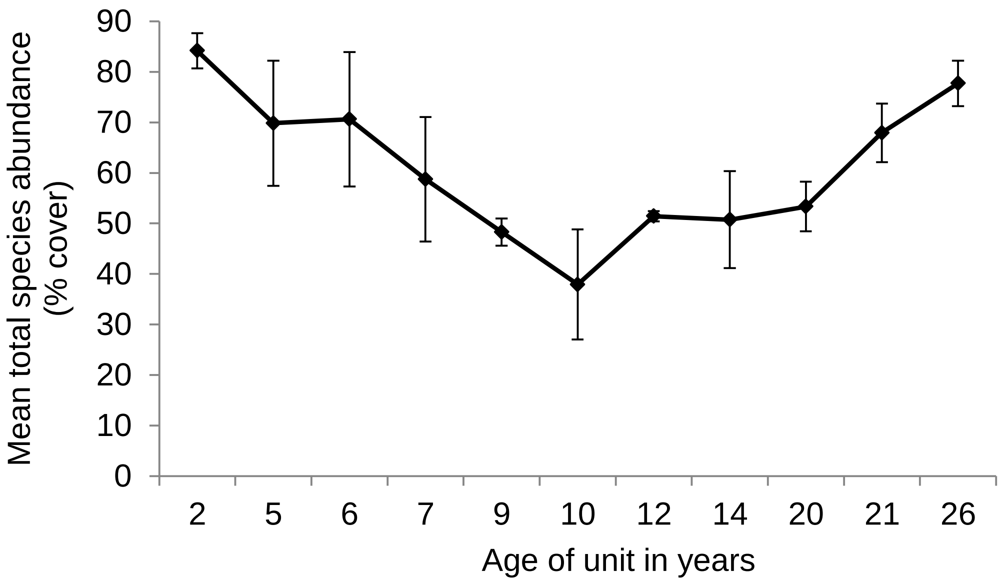


Figure 3.4 a) Species diversity on armour units of different age, expresed as mean number of species; and b) Mean abundance of sessile species, n = 5 for each age displayed on shared horizontal axis, $\overline{x}$ ± standard error.

Juvenile limpets (> 5 mm in shell diameter) were more abundant than mature limpets (> 40 mm in shell diameter) on blocks of most ages (Figure 3.7). The number of juvenile limpets was significantly greater on recently deployed blocks (Table 3.4) than blocks of early and mid phases of succession. Mature limpets were least abundant on blocks of late, mature and weathered phases of succession (Figure 3.7).

Table 3.3: a) A series of one-way ANOVA comparisons of combined species abundance to taxanomic 'class' at different phases of succession. For each age range, n = 10. Significant P values in bold font. b) Student-Newman-Kuels Comparisons with the age group with the highest abundance in the paired comparison given in the table. Ulva spp. (•), Fucoid spp. (□), Total barnacle spp. (x), patellid spp. (•); where two symbols denotes significance P < 0.01 and one symbol denotes P < 0.05.

a)	Cochran's *C*	DF	MS	*F*	*P*
Ulva spp. (♦)		5, 54	955	5	**<0.001**
Fucoid spp. (□)	0.36	5, 54	8802	46.20	**<0.001**
Total barnacle spp. (●)		5, 54	6421	8.40	**<0.001**
Patellid spp. (x)	0.32	5, 54	89	1.61	0.172

b)	Approximate age of units in years 4 – 6 "early"	7 – 10 "mid"	11 – 15 "late"	16 – 20 "mature"	20+ "weathered"
< 3 years "recently deployed"	□□ <3 ●● 4 – 6	♦♦ 7 – 10 □□ <3 ● 7 – 10	□□ <3 ●● 11 – 15	□□ <3	□□ <3
4 – 6 years "early"		♦♦ 7 – 10 □ 7 – 10	□□11 – 15	□□ 16 – 20 ●● 4 – 6	□□ 20+ ●● 4 – 6
7 – 10 years "mid"			♦♦ 7 – 10	♦♦ 7 – 10 □ 16 – 20	♦♦ 7 – 10 □ 20+
11 – 15 years "late"				●● 11 – 15	●● 20+

Ordination by MDS (Figure 3.8) revealed that the assemblage found on recently deployed units that had been partially colonised in the Plym were clustered in a tight group. Assemblages found in early- and mid- secondary successional phases were widely spread, revealing little similarity within and between these phases. Whereas assemblages found on units of late-, mature- and weathered-successional phase were clustered and showed similarity within clusters and between clusters.

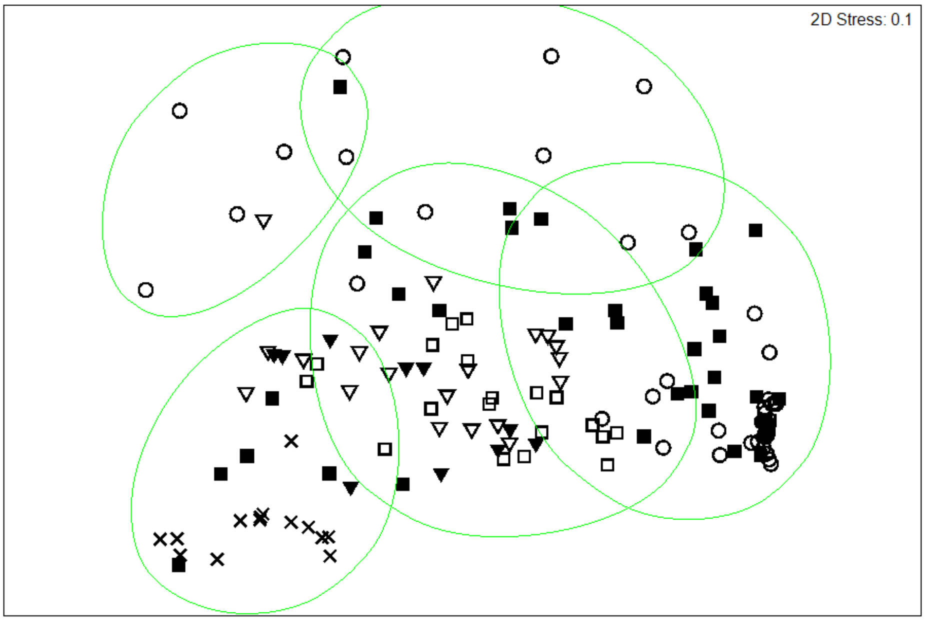


Figure 3.4: Plymouth Breakwater epibiotic macrofauna. MDS ordination plot of Bray-Curtis similarities from √-transformed species abundance data on units of known age. Each symbol represents the epibiotic species abundance within one quadrat on breakwater unit samples within approximate age groups: < 3 years "recently deployed" (×), n = 15; 4 – 6 years "early" (filled square), n = 35; 7 – 10 years "mid" (open circle), n = 40; 11 – 15 years "late" (open square), n = 25; 16 – 20 years "mature" (filled triangle), n = 10; 20 + years "weathered" (open triangle), n = 20.

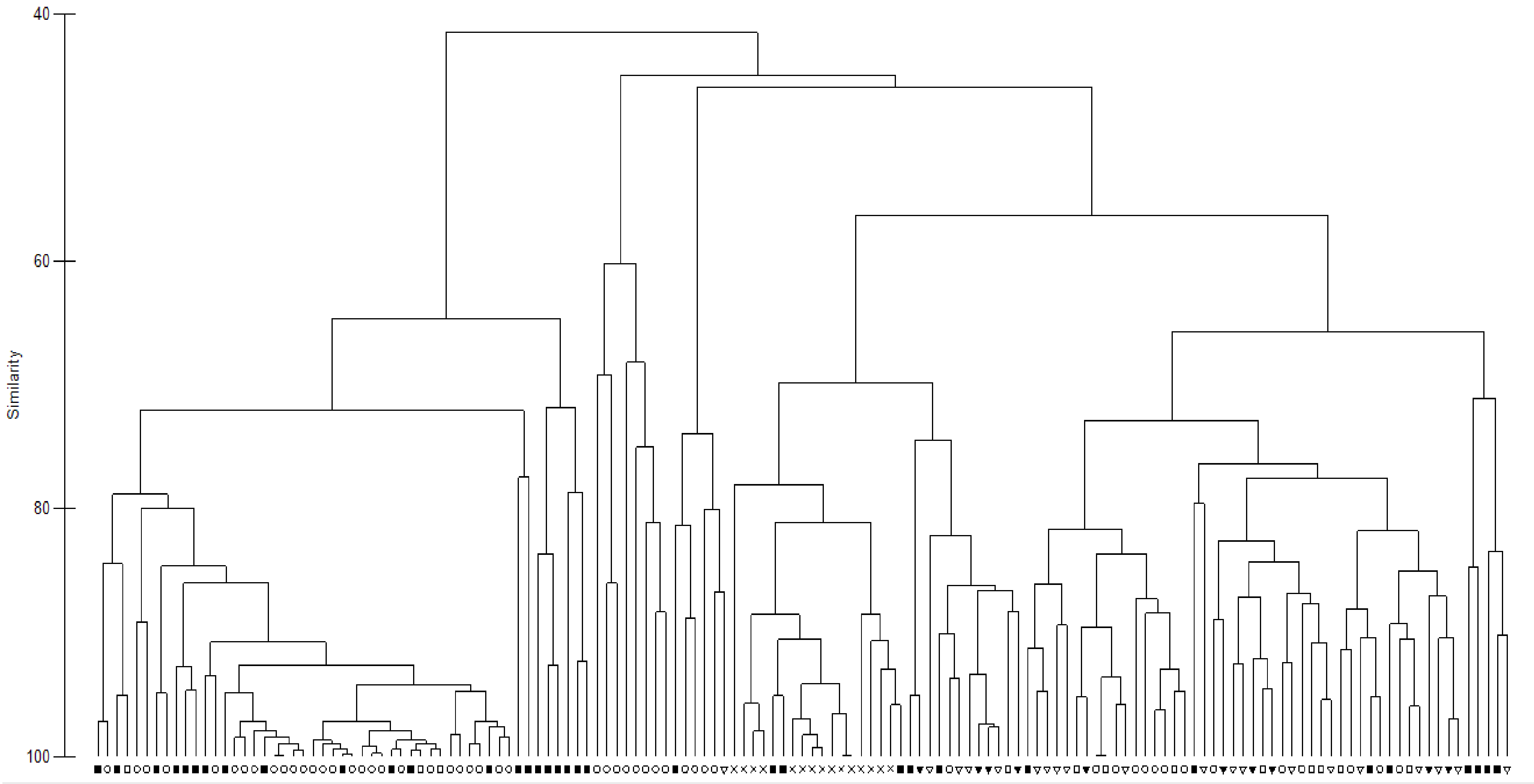


Figure 3.5: Plymouth Breakwater epibiotic macrofauna. Cluster analysis of Bray-Curtis similarities of species abundance (√-transformed) on units of known age, where < 3 years is "recently deployed" (×), n = 15; 4 – 6 years "early" (filled square), n = 35; 7 – 10 years "mid" (open circle), n = 40; 11 – 15 years "late" (open square), n = 25; 16 – 20 years "mature" (filled triangle), n = 10; 20 + years "weathered" (open triangle), n = 20.

The abundance of the specific taxonomic groups is represented in Figure 3.9 (a, b and c) and 3.10 (a and b) by superimposed circles of different sizes.

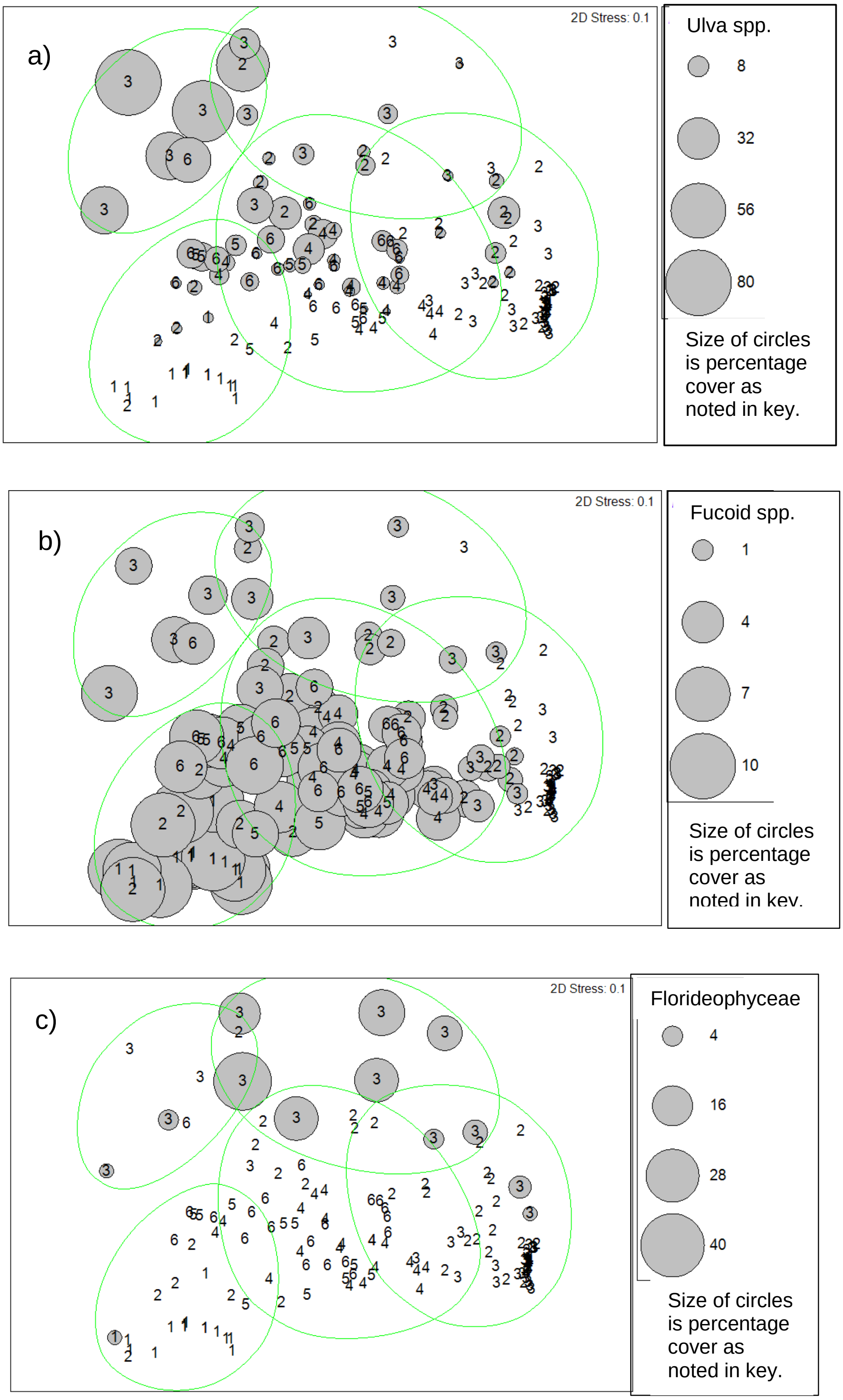


Figure 3.5: MDS ordination for functional taxonomic groups within the meta-data set (Figure 3.8) with superimposed circles of increasing size representing the abundance indicated in the legend of a) Ulva spp cover, b) Fucus spp cover, c) Florideophyceae cover. Numbers 1 through to 6 on the plots correspond to increasing age groups where 1 is < 3 years "recently deployed", n = 15; 2 is 4 – 6 years "early", n = 35; 3 is 7 – 10 years "mid", n = 40; 4 is 11 – 15 years "late", n = 25; 5 is 16 – 20 years "mature", n = 10; and 6 is 20 + years "weathered", n = 20.

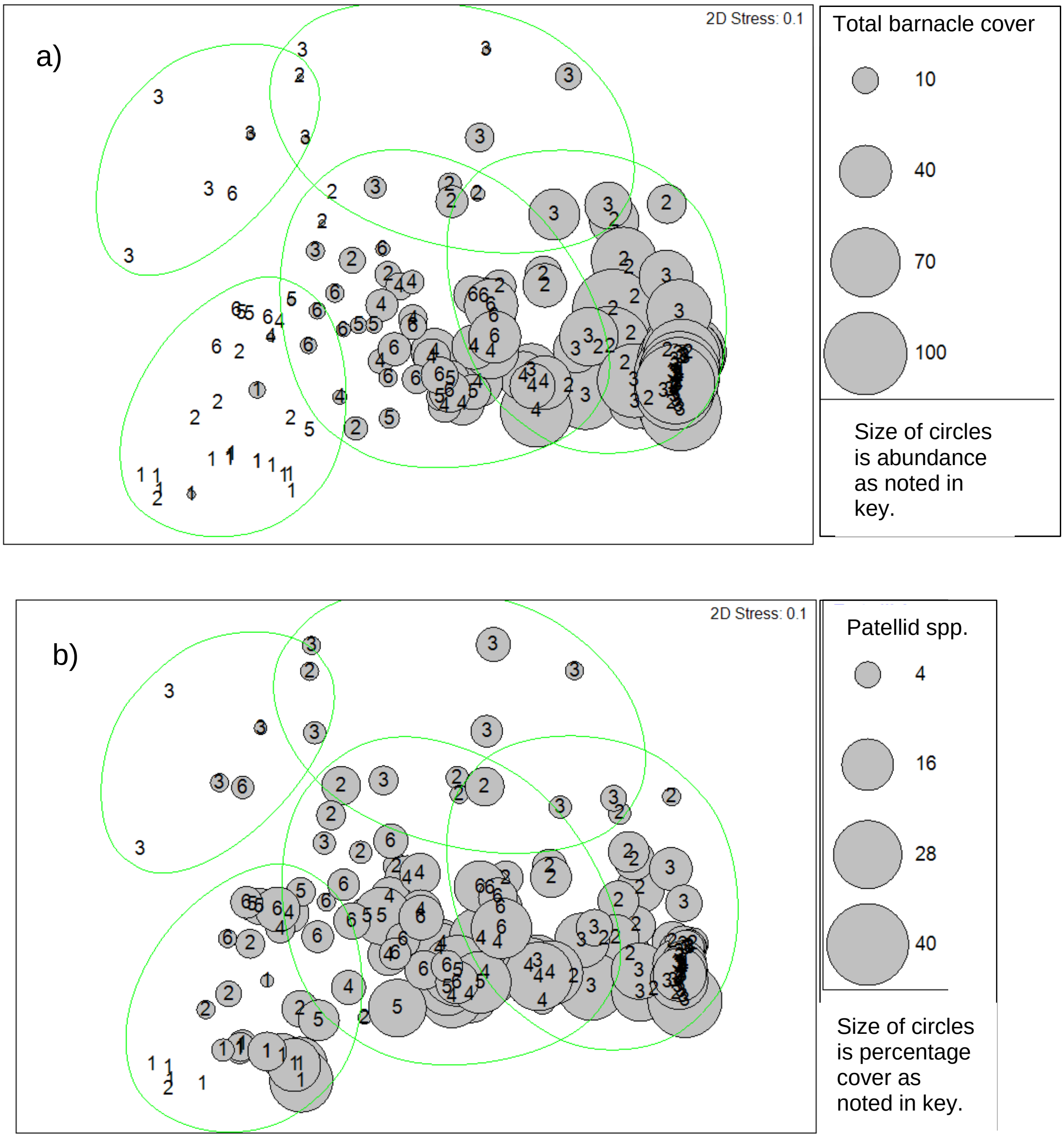


Figure 3.6: MDS ordination for functional taxonomic groups within the meta-data set (Figure 3.8) with superimposed circles of increasing size representing the percentage cover indicated in the legend of a) Total barnacle cover (% cover); and, b) Total patellid spp. (number of individuals). Numbers 1 through to 6 on the plots correspond to increasing age groups where 1 is < 3 years "recently deployed", n = 15; 2 is 4 – 6 years "early", n = 35; 3 is 7 – 10 years "mid", n = 40; 4 is 11 – 15 years "late", n = 25; 5 is 16 – 20 years "mature", n = 10; and 6 is 20 + years "weathered", n = 20.

The results of the SIMPER revealed similarity between assemblage composition on units of different stages of succession. On the newly deployed units an average similarity of 77% exists between contributors. *Fucus* species contributed 71% of this similarity. On the mid-stage units, an average similarity of 74% exists between contributors. Barnacles contributed 47% of this similarity and *Patella* species contributed 33% of this similarity. On older units, 92% similarity exists between contributors with no individual species acting as major drivers of species assemblage.

Assemblages found on the recently deployed units were dissimilar, compared to the early-, mid- and late successional phases (Table 3.5). This reflects the difference between in the assemblage on the curing blocks (primary succession) at the sheltered estuarine Oreston site and following deployment and secondary succession on the exposed breakwater.

Table 3.4: SIMPER comparison of epibiota on units of different phases of succession

Phase / Species	Av.Abundance	Av.Similarity	Contribution %
Recently deployed		86	
Fucus spp.	9	76	89
Patella spp.	2	9	11
Early		55	
Total barnacle cover	5	25	46
Patella spp.	3	18	33
Fucus spp.	2	9	16
Mid		59	
Total barnacle cover	7	36	61
Patella spp.	3	18	30
Late		70	
Total barnacle cover	5	26	37
Patella spp.	4	23	33
Fucus spp.	4	19	26
Mature		75	
Fucus spp.	5	39	52
Patella spp.	4	24	32
Total barnacle cover	2	7	9
Weathered		73	
Fucus spp.	5	33	45
Patella spp.	3	19	25
Total barnacle cover	3	13	18
Ulva spp.	2	9	1

Table 3.5: SIMPER comparison of epibiota on areas of different phases of succession.

Between phase of succession	% Dissimilarity
Recently deployed & Early	64
Recently deployed & Mid	75
Early & Mid	46
Recently deployed & Late	53
Early & Late	40
Mid & Late	42
Recently deployed & Mature	38
Early & Mature	47
Mid & Mature	52
Late & Mature	33
Recently deployed & Weathered	44
Early & Weathered	43
Mid & Weathered	52
Late & Weathered	32
Mature & Weathered	26

*Table 3.6 a) ANOVA for comparisons of the abundance of new recruits of Patella spp. (≤ 5 mm) and mature Patella (> 5 mm). on units of increasing age. (n = 5) for new recruits and mature patellids on units of 11 different ages. Significant P values in bold font. Student-Newman-Kuels Comparisons displayed on Figure 3.7, where * signifies P < 0.05*

a)	MS	*F*	*P*
New recruits	10.69	2.71	**0.011**
Mature	59.71	2.06	**0.049**

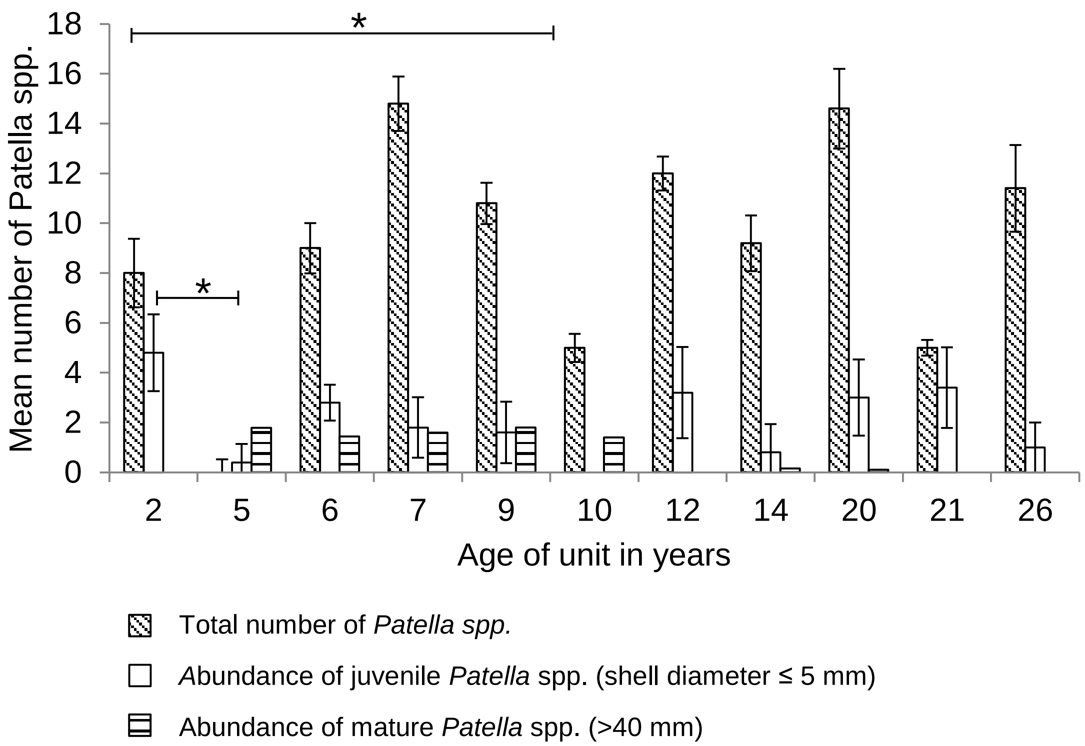


*Figure 3.7: Juvenile limpet structure on armour units of known age on Plymouth Breakwater. * p < 0.05 ($\bar{x}$ ± standard error).*

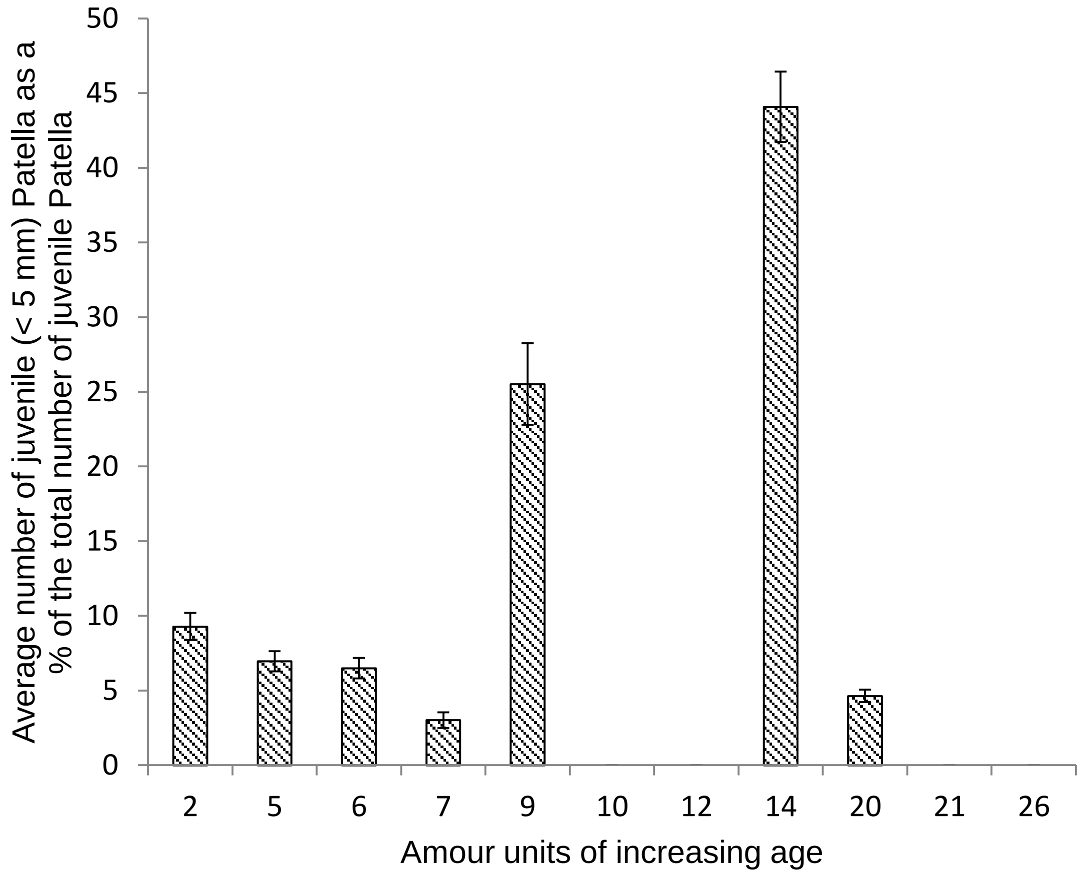


Figure 3.8: Proportion of juvenile limpets in the population

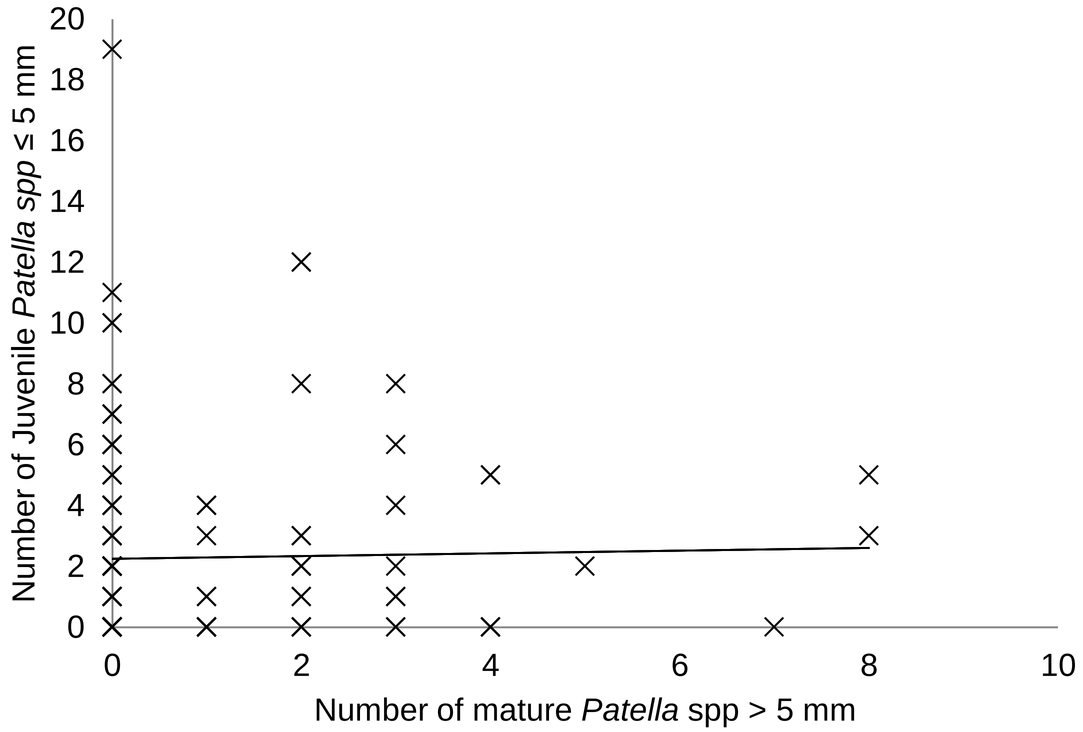


Figure 3.9: Number of juveniles plotted against numbers of adults

3.4. Discussion

3.4.1. Colonisation sequence and processes of succession of intertidal epibiota on artificial structures

To describe the colonisation sequence of the units the main findings are drawn together in a conceptual model of the colonisation on concrete structures deployed on Plymouth Breakwater (Figure 3.8). My results are displayed alongside a model of secondary succession on a similarly exposed natural shore to Plymouth Breakwater. There are several similarities, such as the initial high cover of ephemerals during primary succession, followed by the arrival and dominance of limpets and their subsequent reduction and stabilization of a species assemblage. Therefore, as a consequence of succession, the units on an artificial structure of large extent eventually resemble natural rocky shores of the same exposure.

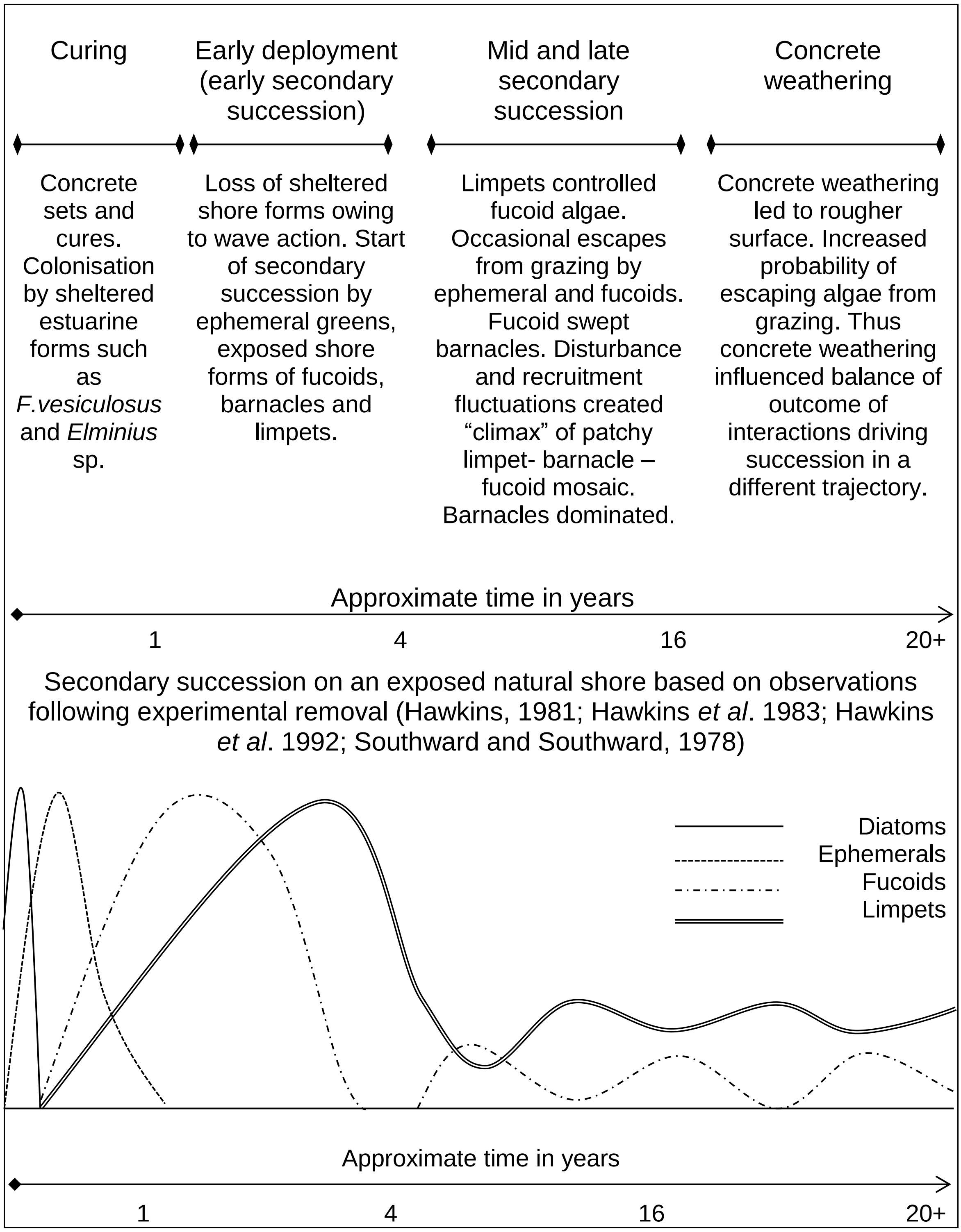


Figure 3.10: Conceptual model of colonisation of concrete structures deployed on Plymouth Breakwater.

Studies carried out by Hawkins *et al.,* (1983) on the breakwater units indicated that species successional processes occur over a longer duration than had been previously accounted for in many studies of succession. This chapter supports and builds on these findings by filling in the gap between 8 and 20 years in the blocks that were not available to Hawkins *et al.* in the 1980s. Detailed observations of species abundance provided extensive data for the units currently at this site; thus aiding the design considerations for the experimental unit modifications (see chapter 4 of this thesis). My data also enabled the influence of weathering of concrete to be considered through comparisons between assemblages on different phases of succession. The assemblages identified on recently deployed and weathered units were similar; owing to the eroded and breaking of the concrete creating patchwork of disturbance where early opportunistic successional species can flourish. The roughest surface also favours fucoids.

At any given time, patches within an area can be at different successional stages, which will reach a state of equilibrium at different times. Succession is potentially a continual process occurring on different time-scales. The timing of placement will influence on the course of succession. It is known that the units were placed from April through to September. Variations in the different times of placement will affect the subsequent settlement of species. This in turn can influence the sequence of succession owing to differential effects of inhibition; e.g. green algae which are common in spring inhibiting fucoids; late summer enabling direct recruitment of fucoids (Hawkins, 1981). An equilibrium with the four dominant taxa present in mosaics seemed to be reached on older units (Figure 3.10).

It is widely accepted that it is difficult to tease out the direct and indirect interactions between species (Raffaelli and Hawkins, 1996). Without detailed experimental investigations (e.g. for Fucus – barnacle – limpet interactions, Hawkins 1981, 1983; Hawkins and Hartnoll 1983a, b, Jenkins *et al*. 2005; Jonsson *et al*. 2006), grazing and wave disturbance are likely to be important processes re-setting succession on the units. Grazing seems to be breaking the inhibition by ephemeral green algae, thus increasing the rate of species replacement and allowing *Fucus* spp., red algae and barnacles to settle. Fucoids in turn reduce barnacle cover as a consequence of sweeping effects (Hawkins, 1983; Jenkins *et al.* 2005)

On units that were previously colonised in the sheltered location of the Plym, the bladdered sheltered shore form of *Fucus vesiculosus* had established. The rapid reduction in *Fucus* spp in high wave exposure (Figure 3.3) can be explained by the relocation of the unit into a less favourable environment for that ecomorph. The sheltered shore form of *Fucus vesiculosus* were less strongly anchored and were rapidly lost. Subsequent colonisation was by the smaller unbladdered more strongly attached exposed shore form of *Fucus vesiculosus evisiculosus*. Early successional species were probably influenced by species that had established on the units prior to mobilisation to the breakwater. The cover of *Fucus* spp. (predominantly *Fucus vesiculosus*) were less on units that were at early to mid-successional phases; when total barnacle (predominantly *Chthamalus* spp. and *Semibalanus balanoides)* cover were at its highest and limpet numbers and grazing most important (Figure 3.9). Barnacle cover appeared early in the successional sequence. The cover of Fucoid spp. were greater on the recently deployed successional phase (2 years old) units, owing to the establishment of the bladdered form of *Fucus vesiculosus* at the sheltered site where the units were cast and cured. After an initial drop in *Fucus* cover, moderately high cover were recorded on units of, 6, 14 years and units greater than 14 years as the exposed shore form colonised; when the total barnacle cover were less. Patchy barnacle cover enhances limpet numbers (Hawkins and Hartnoll, 1982).

In an earlier study of early stage succession on the concrete armour units on Plymouth Breakwater Hawkins (1983) found that after one year *Ulva* spp. were replaced by *Fucus*, which were subsequently replaced by barnacle spp. one to two years later. On the top of the units the biomass of *P. vulgata* increased over 5 years; although from 4-5 years the numbers declined while the biomass still increased. This reflects inter- size class competition (Boaventura et al., 2003).

In this study, *Ulva* spp. were abundant in the early- to mid- phase of succession, as were total barnacle cover (Figure 3.5); both were found, however, on different units within the same age range indicating that stochastic factors also determine succession, for example as a consequence of variations in propagules supply which can lead to seasonal differences in secondary succession (e.g. Hawkins, 1981; Jenkins *et al.* 2005).

The greatest diversity was found between the mid- to late- phases of succession, 7 – 14 years after placement. At this stage *Fucus* – barnacle – limpet mosaics occur, this is typical of moderately exposed shores and maximises diversity, especially by habitat provision for other species (Thompson *et al*. 1996). Thus, without modification, considerable time was required for a community to reach a dynamic equilibrium on artificial structures, and for the associated high diversity to be achieved.

Up to 12 – 15 years the processes of succession on concrete blocks strongly mirrored what has been shown to happen on natural rocky shores. In the next section the consequence of concrete weathering are considered.

3.4.2. Weathering processes and wave exposure on artificial structures

The physical condition of the units generally deteriorated with age. With this deterioration complexity increases. It was likely that the increase in surface features on the older units provided an increase in microhabitats, which support a more diverse array of species and provide opportunities for algae to escape from limpet grazing (Johnson *et al*. 1996, 1998 a and b, and 2003). The extent and time taken for deterioration of the unit to occur was influenced by the mechanical destructive effect of waves. There remains the possibility that the loss of fucoid plants owing to wave action plucks concrete from the surface. *Fucus* algae are known to pluck barnacles and limpets from the surface (Hartnoll and Hawins, 1985; Hawkins and Hartnoll, 1983b). However the extent of this biologically induced damage to the concrete remains to be tested.

Concluding comments

Accurate prediction of the influence of artificial substrates on marine epibiota is an important step in the design of any built structure in the coastal environment. This chapter contributes to understanding the patterns and processes involved in succession. The spatially isolated and therefore independent armour units, with an accurate record of age since deployment, provide ideal systems to describe sequences of colonisation.

As a consequence of succession, artificial structures of large extent eventually resemble natural rocky shores of the same exposure. Successional processes occur over a longer duration than previously described. Accurate description and prediction and description of duration of successional processes are needed to further inform our understanding of timescales over which interventions to enhance diversity can operate. Divergence of successional sequences occurs between concrete structures and natural rocky shores once weathering occurs.

Chapter 4
Experimental modification of existing coastal defence structures to influence biodiversity

4.1. Introduction

Coastal areas are of considerable economic and environmental importance. They provide important ecosystem services including flood control, storm protection, sedimentation, landscape and aesthetics. However, coastal areas are vulnerable to the impact of storm waves, which can cause considerable damage, particularly when the effects are felt in combination with extreme tides and rising sea levels. To protect the shore from damage, including flooding and erosion, it is often necessary to reduce the force with which waves approach the shore by intercepting them or by strengthening the portion of the shore where waves impact. In these cases hard structures such as breakwaters or seawalls are often placed in high-energy environments.

A large proportion of the coastline has been protected with hard defences for decades or centuries (See Airoldi *et al.,* 2005; Charlier *et al.,* 2005 for reviews), and continues to advance as development at the coast expands. For example, hard defences protect more than 50 % of the Italian coastline on the Adriatic Sea (Airoldi, *et al.* 2005), 50 % of Sydney Harbour in Australia is protected by seawalls (Chapman and Underwood, 2011) and 45 % of the coastline of England is protected by either defence structures or artificial beaches (Masselink and Russell, 2010). The construction of artificial structures is detrimental to the environment and can truncate naturally limited areas of habitat (Martin *et al.* 2005). When and where protection of this type is deemed necessary, the design can be sensitive to the natural environment in which they are placed (Burcharth *et al*. 2007).

As detailed in Chapter two of this thesis, biodiversity on breakwaters is regulated by their physical environment and biological interactions between species (Airoldi *et al*., 2005). Breakwaters can be considered as simplified analogues of natural rocky shores (Thompson *et al*. 2002). However, breakwaters are generally seen as being of low habitat value, predominantly because they are topographically less complex than natural rocky shores (Firth *et al.* 2011). Habitat provision is often limited at a variety of spatial scales (Firth *et al.* 2011). On natural rocky shores, a varied, heterogeneous surface with features such as pits, holes, crevices and pools provided important shelter from biological and physical pressures, which assisted colonisation and promoted biodiversity. The importance of rock pools as a habitat and refuge is well documented for rocky shores.

Chapter two of my thesis examined the influence of a variety of features on existing coastal defence structures. Increased habitat diversity at a variety of scales on artificial habitats increased the resemblance to natural rocky shores, thereby increasing diversity and potential value for conservation, amenity and recreation. Even a relatively uniform structure has features that create potential habitat and shelter, for example buttresses and pools as described in Chapter 2. Given the current existence, and future need for coastal defences, chapter 4 examines the opportunity within existing structures and maintenance regimes to increase habitat provision, thereby, influencing colonisation processes and ultimately biodiversity.

As part of the on-going maintenance of Plymouth Breakwater, concrete cast wavebreaker armour units (Figure 4.1) are produced and deployed annually on the seaward side of the main structure (See section 2.2.1 for description and Hawkins *et al.* 1983 for early use of these units in ecological studies). The modifications of these units were the focus of this chapter. The armour units are truncated pyramids, 320 cm x 685 cm at the base, 243 cm x 510 at the top, and 235 cm high. The maintenance aim is for twelve to fifteen units to be cast each year between the months of April and October. Here I examined the influence of experimental modification of existing coastal defence structures to species abundance and biodiversity by experimental modification of the concrete armour units used to strengthen Plymouth Breakwater.

The reduced environmental heterogeneity of artificial environments is assumed to be one factor explaining the lower epibiotic diversity on artificial structures (Moschella *et al*., 2005; Firth *et al*. 2013). Crevices, pits and rock pools are known to provide important shelter from environmental stresses and refuge from competition and predation pressures. Experimental studies have been performed where holes were drilled to increase surface heterogeneity either for the intention of enhanced species diversity (Witt *et al*., 2012), or to purposefully increase the commercially exploited limpet *Patella candei* in the Azores (Martins *et al*. 2010). From these studies it was clear that more than one hole size would provide the best insight to the influence of pits on species biodiversity, and that creating the biggest hole size possible on site (i.e. with a handheld electric drill) would complement experiments performed by others and on the seawall at Shaldon (Chapter 5). The hole sizes selected for this study were therefore the largest hole size practical, and approximately mid-way between the control (no holes) and the largest holes. It is evident from Chapter 2 that orientation was an influence, and it was known that there would be no control as to where the units would be positioned on site by the barge, and whether they would be accessible for survey and monitoring. Thus opposing sides of the unit were manipulated to enable the influence of orientation to be studied and to give the best possible chance of accessing the experimental areas for survey and monitoring. The creation of rock pools and overhangs were also trialled through manipulation of the wet concrete.

The overall aim was to investigate the influence of various design features on the diversity and abundance of marine epibiota through experimental modifications during the maintenance of an existing coastal defence structure to test the following specific hypothesis:

1) Surface complexity created through the addition of holes to the armour units will increase diversity and abundance of intertidal marine epibiota.
2) The diversity and abundance of intertidal marine epibiota will differ between the two hole sizes used to create surface complexity.
3) The diversity will be greater in holes compared to the area surrounding the holes. The diversity will be greater surrounding the holes compared to the control area without holes.
4) The orientation to the sun of the modified surface will influence diversity and abundance of intertidal marine epibiota.
5) Habitat modifications will enhance *Patella* recruitment, thereby reducing algal cover, breaking any inhibition by green algae, thereby speeding up succession and minimising the green algal and fucoid cover stage.

Pools were added to structures. Unfortunately it was not possible to relocate the blocks with pools as they were positioned subtidally.

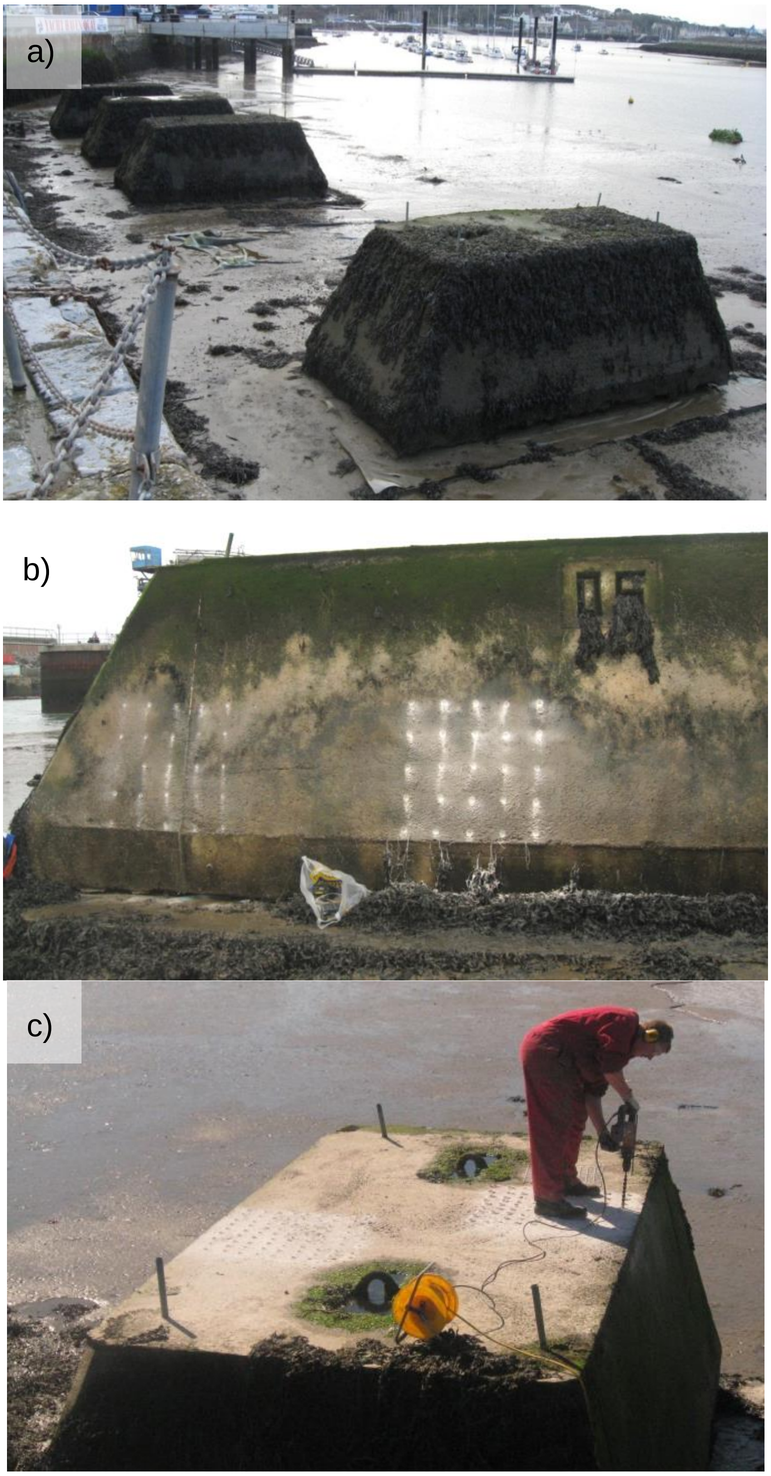


Figure 4.1: a) Armour units cast at Laira, b) Surface complexity created by the drilling of holes within treatment areas on the side of armour units; and, c) Manipulation to the top of an armour unit, note the position of the lifting rings.

4.2. Method

The units were cast on the foreshore in a sheltered dockyard at the mouth of the River Plym. To cast the units, 100 tonnes of concrete were poured into a mould, which were removed after three to five days (Figure 3.2). The armour units were left on the foreshore until they were fully cured and weather conditions were right to transport them. In general, six armour units were on the shore at Oreston at any given time and, as two armour units were deployed, two new armour units were cast in their place.

Experimental modifications of the surface design of the wavebreaker armour units were carried out to add surface complexity. When freshly poured, concrete was easily malleable, which enabled the surface modification for designed features to be incorporated. Thus, heterogeneous habitats were created analogous to features of rocky shores such as cracks, crevices and pools. This method allowed testing of the influence of design on aspects of community development such as species abundance and diversity. It also allowed comparison between the influence of surface heterogeneity on natural rocky shore habitat and influence of design features on artificial structures.

Ten armour units were experimentally modified at the time of casting. Surface complexities were added to the two longer sides of each of the armour units by drilling holes. On each side of the armour units, three experimental areas with different surfaces (hereafter treatments) were modified at a height of 50 cm above the base of the armour unit. Three experimental treatments were included on each of the two longer sides of the ten armour units. Two of the experimental treatments had ten rows of ten equally spaced drilled holes, with 10 cm between them, 14 mm in diameter on one experimental area and 22 mm diameter on the second. The third experimental area was a control with no holes (Figure 4.2). The sequence of treatment areas were randomised between units. Holes were drilled to approximately the same depth (20 – 25 mm), with a slight angle towards the base to retain moisture.

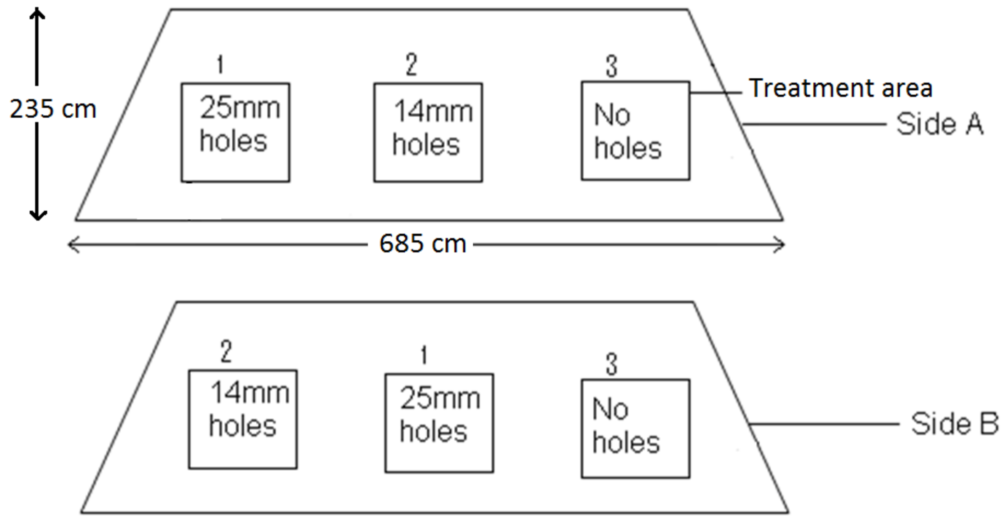


Figure 4.2: The configuration of experimental treatment areas on each side of 10 replicate armour units (not to scale)

The top of one of the armour units was also modified to observe effect on epibiota. One treatment area was drilled with irregularly spaced holes and one treatment area with alternate small and large holes. A treatment area was also drilled at the end of the unit, which had a slope of increased angle; this treatment area was drilled with a higher density of holes (i.e. 6 cm apart).

As both sides of the block were modified, two surfaces with opposing orientations to the sun were created and compared.

The influence of habitat modification on succession can be predicted as a sequence of events starting with the enhancement of Patella recruitment.

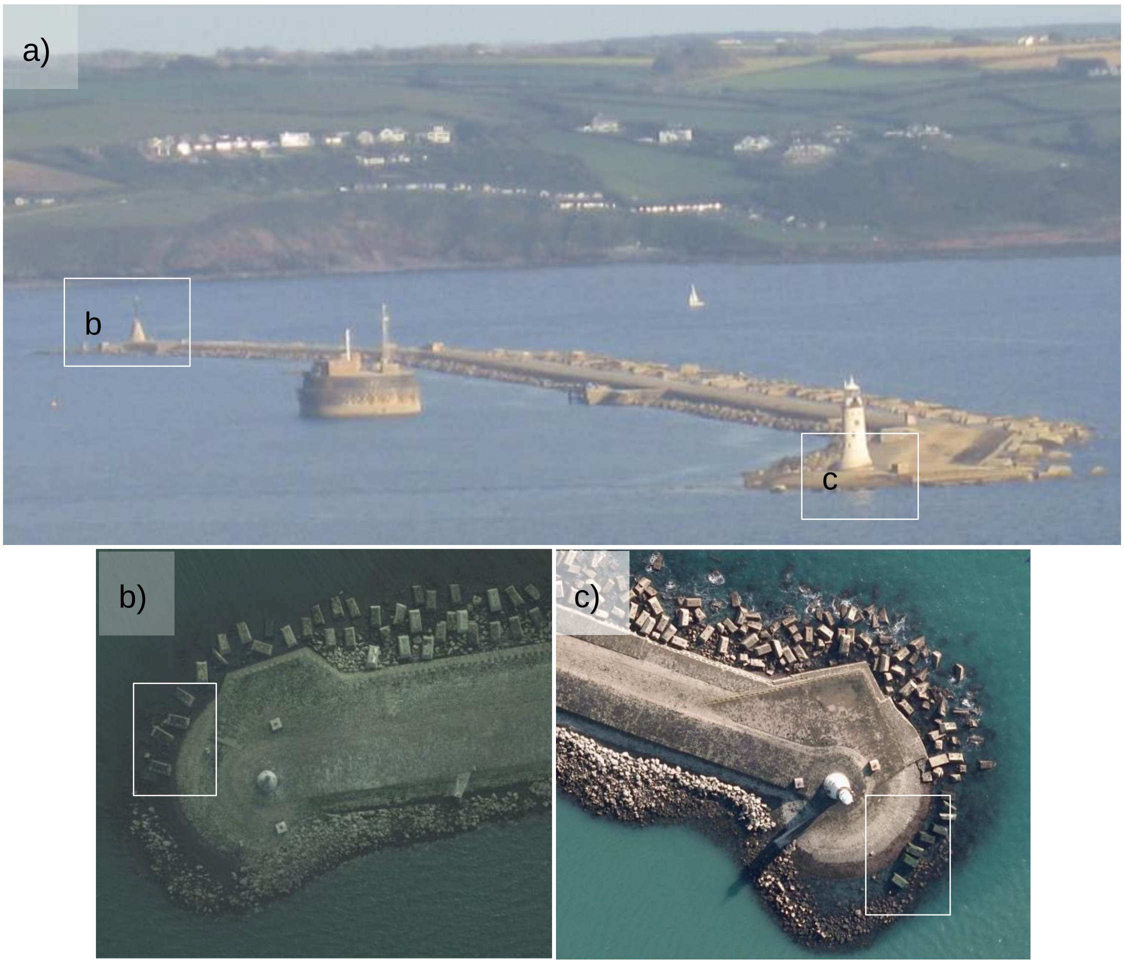


Figure 4.3: a) View of Plymouth Breakwater with the survey areas at the Bovisand (eastern) and Cawsand (western) ends labelled b and c, respectively; b) aerial image of the Bovisand end of the breakwater, with the modified armour units highlighted, and c) aerial image of the Cawsand end of the breakwater, with the modified armour units highlighted. Aerial images provided by Plymouth Coastal Observatory.

The elevations of the armour units were measured with a RTK-GPS system. Two of the armour units were inappropriately positioned owing to the angle of the armour unit and were discarded from the experiment. Of the remaining modified armour units eight of the units with holes were located and subsequently monitored.

Data were collected at low tide when the armour units could be accessed by wading in the water from the main structure. Several species surveys were carried out over the duration of this research between autumn 2011 and Spring 2013, depending on the accessibility at the site of deployment. Data were collected within five months (Cawsand end) and three months (Bovisand end) of the units being placed in situ; and after approximately fifteen months of the units being in situ; an additional sampling occasion was achieved at the east end of the breakwater approximately thirty months after deployment. On each sampling occasion data were collected from as many units and treatments as made possible by the state of tide and weather conditions. Return trips to complete the data collection from all accessible blocks and treatments were made within two weeks to minimise external influences other than treatment, such as season. Access to the Breakwater was very weather dependant, with strict regulations from the Military of Defence (MOD) on the type of weather conditions when landing were permitted, thus reducing opportunities for sampling.

In total eight treatment areas of 14 mm holes and eight treatment areas of 22 mm holes were drilled. Within each area of drilled holes four replicate treatment patches of 50 x 50 cm were identified. Within one treatment patch the surface area created by the walls of holes were increased by 14 – 17 % (for depths of hole between 20 and 25 mm) for 22 mm holes, and 8 – 11% for 14 mm holes, compared to the control surface with no holes.

Species abundances were recorded within holes and within treatment patches, thus including species in holes and in the areas between holes. Species abundances were estimated as the percentage cover of macroalgae and percentage cover of sessile fauna. The numbers of mobile species within the quadrat were recorded as individual counts. Where mobile species were low in numbers the percentage cover and individual count data were included in the same analysis. Identification to species level was achieved for the majority of species. The World Register for Marine species (WoRMs, 2014) has been used as a reference for up to date taxonomy, and the species name is shown with the discoverer name and date in the list of species. For some species, cover were recorded as taxa and the approximate relative proportions of each species were recorded, thus recording cover at a high level of accuracy without sacrificing individuals, thus reducing the impact of the survey. The term “sp(p).” denotes organisms of either one or several unidentified species, and groups of organisms were referred to as “taxa”. The number and size range of individual *Patella* were recorded within four randomly placed 50 x 50 cm quadrats within each treatment. Analysis has been performed at the species level, although for uncluttered presentation some results are displayed at a higher taxonomic rank.

Analysis of Variance (ANOVA) was performed using the statistical package GMAV (Underwood and Chapman 1998). Three designs were used to test the hypothesis of surface complexity and hole size on the influence on the diversity and abudance of marine epibota. The first two analyses were performed on data collected at both sites (east and west end of the breakwater), and collected within similar time frame since unit establishent. The third analysis was a replicate design of the second analysis but performed on data from one site (east) collected approximately thirty months since unit deployment.

The first analysis were performed on data collected from surveys performed at two different ends of the Breakwater, thus site was the first factor, where east and west ends of the Breakwater were surveyed (two levels, random). The north and south orientations of the armour units were the second factor assessed. The third factor was treatment, for treatment the influence of holes and no holes (two levels, fixed) were assesed.

The hypothesis that hole size used to create surface complexity will influence the diversity and abundance of marine epibiota was tested. As with the previous analysis, the first factor was site (east and west), and the second factor orientation (north and south). The third factor was treatment, with three levels representing hole sizes 22 mm, 14 mm and 0 mm (three levels, fixed).

The third analysis were performed on data collected from one survey performed at the east end of the breakwater approximately 30 months after deployment. Orientation was the first factor assessed, this had the two levels north and south facing sides of the armour units surveyed. The second factor was treatment, with three levels representing hole sizes; 22 mm, 14 mm and 0 mm (three levels, fixed).

ANOVA was used for the abundance and species richness. Separate analysis were performed for each taxonomic 'class' of high abundance. Prior to further analysis, a Cochran's C test assessed the homogeneity of variance to determine whether the data needed transforming.

Multivariate analysis were performed using the PRIMER 6 computer program (Plymouth Marine Laboratory, UK) on species community structure. Data were square root transformed and Bray-Curtis measures were used.

Treatment, orientation and location were the factors examined. The one-way ANOSIM permutation test were used to assess the significant differences between species community structure of factors described above. The Similarities Percentage procedure (SIMPER) (Clarke, 1993) were performed on total species cover to identify discriminating features of species abundance within assemblages, as described in section 2.2.2.

4.3. Results

4.3.1. Increased surface heterogeneity by the addition of holes

The elevations measured at the 12 treatment sites were within a 40 cm range relative to chart datum.

A total of 45 species across 14 taxonomic classes were recorded in this study: all except one (*Fucus vesiculosus)* were found within holes, with the highest diversity attributed to the classes Florideophyceae (8 species), Phaeophyceae (6 species) and Gastropoda (6 species). Species of anthozoa, polychaetes, bivalves, hydrozoa and ascidia were unique to the treatments with holes (Table 4.1). The species authority for each recorded species is given in table 4.1.

Two species from the class Maxillopoda were recorded in holes and surrounding the holes (Figure 4.4). These were predominantly the barnacle *Semibalanus balanoides*, which were also present in all controls in large numbers (Figure 4.4). For ease of analysis barnacle species were grouped together as total barnacle cover. The limpet *Patella ulyssiponensis* was found in most of the sample areas surrounding the holes and on most control areas with no holes. In holes more species from the classes Ascidiacea, Gastropoda, Bivalvia and Polychaeta were found than the control (Table 4.1).

Table 4.1: List of species identified on Plymouth breakwater within treatments with holes of 22 mm (n = 52), 14 mm (n = 46) and without holes (0 mm, n = 52); on the east (E) (n = 80) and west (W) (n = 70) ends of the breakwater; on the northerly (N) (n = 78) and southerly (S) (n = 64) facing surfaces of the units. Species authorities for all species referred to in this chapter are given here.

Class	Species/ taxa	Hole size			Orientation			
		22	14	0	N	S	E	W
Ulvophyceae	*Ulva* Spp.	X	X	X	X	X	X	X
Phaeophyceae	*Fucus serratus* (Linnaeus, 1753)	X	X	X	X	X	X	X
	Fucus spiralis (Linnaeus, 1753)	X	X	X	X	X	X	
	Fucus vesiculosus (Linnaeus, 1753)			X		X		X
	Himanthalia elongata (Linnaeus, 1753)	X		X	X		X	X
	Laminaria digitata (Hudson, 1762)	X	X	X	X	X	X	X
	Ralfsia verrucosa (Areschoug, 1845)	X	X		X		X	
Florideophyceae	*Chondrus crispus* (Stackhouse, 1797)	X	X		X		X	
	Corallina officinalis (Linnaeus, 1758)	X	X	X	X	X	X	X
	Dilsea carnosa (Schmidel, 1794)	X	X	X	X		X	X
	Lithophyllum sp.	X	X	X	X	X	X	X
	Lomentaria articulata (Hudson, 1762)	X	X	X	X	X	X	X
	Palmaria palmate (Stackhouse, 1802)	X		X	X		X	X
	Osmundea pinnatifida (Stackhouse 1802)		X			X	X	
	Florideophyceae 1	X	X	X	X	X		X
Bangiophyceae	*Porphyra umbilicalis* (Kützing, 1843)	X	X	X	X		X	X
Anthozoa	*Actinia equina* (Linnaeus, 1758)	X	X		X	X	X	X
	Corynactis viridis (Allman, 1846)	X					X	X
Maxillopoda	*Semibalanus balanoides* (Linnaeus, 1767)	X	X	X	X	X	X	X
	Austrominius modestus (Darwin, 1854)	X	X	X	X	X	X	X
	Perforatus perforatus (Bruguière, 1789)	X	X	X	X	X		X
	Balanus crenatus (Bruguière, 1789)	X	X	X	X	X	X	X
Gastropoda	*Gibbula umbilicalis* (da Costa, 1778)		X		X			X
	Patella pellucida (Linnaeus, 1758)		X	X	X	X		X
	Nassarius reticulatus (Linnaeus, 1758)		X		X			X
	Littorina littorea (Linnaeus, 1758)	X	X		X	X	X	
	Littorina obtusata (Linnaeus, 1758)	X	X		X	X	X	
	Patella ulyssiponensis (Gmelin, 1791)	X	X	X	X	X	X	X
Polychaeta	Green worm	X	X		X	X	X	X
	Spirobranchus sp.	X	X		X	X	X	X
	Filograna Sp.		X		X		X	X
	Spirorbis spirorbis (Linnaeus, 1758)	X			X	X		
Bivalvia	*Mytilus edulis* (Linnaeus, 1758)	X	X		X	X	X	X
	Ostrea edulis (Linnaeus, 1758)	X	X		X	X		X
Gymnolaemata	*Electra pilosa* (Linnaeus, 1767)	X	X	X	X	X		X
	Membranipora membranacea (Linnaeus, 1767)	X			X		X	
	Brozoan 1	X	X		X	X		
Demospongiae	Demosponge	X	X		X	X	X	
	Crambe crambe (Schmidt, 1862)	X	X	X	X	X	X	X
Hydrozoa	*Dynamena pumila* (Linnaeus, 1758)	X	X		X	X		
Ascidiacea	*Botryllus schlosseri* (Pallas, 1766)	X			X		X	X
	3 unconfirmed species of Ascidiacea							
Total		38	35	21	41	29	29	35

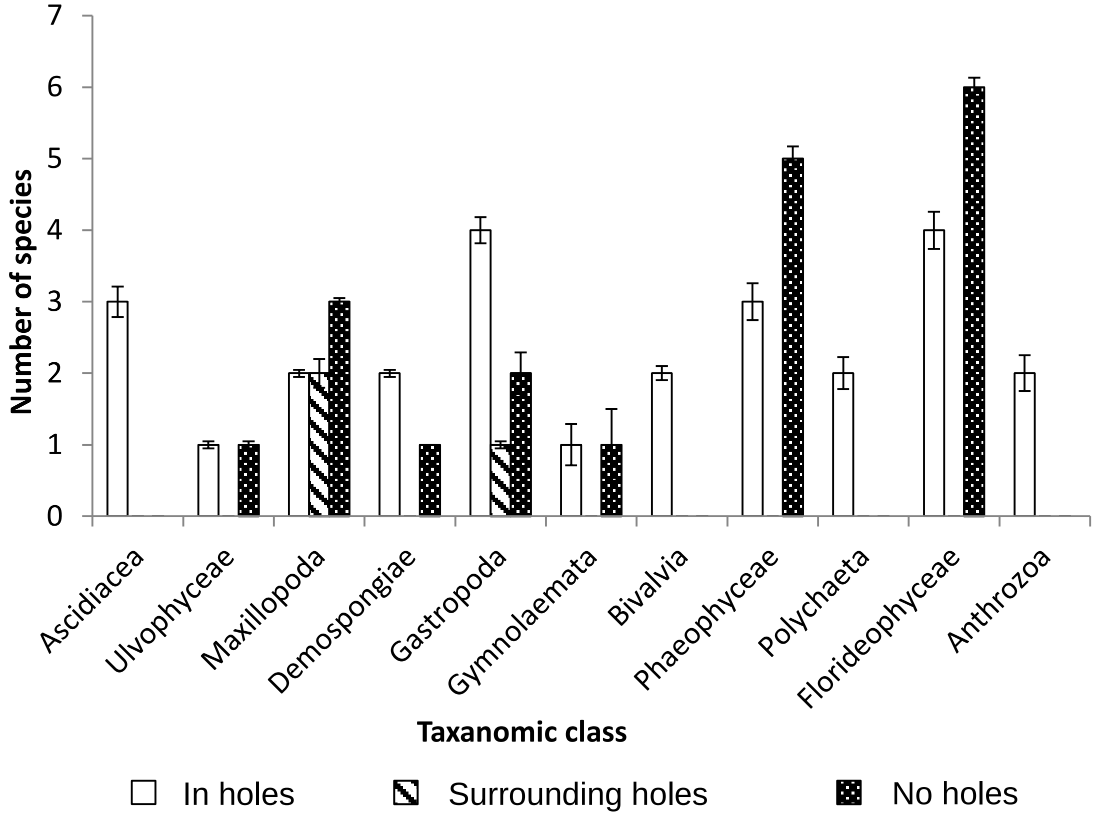


Figure 4.4 Species richness per taxonomic 'class' of assemblages surveyed on treatment areas in holes (n = 44) and surrounding the holes (n = 44), and on treatment areas with no holes (n = 44). $\overline{x}$ ± *standard error.*

Ordination by MDS and cluster analysis revealed that the species assemblage in areas with holes were similar to the assemblages in areas without holes, with a high level of overlap in samples (Figures 4.5 and 4.6).

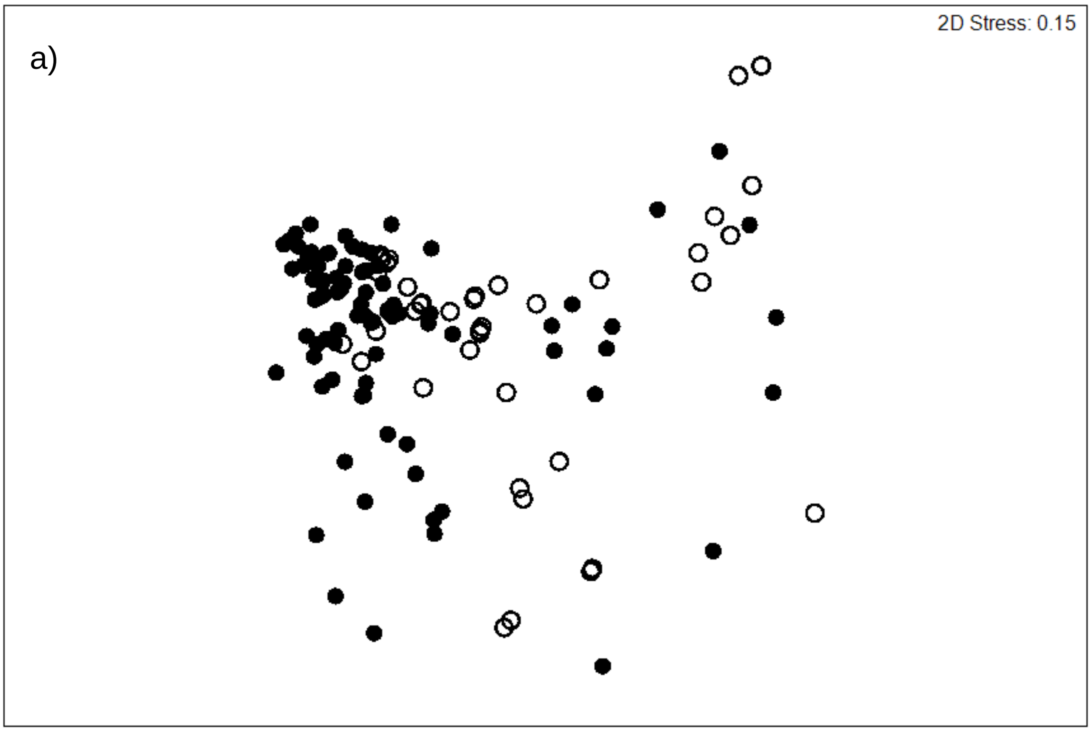


Figure 4.5: Plymouth Breakwater epibiota. MDS ordination of Bray-Curtis similarities of species abundance (√transformed) recorded in areas with holes (shaded circle, n = 44) and without holes (open circle, n = 86).

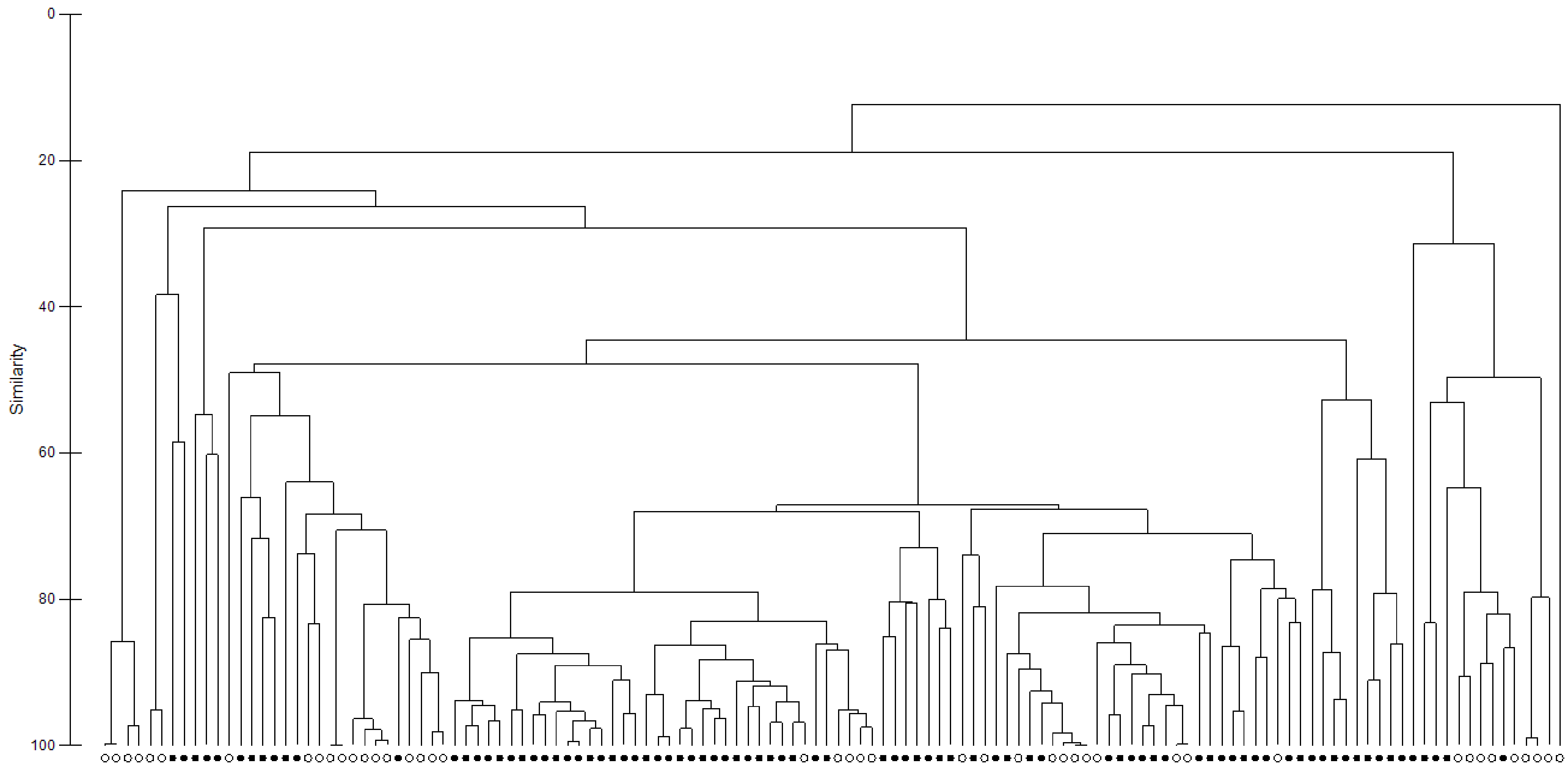


Figure 4.6: Plymouth Breakwater epibiota. Cluster analysis of Bray-Curtis similarities of species abundance (√transformed) recorded in areas with holes (shaded circle, n = 44) and without holes (open circle, n = 86).

Of the 16 species that contributed to the dissimilarity between areas with holes and without holes, eight species contributed more than 3% and cumulatively accounted for > 75% of dissimilarities (Table 4.3). Barnacle spp. and Patellid spp. were the most abundant of all species found in areas with holes and without holes. In total, four species contributed to the similarity with holes (Table 4.3), whereas two species contributed to the similarity in areas without holes.

4.3.2. Increased surface heterogeneity by the addition of holes of different size

An equal sample size of n = 44 were randomly selected for analysis for each factor compared; areas without holes, areas with holes of 14 mm diameter and areas with holes of 22 mm diameter.

Within areas with holes of 22 mm in diameter, thirty-eight of the fourty-five species found at the site. Within areas with holes of 14 mm in diameter thirty-five of the fourty-five species found at the site were present. Areas with no holes contained thirteen of the fourty-five species. Of the species present in both sizes of holes, two were algae (*Ralfsia verrucosa* and *Chondrus crispus*); eight were sessile organisms (*Actinia equina, Ostrea edulis, Mytilis edulis, Dynamena pumila* and four encrusting species difficult to identify to species level; of polychaete, bryozoan, demosponge and ascidian); and, three were mobile species (*Littorina littorea, Littorina obtusata*, and a polycheate) (Table 4.1).

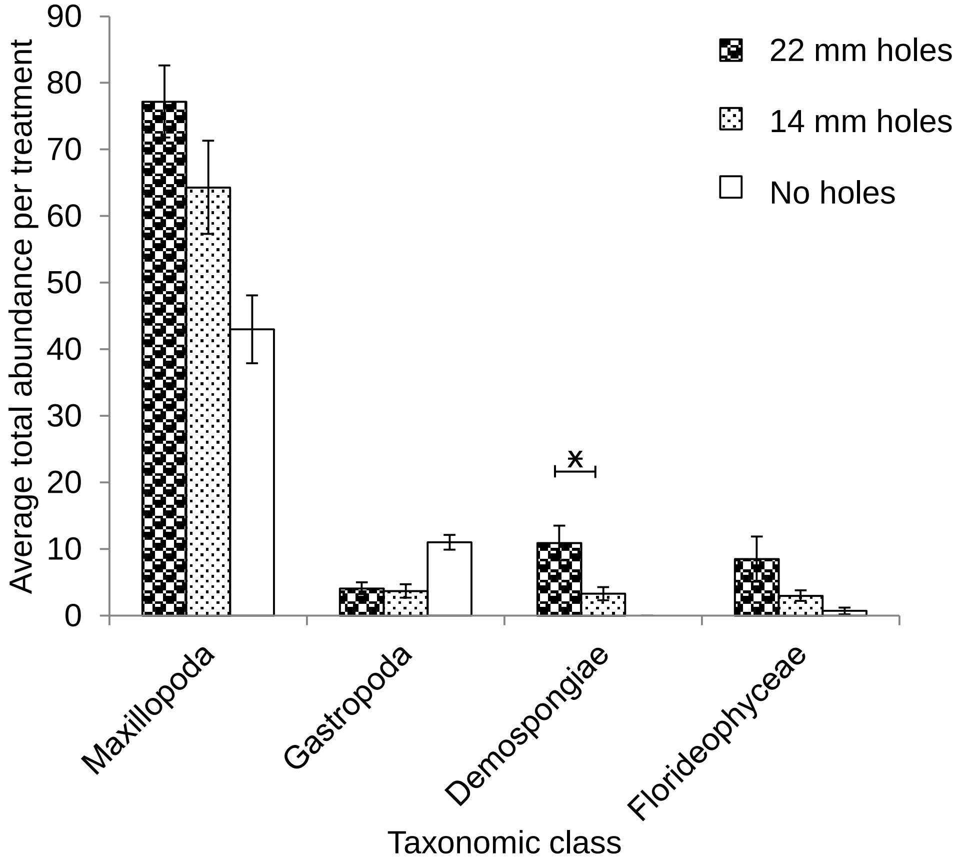


Figure 4.7: Average total abundance (% cover of sessile species, number of individuals per 0.25 of a square meter of mobile species) of the four most abundant taxonomic classes in assemblages observed within treatment areas on Plymouth Breakwater sites. ($\bar{x}$ ± standard error, n = 32 for each of the treatments; 22 mm holes, 14 mm holes and no holes).

Only the significant effects involving the treatments shown with the ANOVA were looked at with the post-hoc SNK tests. Significant differences in the number of species found between treatment areas with holes of different sizes were found ($F_{2,84}$ = 70.33, p <0.05, Table 4.2a), but the interaction between treatments was different according to the orientation of the blocks ($F_{2,84}$ = 34.33, p <0.05, Table 4.2a, as described in section 4.3.3). Typically, more species were found in treatment areas with holes than the control area with no holes.

At the Cawsand end of the breakwater significant differences in the abundance of gastropoda were found between treatment areas with holes of different sizes

($F_{2,84}$ = 15.55, p <0.001, Table 4.2a). At the Bovisand end of the breakwater significant differences in the abundance of florideophyceae were found between treatment areas with holes of different sizes. Demospongiae was absent from smooth surfaces and from most samples at the Bovisand end, thus the ANOVA design used was two-way with orientation (north and south) and treatment (22 and 14 mm holes).

*4.2a): Three-way ANOVA and SNK results for species richness (√ transformed for heterogeneity, Cochran's C = 0.22, NS) 15 months after deployment to Plymouth Breakwater. Factor site (Si), 2 levels: Cawsand (C) and Bovisand (B) ends of Plymouth Breakwater, random. Factor orientation (Or), 2 levels: north (N) and south (S) facing surfaces, fixed. Factor treatment (Tr) 22 mm (22), 14 mm (14) and no holes (0), 3 levels fixed. n = 8. Significant P values in bold. * p < 0.05 and ** p < 0.01.*

Number of species	*Df*	MS	*F*	*p*	SNK:
Si	1	0.84	2.91	0.091	
Or	1	5.51	2.35	0.368	
Tr	2	2.20	70.33	**0.014**	Tr: 22 > 0 *; 14 > 0 *; 22 14 NS
Si X Or	1	2.34	8.08	**0.006**	
Si X Tr	2	0.03	0.11	0.898	
Or X Tr	2	1.07	34.33	**0.028**	Tr (Or): N, 0 = 14 < 22 Tr (Or): S, 0 < 22 < 14
S X Or X Tr	2	0.03	0.11	0.898	
Res	84	0.29			

*Table 4.2b): Series of three way ANOVA results for Maxillopoda, Gastropoda and Florideophyceae (displayed on Figure 4.7), 15 months after deployment to Plymouth Breakwater. Factor site (Si), 2 levels: Cawsand (C) and Bovisand (B) ends of Plymouth Breakwater, random. Factor orientation (Or), 2 levels: north (N) and south (S) facing surfaces, fixed. Factor treatment (Tr) 22 mm (22), 14 mm (14) and no holes (0), 3 levels fixed. ANOVA results for demospongia with a two way, two factor design: orientation (Or), 2 levels: north (N) and south (S) facing surfaces, fixed. Factor treatment (Tr) 22 mm (22) and 14 mm (14) 2 levels fixed. n = 8. Significant P values in bold. * p < 0.05 and ** p < 0.01. Data were √ or log+1 transformed for heterogeneity, Cochran's C value given in table, homogenous variances still tested with ANOVA.*

	Df	*MS*	*F*	*p*	SNK where *p < 0.07*
Maxillopoda √					
C =0.22, NS					
Si	1	5.04	0.89	0.347	
Or	1	8.17	2.42	0.364	
Tr	2	50.39	14.88	0.063	
Si X Or	1	3.38	0.60	0.441	
Si X Tr	2	3.39	0.60	0.551	
Or X Tr	2	17.09	0.75	0.573	
S X Or X Tr	2	5.64	3.03	0.054	
Res	84				
Gastropoda Log+1					
C = 0.17, NS					
Si	1	3.01	21.29	**0.000**	Si: C > B **
Or	1	0.09	9.00	0.205	
Tr	2	1.01	0.46	0.685	
Si X Or	1	0.01	0.07	0.787	
Si X Tr	2	2.20	15.55	**0.000**	C: 0 > 14 **; 0 > 22 **
Or X Tr	2	0.41	1.56	0.391	
S X Or X Tr	2	0.26	1.84	0.165	
Res	84	0.14			
Florideophyceae					
C = 0.79 P<0.01					
Si	1	704.17	6.46	**0.013**	Si: B > C *
Or	1	1261.5	1.11	0.483	
Tr	2	234.97	0.60	0.624	
Si X Or	1	1134.4	10.41	**0.002**	
Si X Tr	2	390.14	3.58	**0.032**	Tr (Si): B, 22 > 14 **; 14 = 0
Or X Tr	2	454.34	1.97	0.336	22 > 0 *. C, 22 = 14 = 0
S X Or X Tr	2	230.34	2.11	0.127	
Res	84	108.95			
Demospongia √					
C = 0.5, NS					
Or	1	12.63	2.81	0.10	
Tr	1	24.33	5.42	**0.03**	22 > 14 *
Or X Tr	1	0.03	0.01	0.94	
Res	28	4.49			

Ordination by MDS revealed distinct species assemblages were found in each treatment, shown by the dense cluster with each symbol present (Figure 4.8a).

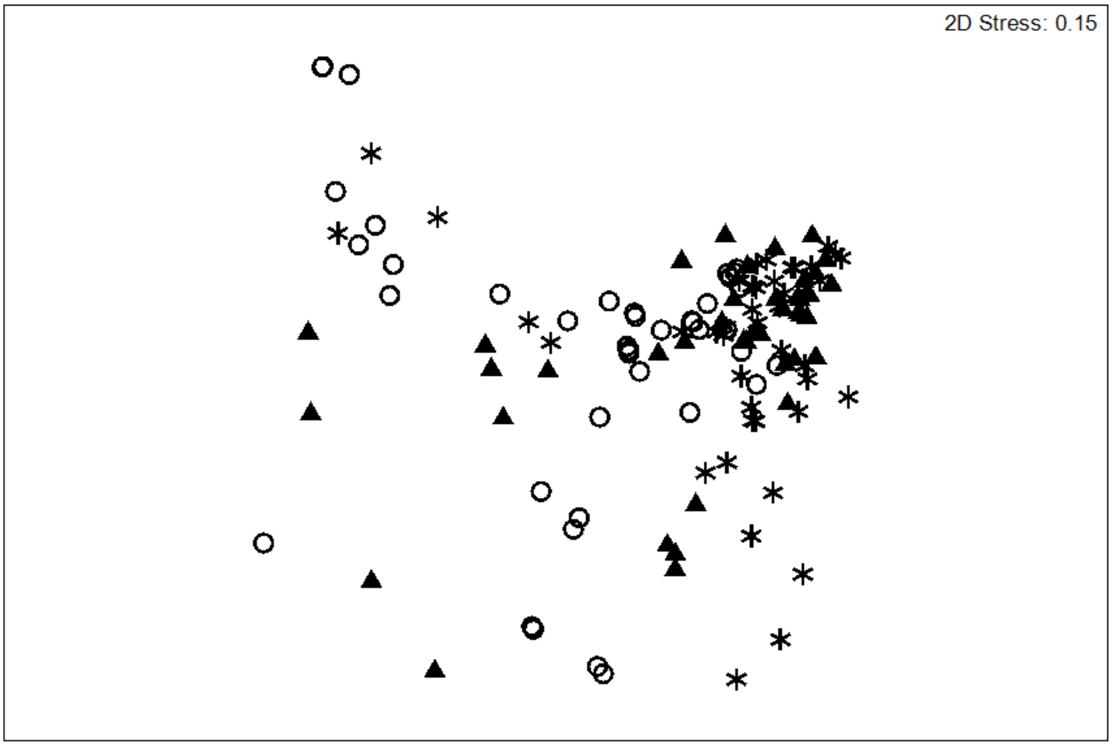


Figure 4.8a: Plymouth Breakwater epibiota. MDS ordination of Bray-Curtis similarities of species abundance (√ transformed) recorded in different treatments areas; 22mm holes (asterisk, n = 44), 14mm holes (shaded triangle, n = 42) and no holes (open circle, n = 44).

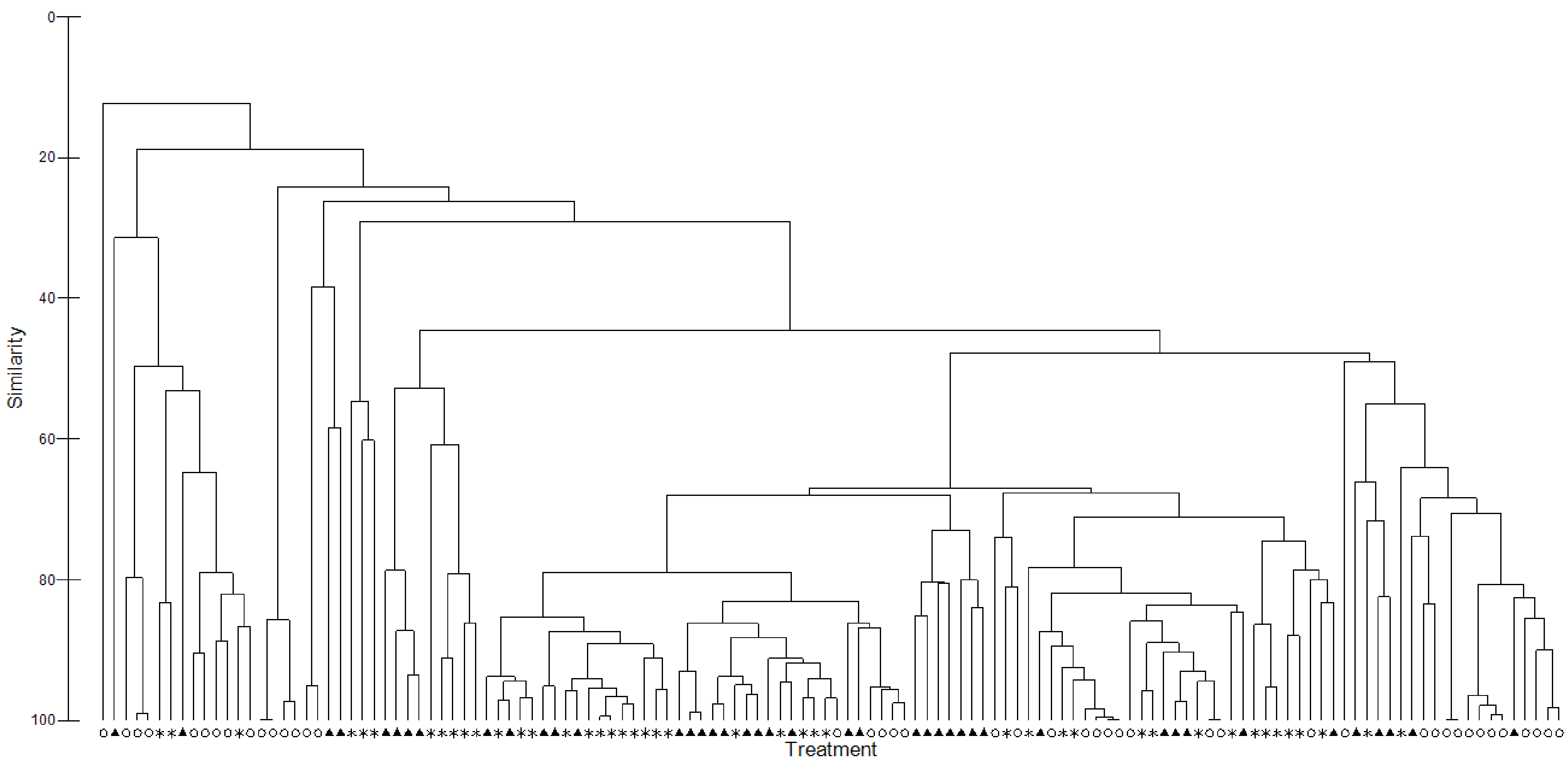


Figure 4.8b: Plymouth Breakwater epibiota. Cluster analysis of Bray-Curtis similarities of species abundance (√ transformed) recorded in different treatments areas; 22mm holes (asterisk, n = 44), 14mm holes (shaded triangle, n = 42) and no holes (open circle, n = 44).

Table 4.3: SIMPER analysis of average species abundance on armour units off Plymouth Breakwater. Bray-Curtis similarity in treatment areas with holes with diameter of a) 22 mm (n = 44), b) 14 mm (n = 42), and c) no holes (0)(n = 44); dissimilarity d) between treatments 22 mm vs. 14 mm, e) between 22 mm vs. no holes, and f) between treatments 22 mm vs. 14 mm. Av. Abund: average abundance; Av. Sim: average similarity; Sim/SD and Diss/SD: a measure in the contribution of the species to similarities/ dissimilarities between pairs of samples; Contrib%: percentage contribution of the species to the average overall similarity between groups of treatments; Cum%: cumulative contribution of the listed species. Values of Sim/SD ≥1 indicated that the contribution of a given species to the percentage dissimilarity were consistent among pairwise comparisons of samples between treatments.

a) 22 Av. Similarity 55%	Av. Abund	Av. Sim	Sim/SD	Contrib%	Cum. %
Total barnacle cover	8.6	43.6	2.4	80	80
Patellid spp.	1.7	6.0	0.8	11	91
b) 14 Av. Similarity 58%	Av. Abund	Av.Sim	Sim/SD	Contrib%	Cum. %
Total barnacle cover	8.0	40.2	2.6	70	70
Mytilus edulis	2.8	10.0	1.1	17	89
Patellid spp.	1.4	4.1	0.9	7	94
c) 0 Av. Similarity 58%	Av. Abund	Av.Sim	Sim/SD	Contrib%	Cum. %
Total barnacle cover	6.2	40.0	1.9	69	69
Patellid spp.	2.5	16.9	1.1	29	98
d) 22 & 14 Av. dissim 48%	22 mm	14 mm	Av.Diss	Diss/ SD	Cum. %
Total barnacle cover	8.6	8.0	9.2	1.1	19
Mytilus edulis	0.4	2.8	7.9	1.4	36
Porphyra sp.	1.6	0.8	5.0	0.8	46
Patella spp.	1.7	1.4	4.7	1.3	56
Spirobranchus sp.	0.8	0.7	2.7	1.1	62
Lomentaria articulate	0.7	0.1	1.8	0.5	65
Corallina officinalis	0.3	0.5	1.7	0.6	69
e) 22 & 0 Av. dissim 49%	22 mm	0 mm	Av.Diss	Diss/ SD	Cum. %
Total barnacle cover	8.6	6.2	13.7	1.1	28
Patella spp.	1.7	2.5	6.3	1.3	40
Porphyra sp.	1.6	0.3	5.0	0.7	51
Spirobranchus sp.	0.8	0.0	2.4	0.8	56
Lomentaria articulata	0.7	0.3	2.3	0.6	60
Fucus serratus	0.3	0.6	2.2	0.5	65
Dilsea carnosa	0.3	0.4	2.0	0.5	69
f) 14 & 0 Av. dissim 53%	14 mm	0 mm	Av.Diss	Diss/ SD	Cum. %
Total barnacle cover	8.1	5.9	12.7	1.1	23
Mytilus edulis	2.8	0.0	9.5	1.4	41
Patella spp.	1.4	2.5	6.5	1.4	53
Elminius modestus	1.0	1.3	4.4	1.1	61
Porphyra sp.	0.8	0.3	2.7	0.6	66
Spirobranchus sp.	0.7	0.0	2.1	0.9	69
Fucus serratus	0.0	0.6	1.7	0.4	70
Dilsea carnosa	0.1	0.4	1.6	0.4	73
Corallina officinalis	0.5	0.0	1.6	0.6	76

Each species was considered important if its contribution to percentage similarity/ dissimilarity exceeded the arbitrary value of 3 %. Modified units with drilled holes of two sizes, 22 mm and 14 mm, were dissimilar from the control area without holes; seven species contributed > 3 % each to the difference between treatments with 22 mm and no holes; and, seven species contributed > 3 % each to the difference between treatments with 14 mm and no holes (Table 4.3). Three species contributed over 10 % to the dissimilarity between treatments with 22 mm holes and no holes. These were total barnacle cover, *Patella* spp. and *Porphyra* sp., which contributed 11, 10 and 10 %, respectively, to the dissimilarity between treatments with 22 mm holes and treatments without holes (Table 4.3). Two species contributed over 10 % to the dissimilarity between treatments with 14 mm holes and treatments without holes. Total barnacle cover contributed 18 % and *Mytilus edulis* contributed 12 % to the dissimilarity between treatments with 14 mm holes and treatments without holes (Table 4.3). Nineteen species contributed to the dissimilarity between treatments with 22mm and 14mm holes; and between treatments with 22mm and no holes; and fifteen species contributed to the dissimilarity between treatments with 14mm and no holes.

Three species were found to be unique to the treatments with holes of larger diameter; *Corynactis viridis, Spirobis spirobis* and *Membranipora membranacea.* Four species were unique to the treatments with holes of smaller diameter; *Osmundea piatifida, Gibbula umbilicalis, Nassarius reticulatus*, Filograna sp. (Table 4.1). The average cover of barnacles was high in each of the treatments. The average cover of *Mytilus edulis* was higher in treatments with 14 mm holes, lower in treatments with 22 mm holes and absent from treatments without holes. The average abundance of *Patella* spp. was greatest in treatments without holes, followed by treatments with 22 mm holes. The average abundance of Porphyra was greatest in treatments with 22 mm holes, followed by treatments with 14 mm holes.

At the Cawsand end of the Breakwater there was significantly greater species richness and species abundance in treatments with 22 mm and 14 mm than in treatments with no holes. Species richness and species abundance in treatments with 22 mm and 14 mm holes were not significantly different (Table 4.2).

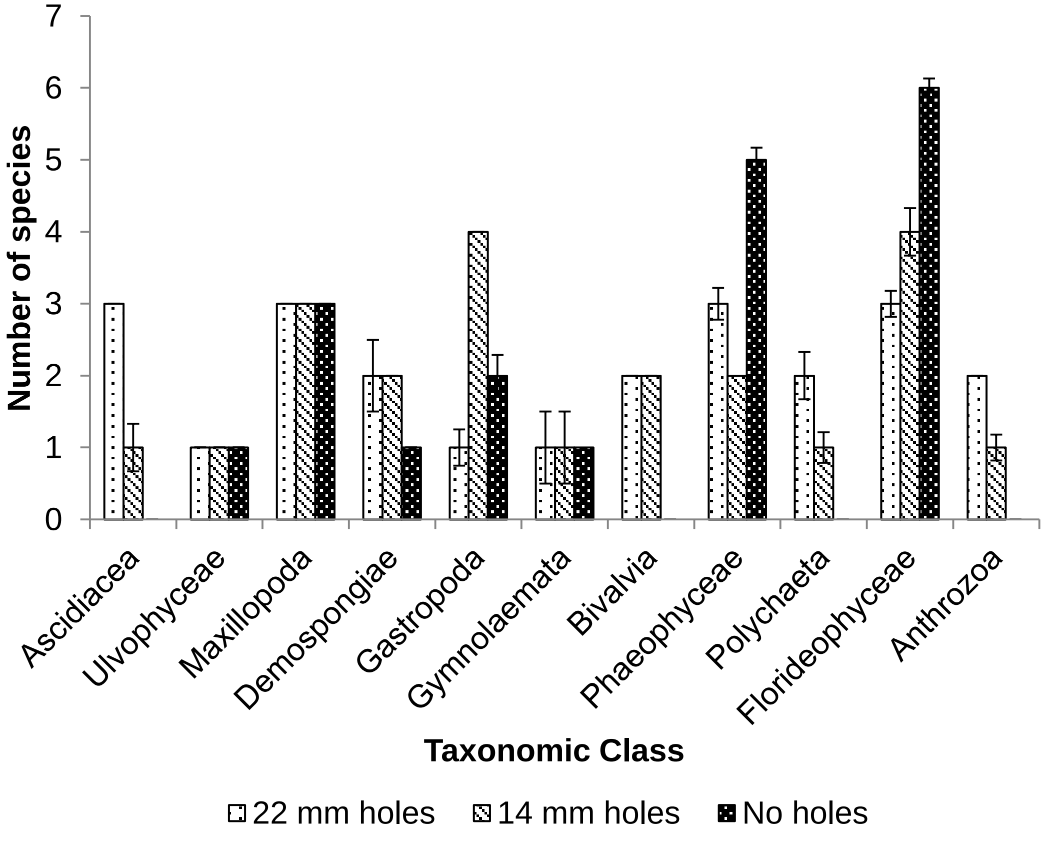


Figure 4.9: Species richness within taxonomic classes in assemblages recorded within treatment areas with 22 mm holes, 14 mm holes and no holes. Each treatment n = 44, $\overline{x}$ ± standard error.

4.3.3. The influence of orientation to the sun on species diversity and species abundance in different treatments

The armour units with a surface of northerly aspect had a greater number of species than the units with a southerly aspect (Table 4.1). All except three species were found on the north facing surfaces (Table 4.1). The three species found on the south facing surfaces of the units and not on the north facing surfaces were *F. vesiculosus, Osmundea pinnatifida* and an ascidian Sp..

The interaction between treatments was different according to the orientation of the blocks ($F_{2,84}$ = 34.33, p <0.05, Table 4.2a). Treatments on the northerly aspect with holes had greater richness of intertidal epibiota than the treatments without holes. However, on the north oriented blocks there was no significant difference between the number of species in treatments with small holes and no holes.

Maxillopoda were the most abundant species across all treatments and positions.

4.4. Discussion

4.4.1. Influence of modifications to surface complexity on intertidal epibiotic assemblage structure

Methods to minimise negative anthropogenic impacts of coastal protection structures are needed (Borsje, 2011; Chapman and Underwood, 2011; Firth *et al.* 2013; Moschella *et al*. 2005). This chapter advances current concepts to increase habitat and species diversity on artificial structures, and bridges the gap between concept and practice.

Experiments have been carried out to assess modifications for the purpose of increasing diversity (Chapman and Underwood, 2011; Moschella et al. 2005) or targeting specific species for commercial gain (Borsje, 2011; Martins *et al.* 2010). Many of these studies used drilled tiles to retrospectively add surface heterogeneity to coastal structures with encouraging results, particularly where the desired outcome is to increase local biodiversity.

Chapman and Underwood (2011) modified a seawall at Farm Cove in Sydney by adding holes of different size. Typically, after 27 months, greater abundances of species were present in small holes (25 mm in diameter by 5 mm depth) than large holes (50 mm in diameter by 5 mm depth) and controls without holes.

Martins *et al*. (2010) examined the influence of pit size on the distribution and survival of the exploited limpet *Patella candei* on seawalls in the Azores. The addition of pits to the otherwise featureless seawalls increased the number of immigrated and recruited limpets.

Features can be incorporated during the design or maintenance of an artificial structure to provide habitats that can be tailored to suit a species' specific environmental tolerance and or needs for community interaction, i.e. to create a refuge from different environmental or community pressures. This may be as simple as positioning a feature with a different orientation to the sun or waves, or incorporating areas of steeper or shallower incline of slope to the structure (as studied in chapter 2). Other types of feature include the addition of crevices, pools and overhangs, and a combination of features. The overall effect of varied habitat availability is increased local species diversity.

This study tested concepts to increase local biodiversity, by incorporating design principles on a bigger scale than previously attempted and by manipulating the surface of structures directly and on surfaces of different orientation to the sun. Experimental modifications of an existing breakwater during routine maintenance were effective in increasing surface complexity. As hypothesized the modifications provided opportunity for a greater diversity of habitats thereby influencing the richness and abundance of intertidal marine epibiota and encouraging a biologically diverse community to establish.

Increased surface heterogeneity was achieved with the addition of holes on concrete armour units on Plymouth breakwater, which resemble cracks and crevices on the natural shore in that they created shade and retained water to protect from desiccation, reduced the exposure to wave and currents and acted as refuge from or for predators (Johnson 1998b). In this study, the majority (98 %) of the forty-five species found during the monitoring were within holes, which were significantly greater in number than in the areas surrounding the holes and the control areas without holes. Given the exposed conditions at the study site, the provision of holes seemed to provide shelter from the physical environmental stresses for a large number of species; rather than shelter from or for predators, where you might expect a high abundance of a few vulnerable, or a few aggressive species. It is likely that the presence of species within holes instigated the presence of species in the immediate surrounding area to the hole, where a halo of species was found.

Of the species present in treatments with holes (in holes and surrounding the holes) and absent from treatments without holes, two were algae (R.verrucosa and *C. crispus*); eight were sessile organisms (*A. equina, O. edulis, M. edulis, D. pumila)* and four encrusting species difficult to identify to species level (spirobranchus sp., bryozoan, demosponge and ascidian); and, three were mobile species (*L. littorea, L. obtusata*, and a green polycheate worm (Table 4.1). Therefore a varied assemblage of attached algae and the sessile epibiota had arrived at the site within the currents and settled within holes.

There may be many reasons for the presence of species in holes and not on the surrounding substrate. In the exposed environment of the Breakwater, holes are likely to be important habitats for species that need to avoid strong wave forces and desiccation. Here, for example, species of anthozoa, hydrozoa and ascidia are likely to inhabit holes for their protective properties. High abundance of demospongia was found within the moist shaded conditions created, conditions needed for the success of these species. In exposed conditions, propagules of planktonic larvae can get trapped and settle in holes and crevices, enabling the attachment processes to occur. Many species are more likely to be swept past smooth surfaces with no opportunity to escape the force of the waves and currents.

In this study the control areas without holes and the expanses of surface within treatment areas surrounding the holes were both dominated by barnacle cover and Patellid sp.. The lowest cover of barnacles occurred inside holes. It was possible that the attachment opportunity for some species, such as the barnacle, was restricted owing to the reduced water circulation within holes; or, that barnacle spp. were better able to settle on areas that experienced greater currents, by attaching quickly. In this second instance, barnacles will have been influenced by bare rock as a valuable resource for space, rather than the presence of holes.

Anemones (Anthozoa) can arrive as free swimming larvae and once attached by their adhesive basal foot to the substrate they have few predators (Fish and Fish, 1996); although many species of fish, seastars and snails will opportunistically feed on them during high tide. Anemones are generally sessile but can move if conditions become unfavourable, for example if they experience prolonged dryness or if space is needed for growth. Their presence within treatments suggested that conditions were suitably moist; therefore a future design consideration should be the space requirement for individuals and for the spreading of the species by reproductive methods such as budding. The distribution of the hydrozoan *D. pumila* is influenced by the degree of exposure to wave action (Fish and Fish, 1996), thus its presence in treatments with holes was likely to be as a result of the holes providing refuge from wave action.

The juveniles of predatory species such as the gastropods occupied holes to a greater extent than the adults. For some species the adult life stage would not fit within holes, but even where the adult stage would fit, for example the littorinids, few adults were present. The quantity of available food may have been insufficient to support an adult population, or the time taken to reach maturity may be longer than the monitoring period.

Thompson *et al.* (unpublished, cited in Witt *et al.,* 2010) drilled holes (5 × 32 mm and 17 × 14 mm holes) into tiles and attached them to a coastal defence structure in SW England. The addition of habitat complexity to concrete surfaces resulted in significantly increased diversity of intertidal organisms, compared to an unmodified control. This positive result informed my experimental design of two different sized holes, although to assess the influence of size here the two sizes were in different experimental areas, in contrast to the mixed size holes within one experimental area, as with Thompson (unpublished data, cited in Witt *et al.* 2010) and Borsje *et al.* (2011). Typically, the numbers of species between the two size holes were not statistically different, although there was a significant interaction between the number of species found in treatments with holes of different size and the orientation to the sun of the modified surface. On the north oriented treatments the larger holes had a greater number of species, whereas on the south oriented treatments the smaller holes had a greater number of species. Thus, the orientation of modification or habitat provision will influence the species present and is an important design consideration. Where the overall aim of modification is to increase the species richness of an area, the creation of different niches should be made at different orientations.

Three species found on the south facing surfaces of the units and not on the north facing surfaces were *F. vesiculosus, O. pinnatifida* and an ascidian sp.. *F. vesiculosus* has developed gel-forming polysaccharides on the thallus which can reduce desiccation stress. Florideophyceae species cover was significantly high on north aspects, compared to south aspects.

The abundance of gastropoda, florideophyceae and demospongia within the treatments with holes of different size was influenced by site. As the Bovisand and Cawsand sites are close and experience similar conditions it is likely that the time of placement or the distance to the shore are possible reasons for this influence. Demospongia was present at the Bovisand end of the breakwater, which is closer to the shore than the Cawsand end, where it had greatest abundance in large holes and greater abundance in small holes than areas with no holes. The high abundance of demospongia in larger holes was possibly owing to suitable water circulation for the arrival and settlement of the larval phase and for supplying suspended food particles; as water motion is an external agent reported to govern the growth in demosponge (Hayward and Ryland, 1995).

Some of the intertidal epibiotic species identified within holes were species that had a pelagic phase, whereby successful transportation and settlement of this stage was likely to be influenced by water current, and their greater abundances within the larger holes may be explained by suitable currents for the arrival and settlement process. Another common factor was that many of the intertidal epibiotic species found within the larger holes including *C. viridis, S. spirobis* and *M. membranacea* were filter feeders, extracting passing plankton and other tiny particles from the passing water. An optimum diameter of hole for filter feeding or for specific life stages may exist. In designing modification or design for increased biodiversity the provision of appropriate habitat for more than one life stage needs to be considered.

Of the species found that were unique to the treatments with holes of smaller diameter, the presence of *O. pinnatifida* may be attributed to the absence of competative fucoids in most small holes. *G. umbilicalis and N. reticulatus* have larval stages that seemed to have found refuge and suitable settlement conditions, including food provision, within the small holes. However, few studies consider the specific life history traits that are encouraged by habitat features such as different sized holes.

Various modification experiments on structures have been carried out to influence the biological diversity through design (Borsje *et al.* 2011; Chapman and Underwood, 2011; Martins *et al*., 2010; Moschella *et al*., 2005). The technique used here of modifying the direct surface rather than retrofitting panels (as in Borsje *et al.* 2011, Thompson et al unpublished data, cited in Witt *et al.* 2010, and retrofitted pots in Browne and Chapman 2011) were beneficial as manipulations were stronger and unlike retrofitted designs experimental units were not lost in exposed conditions. Opportunities were found to incorporate features during maintenance, which were inexpensive, especially when the manipulation cost is considered alongside the cost of the maintenance.

Borsje *et al.* (2011) incorporated modifications such as surface roughness, grooves and pits onto concrete slabs placed on the breakwaters at the entrance to the North Sea Channel at Ijmuiden, the Netherlands. Some results of my study on Plymouth Breakwater were similar to that found by Borsje *et al.* (2011); for example, experimental units were rapidly colonised by barnacles; *M. edulis* were only found in the modified areas; and holes were used by *L. Littorea* during low tide. A comprehensive knowledge base of case studies such as those of Martins *et al*. (2010), Chapman and Underwood (2011) and Firth *et al.* (2014) could be used to inform design and enable an improved prediction of outcomes of different design at comparable sites.

The position within the tidal frame of any structure where modification made for the purpose of habitat enhancement is an important design consideration as the physical conditions experienced must be suitable for the assemblage of species to succeed. In this study, all of the modified armour units surveyed lay within the intertidal area at approximately the same tidal height (within ~40 cm), at a height observed in the surrounding area as suitable to the local epibiotic community.

The holes created in the surface of armour units at Plymouth Breakwater in this study gave species a refuge from environmental pressures, such as reduced impact to strong waves and currents, reduced desiccation stress by creating shade and moist environment, and potential refuge for or from predators. The treatments with different size holes created varied habitat and increased surface area. However, the additional habitat variability were considered to be the major influencing factor rather than the increase in surface areas created by the walls of holes, which were considered insufficient for surface area effects to compromise comparisons between treatments. From an engineering perspective the extent of the surface modified, in m^2, is likely to be important to the design. Further research into identifying the optimum dimensions of modified surface and distances between modified areas should be considered on a site by site basis.

The method of adding modifications such as pools and crevices at the time of casting is recommended, this method could be used to create pools and crevices in larger numbers, which will increase the opportunity for survey and monitoring, thus adding to the supporting evidence of adding habitat to inform future design. The influence of pools can be predicted using information gained from other studies, such as the pools studied in Chapter two, where data were collected from the older armour units from the pools made during the casting as part of the lifting and transportation mechanism of the armour units. Here I found that pool and crevice habitats increased the species richness and abundance of intertidal marine epibiota. It was assumed that depth was an important factor for the colonising assemblage of species. Pools and crevices of different dimensions could be easily created to increase the understanding of the influence of these features and to develop a knowledge base which can inform future design for comparable locations.

4.4.2. Practical considerations and future work

Hard structures are widespread in the marine environment, their construction is likely to increase as a consequence of an increased need to defend expanding coastal infrastructure and developing offshore construction industry. In addition, existing structures will require maintenance to renew and repair structures in response to and in anticipation of sea level rise and detrimental storm impacts.

In this study, modifications of an existing coastal defence structure during the routine maintenance were achieved. Opportunities, such as adding pools and crevices to freshly poured concrete and drilling holes into concrete that was not fully cured, were identified to increase the surface heterogeneity of concrete armoured units. These units are routinely produced to defend coastal defence structures and to replace worn armour units in the maintenance of coastal defence structures. Several methods were used to achieve modifications, such as drilling holes on the sides of recently cured concrete units and using wooden moulds for adding rock pool and crevice habitat in the uncured concrete on the top of the units. The methods employed varied in ease. Creating crevices and pools were less labour intensive than drilling holes and are considered a practical option when modifications are performed by engineers or on a broader scale, however timing is restricted by that of the construction or maintenance project. Drilling holes were achieved by more general labourers and were not restricted by a requirement to coincide with the engineers or other time constraints of the construction process. The influence of these modifications on species abundance and biodiversity during early colonisation were realised.

The addition of pools and crevices to the surface of the armour units at the time of casting were successful and reasonably easy to achieve. Timing when holes were added was an important factor, the sooner the holes could be drilled when the mould was removed, the easier the drilling. Drilling on Plymouth Breakwater was not deemed possible owing to the offshore nature requiring heavy machinery, and specialist modes of transport to get the machinery to the site. Modifying the armour units using additional concrete mixed on site was labour intensive but achievable for a limited extent.

Modifications carried out shortly after the mould had been removed from the units were achieved in greater numbers, when the concrete surface was easier to drill into and when timing with the engineers constructing the units was not a factor to consider. Unfortunately, once placed *in situ* several of the armour units were inaccessible for survey purposes, and it was presumed that several were placed subtidally. However, the majority of the units with holes were located in conditions favourable for surveying, allowing for the influence of the presence of holes, and the influence of holes of different size to be identified. It will be interesting to see if the modified blocks are later located as the area surrounding Plymouth Breakwater is regularly used for dive training. It is expected that pools are unlikely to influence subtidal species, whereas crevices in the subtidal may provide refuge for species such as crustacia and fish.

The modification of structures, particularly concrete structures such as armour units that are regularly cast to give protection to our coasts and to protect much harder coastal defences present an ideal opportunity to increase species abundance and biodiversity. A variety of modifications can be easily achieved. Experimental trials are important to gain a clear understanding of the influence of modifications on the local species assemblage and to identify suitable modifications that will enable the desired outcome. In this study practical modifications, which can be incorporated into the design or maintenance plans of coastal defence structures, showed that increased surface complexity increased species abundance and the species richness within the assemblage of species. In an earlier study Browne and Chapman (2011) recognised that although successful in enhancing the number of species living on walls in the shorter term, adding holes and crevices can be less successful longer term as their created habitat filled with sessile animals, so that the available habitat was lost. With this in mind it may be worth investigating whether there is an optimum hole size to support higher diversity for the long term. Also, it may be that the desired outcome in some situations is to increase the rate of early colonisation and species succession, which I demonstrated can be achieved with the smaller holes.

Results also showed that the influence on species diversity and abundance were different when the surfaces were modified with a variation in hole size and with the treatments positioned at different orientations. Thus a combination of factors for giving a broader range of conditions is recommended where varied habitat to support a more diverse assemblage of species.

Chapter 5
Incorporation of varied habitat during the construction of a sea wall to influence biodiversity

5.1. Introduction

Increased urbanisation at the coast creates the need for man-made structures to be built within the narrow transitional zone between land and sea, often as a necessity to defend vulnerable areas against flooding and erosion (Borsje *et al.* 2011, Diez *et al.* 2011, IPPC 2007, Jackson and McIlvenny, 2011, Li *et al*., 2005, Martin *et al.* 2005, Masselink and Russell, 2007, Moschella *et al.* 2005, Taylor et al., 2004). More than two million properties are at risk of flooding from rivers or the sea in England and Wales (House of Commons report on Managing flood, 2013). The frequency and severity of flood events are predicted to increase in future years (Airoldi *et al*. 2005; Bulleri and Chapman, 2010; Chapman and Bulleri, 2003; Davis *et al.* 2002; IPPC, 2007; Moschella *et al.,* 2005), thus the need for coastal protection from potentially devastating effects of flood and erosion is likely to increase. Parts of the coastline will need to be defended by building new hard infrastructure or replacing and upgrading existing defences (Coombes *et al*. 2012, Reeve *et al.* 2012). The Government recognises that effective flood protection is essential for economic growth and for the regeneration of key parts of the country (House of Commons report on Managing flood, 2013).

Coastal flooding arises from one or more processes. These processes include overflow, where the water level exceeds the top of the defence; overtopping, where the waves break over the top of the defence; breaching, where a combination of wave and water level loading causing a defence to fail; and, toe failure, where the foreshore level lowers to a level that compromises the structural stability of the defence (Reeve *et al.,* 2012). Flood risk would dramatically increase should the extreme increases in the main water sources coincide: namely mean sea-level, waves, tidal surge and river flow (Coombes *et al*. 2012).

As with structures that defend coastal assets against storms and waves (described in chapter 2), flood defences can be hard structures that act as static barriers, which can be placed within inshore waters, the intertidal or onshore (Airoldi *et al.,* 2005; Firth *et al*., 2012; Taylor *et al*., 2004) . Construction of hard defences inevitably causes a destructive effect on the immediate environment and will often contribute to coastal squeeze (Jackson and McIlvenny, 2011; Taylor *et al*., 2004).

Many similarities between artificial structure and rocky shore are recognised and described in throughout the earlier chapters of this thesis. The physical, environmental and biological interactions between intertidal species determine community structure. Earlier in this thesis, I showed that structural features on coastal defences can provide areas of diverse surface and create different habitat and shelter, which are considered essential to accommodate a diverse array of species (Chapman and Bulleri 2003; Jensen 1998). The topographic structure of habitat can provide protection from stressful environmental extremes and modulate biological processes (Johnson *et al*. 1998).

In this chapter I investigated how the incorporation of a number of different micro-habitats into the engineering design of a new seawall defence can influence various ecological processes and hence the composition and diversity of assemblage.

On the sea front at Shaldon, in South Devon, England, a major flood defence scheme was constructed between January 2010 and June 2011 costing approximately £8.3 million. The primary function of the scheme was to prevent storm and flood damage to the village of Shaldon, following two near miss events in October 2004 and March 2008 (Coombes *et al.* 2012). The flood risk area is a 'basin', where 453 properties were at risk of flooding in the event of overtopping. All four of the main water sources (mean sea-level, waves surge, river flow and rainwater run-off) influence the area and contribute to the flood risk, and the previous defences were not considered adequate to protect Shaldon should extreme increases of the water sources coincide (Coombes *et al.* 2012).

The site, situated at the mouth of Teign Estuary, is sheltered by a permanent spit "the Point", on the north bank at Teignmouth (Figure 5.1 insert). Shifting sands in the estuary mouth require "plough" dredging almost daily. The Southwest of England is also a region of continuing subsidence created by glacial isostatic readjustment, thus when combined with predicted sea level rise, the area is particularly susceptible to flooding. Sea level rise calculations that also incorporate climate change effects anticipate an effective sea level rise of 1m in this region over the next 100 years (PPS25, 2006). The wave climate in the area is predominately driven by swell waves from the Atlantic in the southwest direction, with yearly mean significant wave height of 2.0 m and a maximum wave height of 4.0 m (Reeve, 2012). Wave surge levels indicate 1 in 20 year maximum surges in the region of 1 m, and 1 in 2000 year surges of up to 1.8 m. The mouth of the estuary has a spring tidal range of approximately 3.8 m, with the maximum tidal current up to 3.0 m/s (Immray chart).

During the flood defence scheme, 940 m of existing foreshore walls were raised, 470 m of new foreshore wall built, along with new steps, ramps, floodgates, flood windows and doors. The seawall was designed with future upgrading in mind, through the construction of suitably strong foundations. The aesthetic appearance and potential environmental impacts of the new wall were recognised during the planning process and the design involved extensive end-user consultation to overcome objections related to the scale and look of the protection measures. To achieve an attractive structure with minimal negative environmental impact, the new seawall was clad with local stone (Naylor *et al.,* 2012). For this scheme, the Teignbridge District Council planning conditions set out a requirement that niche habitat creation be fully investigated for the new tidal walls, thus options for ecological enhancement were incorporated on a trial basis. This trial was an opportunity for the Environment Agency and experimental ecologists to collaborate to test the efficacy of habitat modification. The ecological enhancements of a newly constructed stretch of reinforced wall were thus addressed and monitoring of the influence on intertidal epibiota forms the basis of this chapter of the thesis.

I tested the influence of the incorporation of different habitat features. namely holes, pools and scratched surfaces on species composition, abundance and diversity during early colonisation. I describe the creation of habitat niches at construction of the new seawall at Shaldon.

In addition, the species assemblages on new wall were compared to the species assemblage on an adjacent similar section of old wall with an established species assemblage.

5.2. Method

The seawall on the foreshore that forms the basis of the tidal flood defence scheme at Shaldon (50^{o}32'N, 03^{o}30'W) (Figure 5.2) is 1410 m long.

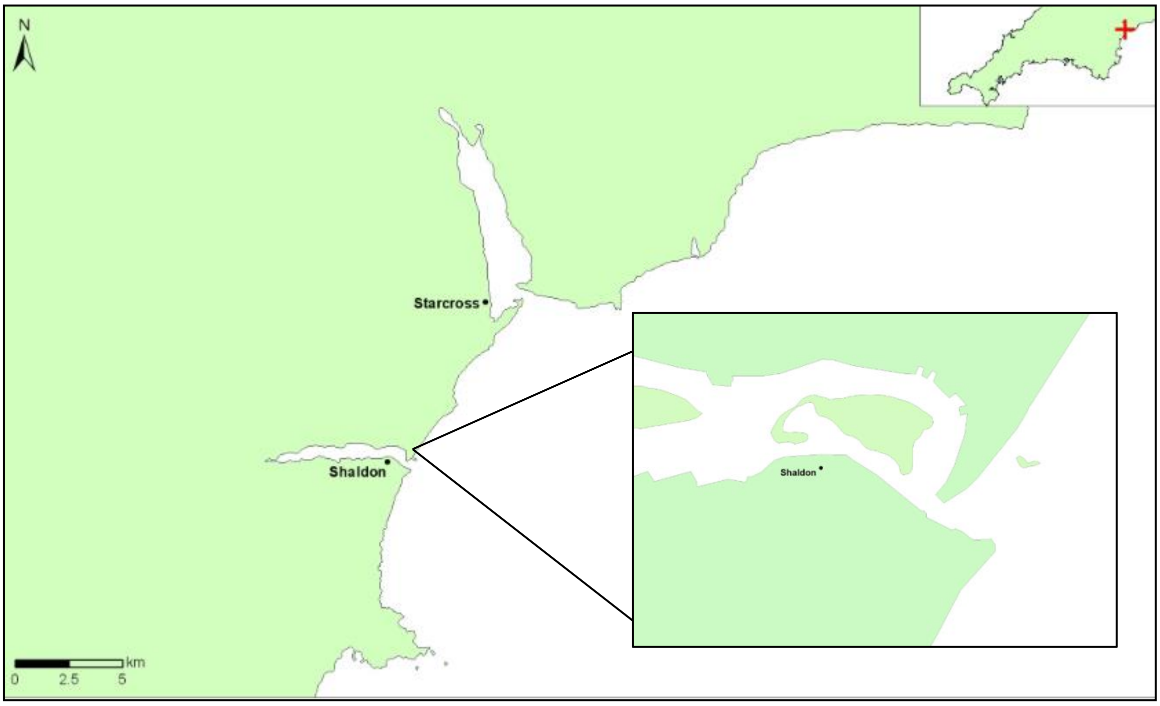


Figure 5.1: Location of the Shaldon study site in SW Devon, UK and satellite image of the mouth of the River Teign.

The ecological enhancements were part of a collaborative project between Plymouth University, the Environment agency, the University of Exeter and contractors (Interserve). I provided input from results from Chapter 4 of my thesis to influence the designs chosen and the experimental setup. My PhD provided the opportunity to monitor the trial.

Observations of local comparable existing seawalls and the marine life associated with them, revealed that the potential uptake were likely to be restricted by the high position of the planned walls in the intertidal. Localised scientifically robust experimental design for habitat enhancements were based on experimental designs that had previously shown promise in trials with test panels conducted by Martins *et al.*, (2010) and Thompson *et al.* (Unpublished data cited in Witt *et al., 2012*). The ecological enhancement designs on a new section of seawall, 44m long were achieved as a full scale experimental trial of habitat incorporation (Figure 5.3).

Figure 5.2: The new stretch of seawall with ecological enhancement (below the weep holes), prior to settlement of sediment at the foot of the wall.

The four design features (hereafter treatments) were: smooth surface (control), millimetre scale grooves, centimetre scale holes and a recess to act as a shaded water retaining pool (Figure 5.3).

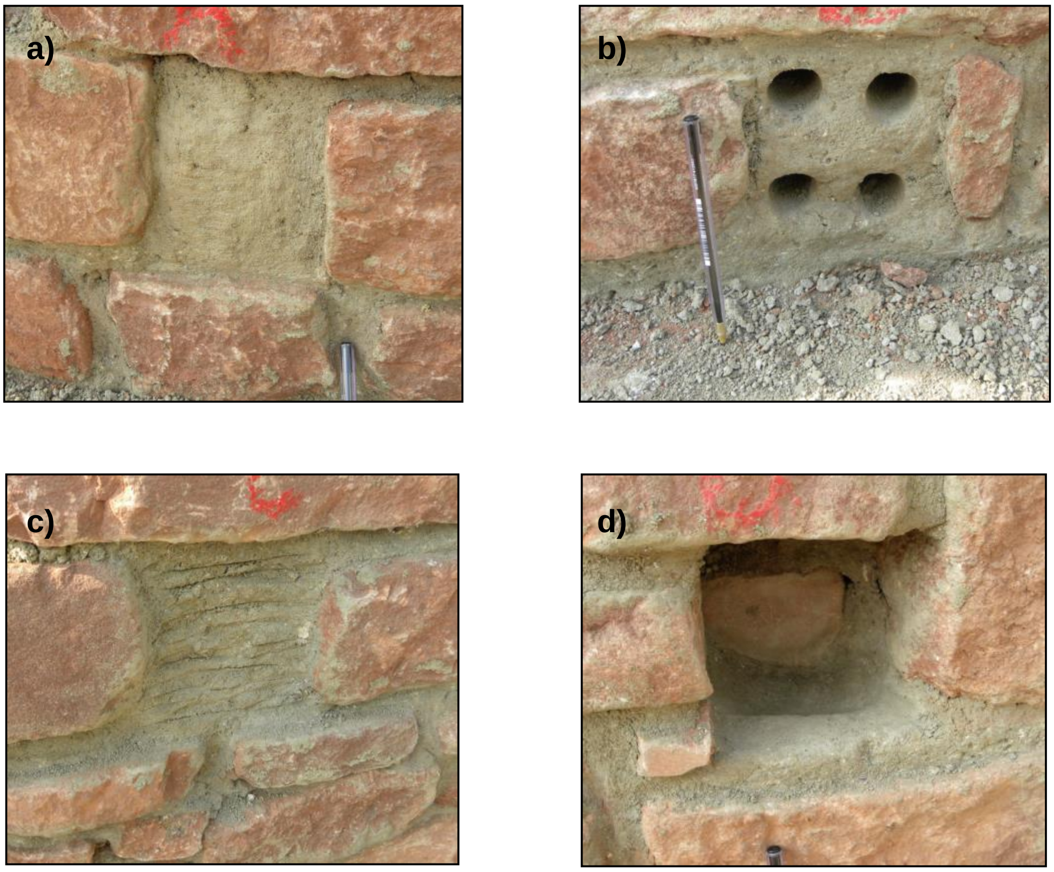


Figure 5.3: Treatments on the newly constructed seawall at Shaldon, a) smooth, b) holes, c) grooves (scratched) and d) recessed.

Design features were incorporated into the stone built seawall by omitting evenly placed stones and moulded concrete units were incorporated that imitate different habitats. The aims of the treatments were to provide additional habitat to an otherwise relatively homogenous seawall.

Grooves were formed by scratching at the surface of the wet concrete with a trowel, holes were made by pushing the end of a broom handle into wet concrete to an approximate depth of 25 mm, at a slight angle down, and the recesses were moulded using the broom handle and by manipulating the concrete by hand to create a fist shaped pool with a lip to hold water. After the first visit it was apparent that the pools were not retaining water, and they were subsequently lined with a thin layer waterproof concrete, of the type used in drinking water storage tanks. The treatments were positioned horizontally near the base of the sea wall but above the anticipated sediment level. Within this area treatments were added with even spacing with a minimum of nine replicates of each treatment at each of three heights on the wall. The treatments were positioned at heights 15 cm apart, thus the treatments were within a 50 cm vertical band. Experimental treatments and the surrounding new sea wall as a whole, and a nearby existing sea wall of similar construction and position in the tidal frame but > 10 years of age, were monitored for 16 months. The treatments were monitored nine times after construction of the wall at intervals of 1, 1.5, 5, 3.5, 2, 5, 5.5, 10 and 16 months.

The elevation of the treatments were measured with a RTK-GPS system.

Data were collected at low tide when treatments were exposed to the air and easily accessible. Data were collected from within holes, pools, on the smooth and scratched surface and the immediate area outside holes and recessed area. A minimum of six 50 cm x 50 cm quadrats were surveyed on the new stone wall surrounding the treatments, and a minimum of six 50 cm x 50 cm quadrats were surveyed on a nearby “mature” wall, which were of similar construction, at a similar tidal elevation and orientation to the sea as the new wall. Species abundances were estimated as the percentage cover of macroalga canopy, percentage cover of ephemeral green algae and sessile fauna. The numbers of mobile species were recorded as individual counts. Where mobile species were low in numbers the percentage cover and individual count data were included in the same analysis. For some species, cover were recorded as taxa and approximate relative proportions of each species were recorded, thus recording cover at a high level of accuracy without sacrificing individuals, thus reducing the impact of the survey. The term “sp(p).” denotes organisms of either one or several unidentified species, and groups of organisms are referred to as “taxa”. The World Register for Marine species (WoRMs, 2014) has been used as a reference for up to date taxonomy, and the species name is shown with the discoverer name and date in the list of species. Analysis has been performed at the species level, although for uncluttered presentation some results are displayed at a higher taxonomic rank.

Prior to further analysis, Cochran’s C tests were performed to assess the homogeneity of variances to determine whether the data needed transforming. Data from the species survey were analysed by a one-way analysis of variance (ANOVA), performed using the statistical package GMAV (Underwood and Chapman 1998). Post-hoc Student-Newman-Kuels (SNK) comparisons were performed. To test for the influence of treatments on the diversity and abundance of marine epibiota, the factor treatment had four levels representing recess, holes, smooth and scratched. To test the level of community establishment, the factor wall age had two levels new wall and mature wall.

5.3. Results

5.3.1. Species assemblage consequences of habitat enhancement trials

The colonisation of intertidal epibiota was examined to test the influence of the incorporation of different habitat features, namely holes, pools and scratched surfaces, on species composition, abundance and diversity.

A total of eleven species across five taxonomic classes were recorded in this study (Table 5.1). The species authority for each recorded species is given in table 5.1.

Table 5.1: List of species identified at the Shaldon study site within the treatments with holes (H), scratches (S), recess (R) and the control (C). Species authorities for all species referred to in this chapter are given here.

		Treatment			
Class	Species	H	S	R	C
Ulvophyceae	*Ulva* Spp. (2 species)	X	X	X	X
	Fucoid germlings	X	X		X
Maxillopoda	*Chthamalus montagui* (Southward, 1976)			X	
	Chthamalus stellatus (Poli, 1791)			X	
	Austrominius modestus (Darwin, 1854)			X	
Gastropoda	*Littorina littorea* (Linnaeus, 1758)	X	X	X	X
	Phorcus lineatus (da Costa, 1778)			X	
	Littorina saxatilis (Olivi, 1792)	X	X	X	X
	Gibbula umbilicalis (da Costa, 1778)	X			
Isopoda	*Ligia oceanica* (Linnaeus, 1767)	X			

Seven species across four classes were recorded within holes, with the highest diversity attributed to the class Gastropoda (*L. littorea, L. saxatilis and P. lineatus*). Four species across three classes were recorded within scratches, with the highest diversity attributed to the class Ulvophyceae (ephemeral green algae and *Ulva* spp.). Eight species across three classes were recorded within recessed pools, with the highest diversity attributed to the classes Gastropoda (three species) and Maxillopoda (three species). Five species across three classes were recorded within the smooth treatment, with the highest diversity attributed to the class Gastropoda (two species) and Ulvophyceae (*Ulva* spp.). Isopoda were unique to treatments with holes. Barnacles (*Austrominius modestus*, *Chthamalus montagui* and *Chthamalus stellatus*) were unique to treatments with recessed pools. The highest numbers of species across treatments were found in recesses, and the lowest number in treatments with scratches, closely followed by the smooth control.

The two species of *Chthamalus* were recorded together for ease of sampling as Chthamalid barnacles.

Within three months of the seawall construction the treatment area with holes supported a greater number of species than the other treatments, and was the only treatment with a grazer species present (Figure 5.4). After 18 months the recessed treatment had significantly more species than smooth (control) and scratched treatments ($F_{3,20} = 4.63$, $p = 0.013$; SNK $p < 0.05$, table 5.2).

Ephemeral green algae were the most abundant species, with a high abundance in three out of four of the treatments. *L. littorea* were the second most abundant species across the treatments, and the species with the highest abundance in the recessed treatment. The abundance of I*sopoda* and *Fucoid* algae over were very low.

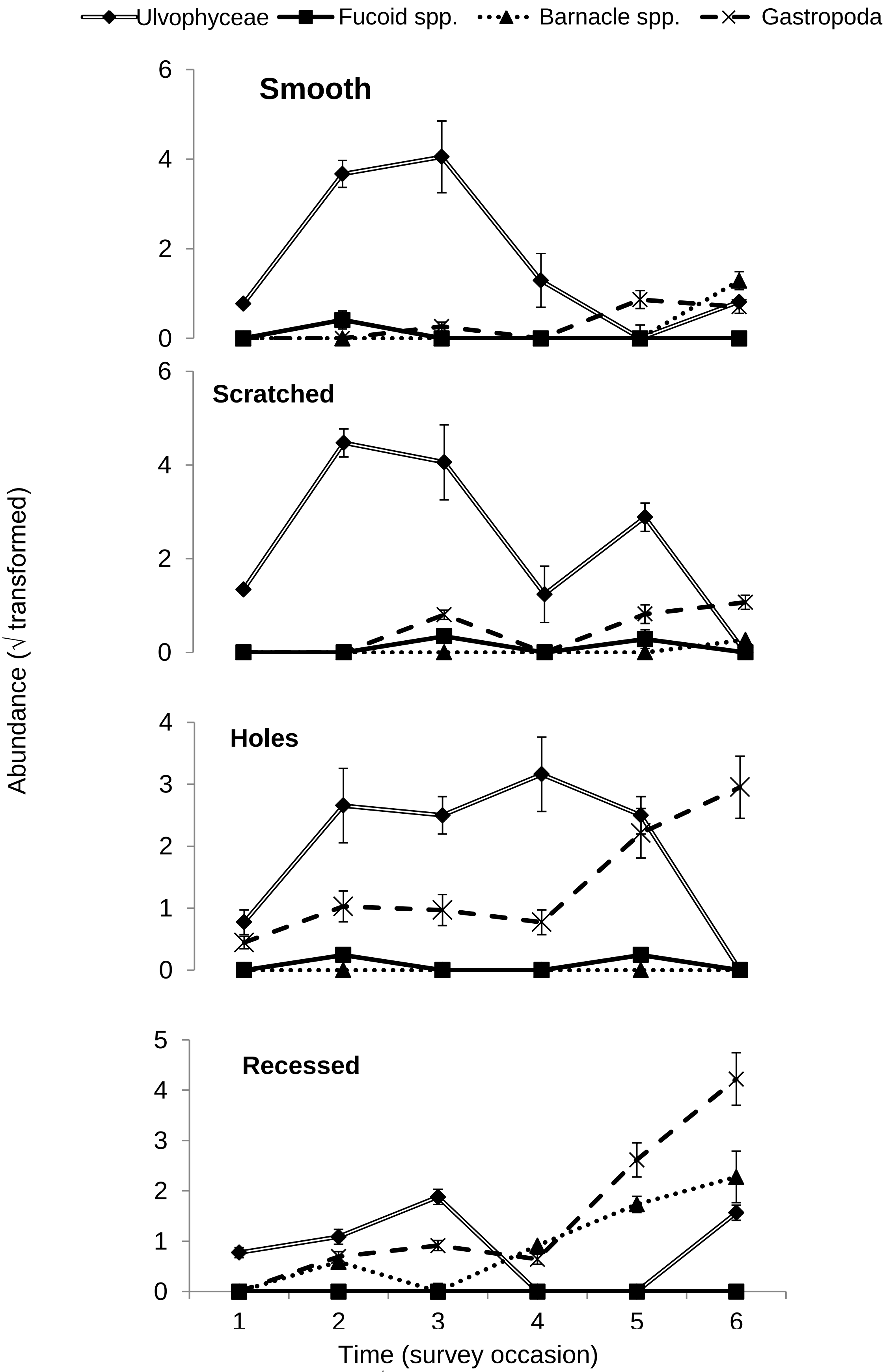


Figure 5.4: Species abundance (√ transformed) aggregated to taxonomic class, in assemblages observed in different treatments. $\bar{x}$ ±standard error. Treatments with holes (H) n = 88; scratches (S) n = 80; recess (R) n = 85 and smooth control (C) n = 63.

Ordination by nMDS and cluster analysis of species samples in different treatments revealed that assemblages in the smooth control and scratched treatments were generally more dispersed and less tightly clustered than assemblages from the recessed and hole treatments (Figure 5.5a, b and c).

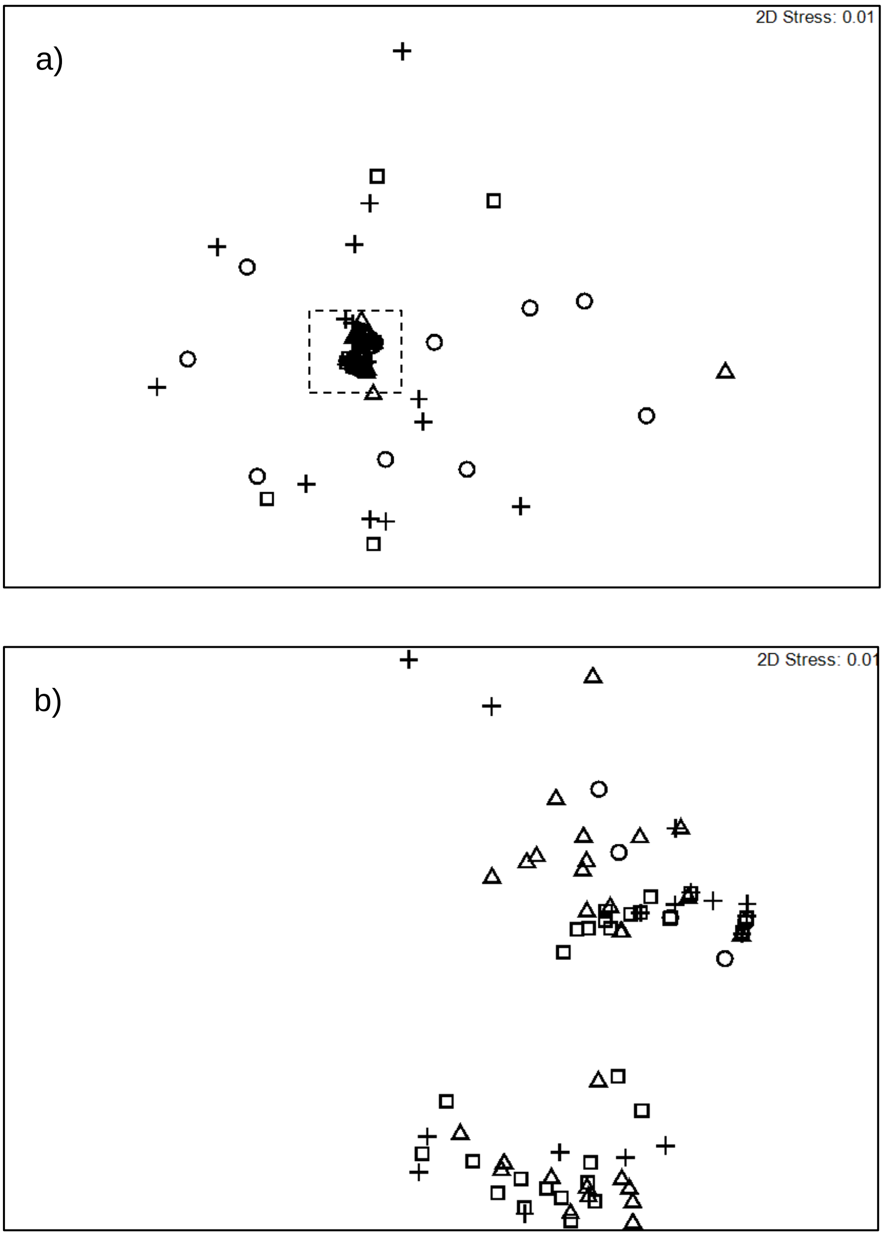


Figure 5.5: a) Shaldon epibiota. MDS ordination of Bray-Curtis similarities of mean species richness (√ transformed) for the treatments with recess (triangle, n = 34), holes (square, n = 32), scratches (cross, n = 15) and a smooth control (circle, n = 27) along the same stretch of seawall, at Shaldon, Devon; and b) as a) but area within dashed box is displayed at an increased scale.

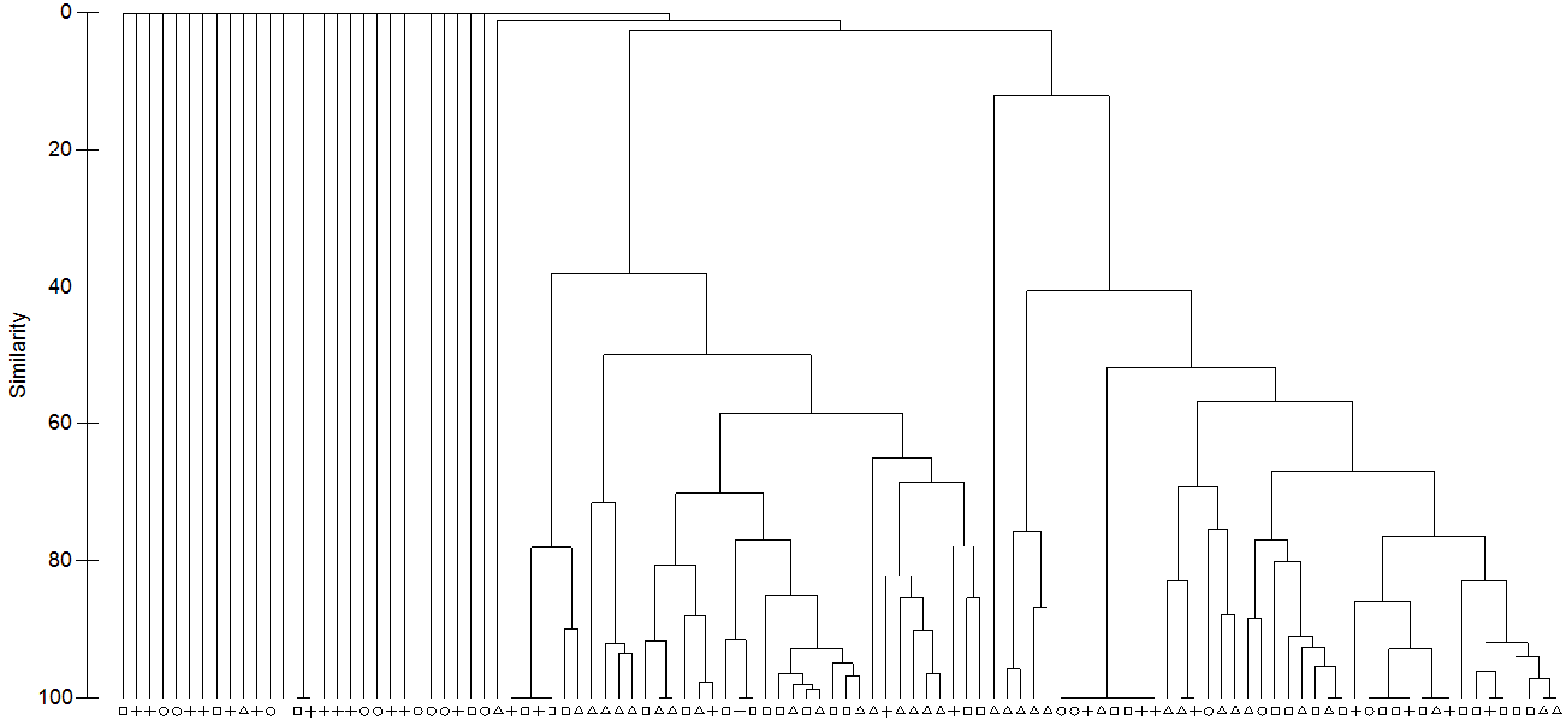


Figure 5.5 c) Shaldon epibiota. Cluster diagram of Bray-Curtis similarities of mean species richness (√ transformed) for the treatments with recess (triangle, n = 34), holes (square, n = 32), scratches (cross, n = 15) and a smooth control (circle, n = 27) along the same stretch of seawall, at Shaldon, Devon.

Table 5.2: Species assemblages on surfaces with the different treatments of holes, scratches, recess and a control on a new seawall at Shaldon, Devon. A series of one-way ANOVA comparisons of total species cover, species richness and Gastropoda abundance between areas of seawall with different treatments. SNK post hoc analysis, where Holes = H, Scratches = S, Recessed = R and Control = C, n = 6. ~~x~~ p < 0.05, ~~xx~~ p < 0.01, NS Not significant.

	C	**DF**	**Ms**	***F***	***p***	**SNK**
Abundance	0.4	3	403	1.14	3.5	
Res	NS	28	351.83			
Number of	0.4	3	2.8	4.63	**0.013**	R = H > C = S
species	NS	20				
Res			0.61			
Gastropoda (√)	0.5	3	21.24	19.14	**< 0.001**	R > H > C = S
Res	NS	20	1.11			

Table 5.3: The global ANOSIM pair-wise comparison between species identified on areas with different treatments; recessed, holes, sratched and smooth control.

Comparisons	***R* Statistic**	**Level**
Global	**0.099**	**0.1**
Recessed *vs.* Smooth	0.266	0.1
Recessed *vs.* Holes	0.012	18.3
Recessed *vs*. Scratched	0.119	0.3
Holes *vs*. Scratched	0.72	1.8

Table 5.4: Results of SIMPER analysis of average abundance of species on treatments on the seawall at Shaldon. Bray-Curtis similarity in species in assemblages between the treatments; recessed, R (n = 85), smooth control, C (n = 63), holes, H (n = 88), scratched, S (n = 80) . Sim: similarity; Sim/SD: a measure in the contribution of the species to similarities between pairs of samples; Contrib%: percentage contribution of the species to the average overall similarity between groups of treatments.

R Av. similarity 26 %	Av. Abund	Av. Sim	Sim/SD	Contrib%
Ulva spp.	2.0	10.8	0.5	42
Littorina Littorea	1.4	10.0	0.5	39
Total barnacle spp.	0.8	2.4	0.3	9
Phorcus lineatus	0.5	1.7	0.3	7

C Av. similarity 10 %	Av. Abund	Av. Sim	Sim/SD	Contrib%
Littorina littorea	0.5	9.6	0.4	96
H Av. similarity 26 %	Av. Abund	Av. Sim	Sim/SD	Contrib%
Littorina Littorea	1.2	14.4	0.5	56
Ulva spp.	1.4	9.6	0.5	37
S Av. similarity 10 %	Av. Abund	Av. Sim	Sim/SD	Contrib%
Littorina Littorea	0.5	7.3	0.3	73
Ulva spp.	0.8	2.7	0.2	27

Table 5.5: Results of SIMPER analysis of average abundance of species on treatments on the seawall at Shaldon. Bray-Curtis dissimilarity in species asseblages between the treatments; recessed, R (n = 85), smooth control, C (n = 63), holes, H (n = 88), scratched, S (n = 80). Diss: dissimilarity; Diss/SD: a measure in the contribution of the species to similarities/ dissimilarities between pairs of samples; Contrib%: percentage contribution of the species to the average overall similarity between groups of treatments; Values of Sim/SD ≥1 indicated that the contribution of a given species to the percentage dissimilarity were consistent among pairwise comparisons of samples between treatments. Each species were considered important if its contribution to percentage similarity/ dissimilarity exceeded the arbitrary value of 3%.

a) Av. diss 91 %	**Recessed**	**control**	**Av.Diss**	**Diss/ SD**	**Contrib %**
Ulva spp.	2.0	0.0	30.3	0.9	33
Littorina littorea	1.4	0.5	28.8	0.9	32
Total barnacle spp.	0.8	0.3	14.4	0.7	16
Ligia sp.	0.7	0.0	7.7	0.4	*8*
Phorcus lineatus	0.5	0.0	6.3	0.7	*7*
b) Av. diss 75 %	**Recessed**	**Hole**	**Av.Diss**	**Diss/ SD**	**Contrib %**
Ulva spp.	2.0	1.4	1.1	1.1	36
Littorina littorea	1.4	1.2	1.0	1.0	30
Total barnacle spp.	0.8	0.0	0.6	0.6	11
Phorcus lineatus	0.7	0.3	0.8	0.8	10
Ligia sp.	0.5	0.0	0.4	0.4	7
c) Av. diss 90 %	**Control**	**Hole**	**Av.Diss**	**Diss/ SD**	**Contrib %**
Littorina littorea	0.5	1.2	39.3	1.0	44
Ulva spp.	0.0	1.4	31.8	0.9	35
Phorcus lineatus	0.0	0.3	6.7	0.5	8
Littorina saxitalis	0.1	0.2	4.9	0.5	5
d) Av. diss 87 %	**Recessed**	**Scratched**	**Av.Diss**	**Diss/ SD**	**Contrib %**
Ulva spp.	2.0	0.8	31.8	1.0	36
Littorina littorea	1.4	0.5	26.7	0.9	31
Total barnacle spp.	0.8	0.0	11.7	0.6	13
Ligia sp.	0.7	0.0	7.1	0.4	9
Phorcus lineatus	0.5	0.0	6.3	0.7	7
e) Av. diss 90 %	**Smooth**	**Scratched**	**Av.Diss**	**Diss/ SD**	**Contrib %**
Littorina littorea	0.5	0.5	48.5	1.1	54
Ulva spp.	0.0	0.8	24.9	0.6	27
Total barnacle spp.	0.3	0.0	9.3	0.5	11
f) Av. diss 85 %	**Hole**	**Scratched**	**Av.Diss**	**Diss/ SD**	**Contrib %**
Littorina littorea	1.2	0.5	35.5	1.0	42
Ulva spp.	1.4	0.8	35.0	1.0	34
Phorcus lineatus	0.3	0.0	6.5	0.6	8

5.3.2. Species assemblage consequences of a new seawall

Six species across five clases were recorded on the new wall, with the highest diversity attributed to the class Gastropoda (two species). Four species across two classes were recorded on the mature wall, Maxillopoda (two species) and Gastropoda (two species).

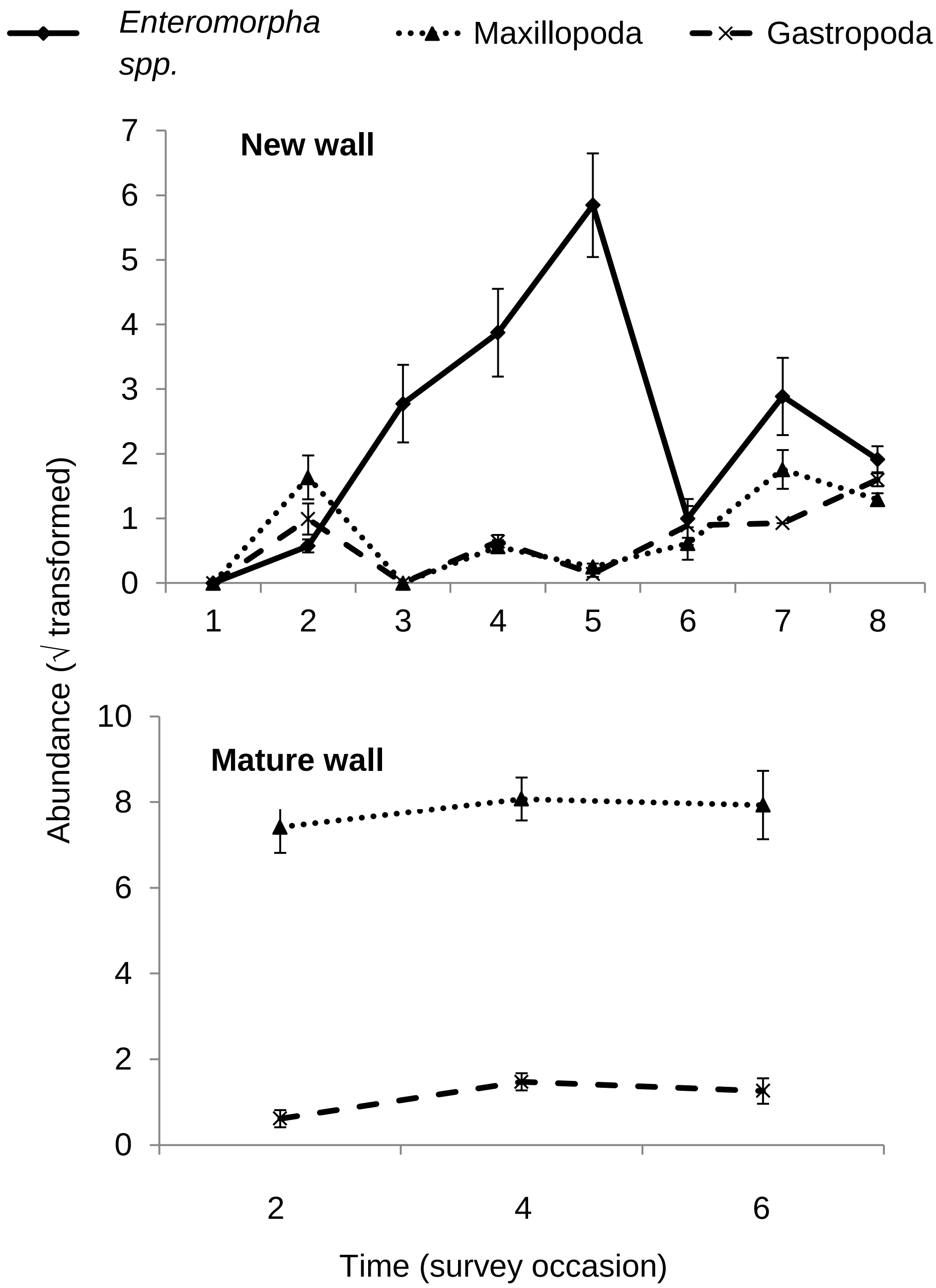


Figure 5.6: Species abundance (√ transformed) within taxonomic classes in assemblages observed outside the treatment area on the new wall and on an adjacent mature wall ($\bar{x}$ ±SE New wall n = 40; Mature wall n = 24)

Maxillopoda were the most abundant class, with the highest cover on both the new and the mature wall. Ulvophyceae were the class with the second highest cover on the new wall, and were absent from the mature wall. The remaining four classes were present in low abundance.

*Table 5.6: Species assemblages on surfaces of old and new wall at Shaldon, Devon. One-way ANOVA of site (random, 2 level: NW = New Wall, MW = Mature Wall). Significant P values in bold script. Post hoc Student-Newman-Kuels (SNK) comparisons, where ** p < 0.01, n = 12 for each level.*

	C	**MS**	***F***	***p***	***SNK***
Abundance	0.73	2460	9.82	**0.0048**	MW >NW **
Number of species	0.66	1.04	2.07	0.1165	

5.4. Discussion

5.4.1: Community consequences of habitat enhancement trials

In this study, the incorporation of habitat niches to a recently constructed seawall to influence species abundances and species richness during early colonisation was analysed. The habitats added were holes, shaded pools and scratched surfaces. It was expected that areas with added habitat would have a greater number of species than the smooth control areas. It was also expected that the different habitats may support distinct assemblages of species.

The number of species ($F_{3,20}$ = 4.63, p = 0.013, Table 5.2) differed significantly between the added habitats and smooth areas, referred to as treatments (Table 5.2). The recessed treatments had the greatest number of species, followed by the treatments with holes. The assemblages of species within treatments with recesses and holes were also more varied than the assemblages of species found in scratched and smooth treatments (Tables 5.3, 5.4 and 5.5, Figure 5.5a, b and c). Treatments with recesses and holes have an equal average similarity (Table 5.4, 26%) and relatively low dissimilarity (Table 5.5, 75%) compared to other comparisons of treatments. The presence of Ulva spp. and *L. littorea* contribute to this similarity.

L. littorea grazes on microorganisms and detritus, and is also known to feed on ulva spp. (Fish and Fish, 1996). After a pelagic phase, *L.littorea* will settle in crevices (Fish and Fish, 1996) and even where present on scratched and smooth surfaces the species seemed to take advantage of small naturally occurring crevices such as those created by the indentation in mortar between the blocks.

The Number of species and the assemblage of species found on the treatments with scratched surfaces and the smooth control were similar to each other (Table 5.2 and Figures 5.5a, b and c). Smooth and scratched treatments had an equal average similarity (Table 5.4, 10%), which is lower than the treatments with recesses and holes.

Recesses and holes were successful in providing habitat for a greater number of species and are a recommended addition to seawalls where increased species richness is desired.

Barnacles and the gastropod *P. lineatus* were unique to the recessed treatments; the gastropod *G. umbilicalis* and the Isopod *L. oceanica* were unique to the treatment with holes. No species were unique to the control or the treatment with the scratched surface. It is likely that as Ligia sp. are common in crevices on the upper shore and will emerge at night to feed on detritus and decaying seaweed (Hayward and Ryland, 1995) they occupied the treatments with holes because of the dark refuge created by the holes.

The overall abundance of species varied greatly across taxonomic classes and between treatments. Ulva spp. dominated the treatments with holes, scratches and the control with the smooth surface. Low cover of Ulva spp. in the recessed treatment areas may be explained by the unfavourable light conditions for plant species. Gastropods were more abundant in treatments with holes and recesses than the control and scratched treatment ($F_{3,20}$ = 19.14, p = < 0.001, Table 5.2); these are considered as treatments which create potential refuge from predators (i.e. birds and crabs) and shelter from desiccation.

5.4.2. Established species assemblage

Species assemblage on areas of the new wall with no treatments was compared to the established species assemblage on an adjacent section of mature wall. The mature wall experiences similar environmental conditions to the new wall, especially in respect to the position in the tidal frame, orientation to the sun and shore, and material type. It was expected that at the point in time when the mature wall and new wall supported similar assemblages of species, the new wall, and the treatments are likely to be supporting established assemblages.

In contrast to the higher cover of Ulva spp. on the new wall outside of the treatment areas and smooth control; barnacles and littorinids were dominant on the mature wall. However, with a longer period of time to establish (two seasons), on the new wall the Ulva spp. became less abundant and barnacles and littorinids increased in abundance. This suggests that assemblages found on the latter two survey occasions (month 23 and 33) were approaching that of an established species assemblage but had not yet reached an established climax assemblage.

The higher abundance of gastropoda on the treatment areas compared to the new and mature wall may be influenced by the grazing opportunity of Ulvophyceae in addition to the shelter created by the holes and recess. The absence and low cover of barnacles recorded within treatment areas may be a factor of the time required for the species to settle and establish within harder to reach spaces.

The community assemblages recorded outside of the treatments on the new wall and the adjacent mature wall were different, suggesting further that a climax assemblage had not been reached. It was assumed that if the climax assemblage had not been reached outside the treatments, the same was likely within the treatments. Hence further monitoring is necessary to reveal the ultimate effect of the experimental treatments on epibiota present; the preliminary findings of this trial were that addition of enhancements can lead to an increase in the diversity and abundance of intertidal organisms. The overall effect of biological enhancement in terms of mitigation need to be considered however in relation to the availability of existing habitat for epibiota, the prevailing diversity and abundance of epibiotic species and the potential for the new structure as a consequence of its elevation in the intertidal and adjacent sediment levels.

Opportunities were identified to increase the surface heterogeneity during the construction of a new seawall. Several methods were used to achieve modifications, as described above. The methods employed were practical and repeatable on a large scale with simple guidelines.

With consideration of the site, it can be expected that the vertical gradient from land to sea was one of the most influential to marine animals, with the rise and fall of the tide creating the most challenging physical conditions.

In designing the treatment positions on the new wall, three heights were considered necessary to increase the likelihood that some treatments would remain above the final sediment resting level and be available for colonisation. Upon completion of the new seawall, the seabed level settled in a position that covered a small number of the bottom treatments and left the top treatments close to the high water mark uncovered. Elevation is an important structuring force for species assemblages.

The new wall was rapidly colonised by marine organisms. Mobile species were first to be recorded in the plots, with high number of gastropod molluscs present just one month after completion. The numbers of gastropods declined markedly thereafter and it seems likely that initial high numbers were the result of individuals that had become displaced following removal of the sheet piling moving on to the wall from the seabed. All of the treatments and the wall itself were colonised by organisms within two months.

Experimental manipulations were constructed by an external contractor to specified designs and these were partially successful in creating the range of conditions anticipated. The pools leaked and water proofing had to be added in the spring after construction. Relief in the scratched treatment was also relatively shallow and after initial curing of the surface it was in many cases difficult to see any tangible difference between scratched surfaces and smooth surfaces. In addition, the final finish of the wall was in itself relatively heterogeneous with deep pointing around local stone blocks. Hence the additional habitats created by the experimental treatments were less than that which would have been created were they placed in a more homogeneous wall surface.

On the seawall at Shaldon recesses and holes were successful in providing habitat and refuge to increase the species richness of an artificial structure. Other examples of successful environmental design and retrofitted modifications provide shaded pool habitat on seawalls.

Chapman and Blockley (2009) engineered novel habitats on a seawall in Sydney harbour to increase intertidal biodiversity. During the construction of a seawall they created water retaining features by omitting a large sandstone block and in its place adding a sandstone lip, and a temporary sandbag. Diversity was increased both by the pool environment and the creation of shaded surfaces. Browne and Chapman (2011) added water retaining features to existing walls in the form of flowerpots with a flat back. The flowerpots that survived the environmental conditions were successful in increasing species richness by 110 % and in increasing the diversity of mobile species which are not normally able to survive on the vertical faces of seawalls.

Firth *et al.* (2012) produced and installed a large-scale precast habitat-enhancement unit ('BIOBLOCK') into a new coastal defence scheme at Cowlyn Bay, Wales. The BIOBLOCK is a large precast concrete unit that can be installed into riprap structures (breakwaters, groynes, rock revetment) either during the construction phase or retrospectively (Firth *et al.* 2012). The 1.5 × 1.5 × 1.1 m unit incorporated different habitat types including pools of two diameters and two depths; pits of two depths; and, longitudinal crevices. The colonising epibiota were compared to that on adjacent granite boulders. Thus far, five months after the BIOBLOCK was installed, results showed that the larger deeper pool habitats support greater biodiversity than small, shallow pools which in turn support a greater number of species than pits and crevices or bare substrata (Firth *et al*. 2012).

Continued trials of different design are important to improve the accuracy of environmental design to the desired outcome, which in many cases is to resemble as far as possible the nearest natural equivalent habitat, such as the species rich rocky shore.

Chapter 6
General discussion

6.1. Summary of main findings

In this final overview section I first outline my main findings, before considering the similarities and the differences between natural and artificial hard substrate assemblages. I then make recommendations for future implementation before outlining future research and demonstration projects. Understanding what man-made habitats occur and how they function on artificial structures in coastal environments is fundamental to creating successful design to promote marine biodiversity or other desired goals (Airoldi *et al*. 2005; Bulleri and Chapman, 2010; Chapman and Blockey, 2009; Firth *et al.* 2013). In the first instance when considering possible ecological enhancement on artificial structures the factors which are controllable must be considered, followed by practicality in conjunction with the most likely design to give the desired result. Some general uncontrollable and controllable factors are listed in Moscella *et al.* (2008) and Firth *et al*. (2012). The extent of control for some of the factors will be context dependant and hence site specific. I examined features on existing structures to identify their influence and consider their replicability for consideration in future designs of new structures as controllable factors for the purpose of adding habitat complexity. Although factors such as wave action and tidal range are listed as uncontrollable in themselves, it may be possible to control and thus abate the influence of these uncontrollable factors by siting of structures or by providing shelter.

My observations on existing artificial structures such as seawalls and breakwaters provide evidence that design features provide habitat which support distinct assemblages of species, furthermore, that a greater variation in the type of features will in turn lead to a higher species diversity occupying the structure. Some features, such as those which retain water and create pools will support species that would otherwise not be present on the structure.

The results from all of the manipulation experiments I have carried out in this thesis support the hypotheses that the assemblages of species differ in composition and diversity between habitats. Rock pools, surface heterogeneity, slope, orientation and shade provide habitat for the settlement and survival of many epibiotic marine species. Combinations of these habitat types are also beneficial in supporting species that would otherwise not be present in the local area, for example shaded pools. The incorporation of variability in habitat types will support distinct assemblages and promote local biodiversity. It is expected that examination of further combinations of habitat, such as shaded slope with surface heterogeneity, will support additional species and different assemblages to the surrounding area.

The study of species succession on artificial structures in chapter 3 of this thesis provides evidence on the type of assemblage that can be expected; with an initial high cover of ephemerals, followed by the arrival and dominance of limpets, and their subsequent reduction and stabilisation with fucoids and barnacles. The results indicate that the time taken for an assemblage to establish and fluctuate around equilibrium is 4 to 16 years. Weathering and erosion happens quickly in coastal areas as water circulation, wave action and water transported material causing scour are regular occurrences. Flaking and cracking of the surface substrate, particularly around the edges, is common on older structures. Long term patterns of succession, in conjunction with a measure of material changes over time, can indicate possible changes in assemblage with time and inform expected changes in assemblages on modified and unmodified units with the natural weathering and aging process. This can lead to a different community end-point on weathered structures.

Similarities and differences with Rocky Shores

Any hard substrate put into the sea will be colonised whether natural or artificial. When this occurs on ships and structures it is often considered fouling. Artificial structures have been successfully used as model rocky shore systems to understand distribution patterns (Southward and Orton, 1954), successional processes (Hawkins *et al.* 1983) and the respective roles of physical disturbance and biological interactions on distribution patterns (Jonsson *et al.* 2006). All these studies used rocky shore as simplified systems. *Thompson et al*. (2002) considered artificial hard substrates to be analogous to rocky shore, as did Moschella *et al.* (2005). However, both these papers emphasized their simplified nature.

More recently, various authors have emphasized that artificial habitats differ from natural rocky shores: they are typically less diverse (Bulleri and Chapman, 2004; Chapman and Bulleri, 2003; Gacia *et al.,* 2007; Moschella *et al.* Southward and Orton*,* 1954; Vaselli *et al.,* 2008). There are various reasons for this lower diversity. Artificial habitats are less topographically complex than natural shore, at various scales from millimetre to centimetre (*i.e.* surface roughness), centimetre to metre (*i.e.* cracks, crevices, rock pools and overhangs), metre to tens of metres (*i.e.* gulley's, outcrops and large pools) and tens of hundreds of meters (*i.e*. variation in tidal height and wave action related gradients).

The lesser extent of artificial shores reduces diversity due to the species-area relationship. As artificial structure are usually placed on the interface of sedimentary or eroding environments, disturbance due to scour is much greater, reducing diversity when extreme. Artificial structures are often newly placed in the sea, and thus successional processes have not led to increases in species number, the exception being long-lived structures such as Plymouth Breakwater, built in 1812. Frequent maintenance can also lead to disturbance, re-setting succession and decreasing diversity.

Comparison of artificial structures is often made to the nearest natural equivalent habitat, the rocky shore. Rocky shores are diverse and intrinsically attractive environments. Thus the environmental enhancement of artificial structures towards resembling a natural rocky shore type of environment is beneficial. There is much information we can draw in from comparative studies between natural and artificial shores to demonstrate habitat value and to evidence likely influence of specific features and strengthen the success of various habitat enhancements. Clear foundations for design trials will extend from consideration of the factors which give these natural habitats biological richness, *i.e.* suitable habitats created by localised features to accommodate different species, and life stages of species.

Engineering enhancement can be carried out during the construction stage or retrospectively. Generally, modification at the construction or maintenance phase will provide greater opportunity for larger scale enhancements, taking advantage of the construction process, machinery and expertise available on site. Opportunities for large scale enhancement are limited; thus smaller scale demonstration trials, which are in some ways easier to arrange and perform, become valuable to provide the evidence that is essential to inform larger scale enhancements to increase their success.

Recommendations for increasing habitat and species diversity

Artificial structures of large extent eventually resemble natural rocky shores of the same exposure (Chapter 3). To increase the resemblance of artificial structures to rocky shores, specific modifications to artificial structures are recommended to increase habitat and species diversity. Based on the findings of chapters two and four of this study on existing structures and their modification, the addition of holes of different diameter and on surfaces of different orientation is recommended to increase habitat diversity on structures, which can be added with greatest ease to new concrete that has not cured. We found evidence that slope also influenced species present on structures, thus adding holes on surfaces of different slope is also recommended for increased habitat diversity.

Based on the findings of chapter five of this study during the construction of a new seawall, the addition of holes, shaded pools and scratched surfaces were created with ease. Holes and shaded pools were particularly successful in supporting species that would not have been present without the habitat creation, and are a recommended addition to intertidal seawalls and structures where the aim is to increase habitat and species diversity. Opportunities to add pools and holes on surfaces of different orientation and slope should be used for additional habitat diversity.

Future research and demonstration needs

The influence of features on intertidal epibiota will be site specific, as multiple factors, such as geographic location, species recruitment and even season of construction, will interact. For this reason, to strengthen the findings of this study, further example sites should be identified and tested. Additional types of feature should also be investigated, for example, the small irregular pools created by erosion (Figure 6.1). It was considered that coastal defences are too often described as uniform, although there are a plethora of features that provide areas of different habitat. Local enhancement of diversity can scale up to larger scales such as a whole structure.

Figure 6.0.1: An example of a irregular pool created by the erosion of a drilled hole, which were made as a consequence of construction process.

Scheme implementation

My research, like that of Chapman and colleagues on the modifications on seawalls, and of Firth and colleagues with the BIOBLOCK and drill-cored, required close collaborations between ecologists and engineers; the latter were very responsive to the benefits of artificial habitat enhancement. Constraints are inevitable, for example the moulds for the breakwater armour units are very expensive and manipulations had to be made to the surface only, or after the mould had been removed. However, opportunities can often be found during construction and maintenance processes. For example, further manipulations on the top of the armour units at Plymouth Breakwater could easily be performed, perhaps in conjunction with the research on the BIOBLOCKs, with modifications of different pool dimensions to match those on the BIOBLOCK to further inform the likely outcomes of these design features. Also, further manipulations on the side of the units, for example the use of a chisel to create a groove with an overhang and shade may be possible immediately after the mould is removed, before the concrete hardens with an increase in time.

The tide and weather constrain the time available to perform the manipulations, and in turn influenced the scoped trial modifications. Heavy tools are difficult to carry in rocky, coastal environments; and mains power driven tools can be hazardous in the wet environment. Similar problems were also recognised by Firth *et al*. (2012) during the drill-core rock pool creation at Tywyn. The identification of easier and speedier methods for modification could improve the experimental designs of evidence gathering trials and create more enthusiasm for implementation in real schemes, if manipulations can be achieved with greater ease. A possible method worthy of investigation is the use of a stonemasonry chisel on concrete that has not fully cured. A chisel could be used in the rain without the hazard and restriction of using electrical equipment in a wet environment.

The tidal level to which a structure is placed will influence the colonising assemblage of species, generally with a higher diversity of species on structures placed in the lower shore. The position in the tidal frame of any engineering enhancements will influence the outcome. The suitability of a potential habitat and the relative importance of the habitat to the local population will be influenced by position within the tidal frame. Species need to be able to access the habitats. Suitable habitats on artificial structures that are regularly submersed by the tide will increase colonisation and survival of many species. Where habitats are located high in the tidal frame, sustained emersion for duration that is greater than one tide cycle will result in deterioration of conditions, which is likely to be beyond the survival capability of many species, unless pools or crevices acting as refuges from physical stresses are put in place (Skov *et al*. 2011)

The extent of the structure will govern the extent of modification possible. There will be an optimum distance between added holes, or other habitats. The increased number of species in the experimental area surrounding modification with drilled holes compared to a control area without modification indicated a halo effect, which is expected to extend with time to influence an increasingly larger area. Understanding the halo effect will inform the distance that suitable habitat should be created from one another and the optimum extent of suitable habitat.

There will be a host of scenarios depending on environment context. Performing field trials and collating information will help inform possible outcomes. Site specific studies and trials are required to identify the desired outcome, the possible outcomes and the best method to achieve the desired outcome.

Other features of existing structures to those examined in my thesis should be investigated to build on the evidence needed to persuade engineers and stakeholders that the effort to incorporate design features will give a rewarding environmental benefit. Resulting assemblages from different design will be very site specific, assessing different types of design and examining the impact of factors such as position of the design features in the tide frame will aid to inform future research trials and demonstration projects.

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