An assessment of the interactions between maritime built heritage and the marine wildlife it supports



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Abstract

Representing an important component of coastal infrastructure in the UK and around the world, historic maritime structures with a traditional block-masonry design (e.g. historic seawalls, harbours, breakwaters, etc.) are valued as heritage assets and for the functional benefits they provide coastal communities. Due to their age and traditional construction, stone-built heritage assets may also provide important, but largely unrecognised, benefits to marine wildlife. At the same time, colonising wildlife may either enhance or retard damaging weathering and erosional processes acting on a structure and/or transform the values associated with heritage sites. As of yet, however, the interrelationships between stone-built heritage and marine wildlife are poorly understood.

By adopting an interdisciplinary, multi-method approach that draws on methods and understanding from geomorphology, heritage science, and marine ecology, this thesis investigates the two-way interactions and feedbacks between stone-built heritage and marine wildlife as well as potential opportunities for joint wildlife-heritage conservation.

A perception study was used to identify current management practices and attitudes towards marine wildlife by asset managers responsible for the conservation of stone-built heritage assets. Perceived gaps in research relating to wildlife-heritage interactions that were identified in this study were used to inform subsequent fieldwork. A field-block exposure trial was used to evaluate the impacts of seaweed growth on the deterioration of natural-cement-based mortar, a material regularly used in built heritage restoration. Ecology surveys and physical habitat assessments at several locations across the UK were then used to determine the ecological value of heritage assets in comparison to natural rocky cliffs and modern concrete infrastructure. Finally, a novel methodology for identifying priorities for the joint conservation of cultural heritage and marine wildlife was developed, applied, and tested on the Isles of Scilly.

Given the broad geographical scope of this research, the results are relevant to other stone-built heritage sites in the UK and further afield. The main findings showed that: (i) attitudes towards marine growth are generally in agreement among practitioners, however concerns exist regarding the impacts of marine wildlife on maintenance regimes, the condition of mortar, and health and safety; (ii) seaweed does not significantly enhance the deterioration of natural cement-based mortar during the first few months of exposure, and instead, may provide broadly bioprotective functions; (iii) historic masonry walls support more diverse ecological communities than modern concrete infrastructure, and in some locations, nearby rocky cliffs; (iv) combined ecological-heritage evaluations allow for the identification of structures with the greatest potential for the joint conservation of built heritage and marine wildlife.

Together, these findings have significant implications for the sustainable management of stone-built heritage and marine wildlife. Future work is now needed to develop management strategies designed to deliver joint wildlife-heritage conservation goals in response to growing threats from coastal urbanisation and climate change.

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List of Abbreviations

AI	Agreement Index
BST	British Summer Time
BTM	Benthic Terrain Modeler
CNQ	Carn Near Quay
CPS	Conservation Priority Score
CS	Construction Score
CSHER	Cornwall and Scilly Historic Environment Record
CT	Carn Thomas Lifeboat Station
DEM	Digital Elevation Model
EA	Environment Agency
EMODnet	European Marine Observation and Data Network
EPS	Ecological Potential Score
GLMM	Generalised Linear Mixed Effects Model
GMT	Greenwich Mean Time
H’	Shannon-Wiener Index
HAR	Heritage at Risk
HER	Historic Environment Record
HL	‘Leeb’ value
HTBO	Hugh Town Beach Outflow
HTQ	Hugh Town Old Quay
HTSR	Hugh Town Shipyard Remains
HTSW	Hugh Town Beach Seawall
HVS	Heritage Value Score
INNS	Invasive Non-Native Species
IQR	Interquartile range
LEDs	Light Emitting Diodes
LiDAR	Light Detection and Ranging
LMM	Linear Mixed Effects Model
MarLIN	Marine Life Information Network
MCZ	Marine Conservation Zones
MHWN	Mean High Water Neap
MLWN	Mean Low Water Neap
N	Abundance
NBN	National Biodiversity Network
NHLE	National Heritage List for England
nMDS	Non-metric multidimensional scaling
NNSS	Non-Native Species Secretariat
OS	Ordnance Survey
OTQ	Old Town Quay
OTSL	Old Town Slipway
OTSW	Old Town Seawall (West)
PCRA	Porth Cressa Rock Armour
PERMANOVA	Permutational Multivariate Analysis of Variance
PHO	Porth Hellick Outflow
PHQ	Porth Hellick Quay
PMRA	Porth Minick Rock Armour
PUNDIT	Portable Ultrasonic Non-destructive Digital Indicating Tester
R	Species Richness
Ra	Arithmetic roughness
R_C	Total species richness of cryptic microhabitats
RCZA	Rapid Coastal Zone Assessment
RII	Relative Importance Index
R_Q	Species Richness of Quadrats

R_s	Spearman-rank Coefficient
R_T	Total species richness
S	Slope
SAC	Special Areas of Conservation
SEAHA	Science and Engineering in Arts, Heritage, and Archaeology
SfM	Structure from Motion (Photogrammetry)
SIA	Stable Isotopic Analysis
SIM	Single Impact Method
SIMPER	Analysis of Similarity Percentages
S_{sqrt}	Square-root Slope
SSSI	Site of Special Scientific Interest
SWRCMP	South West Regional Coastal Monitoring Programme
$T_{\Delta 30}$	Mean daily highest rate of change in temperature over consecutive 30-min periods
THS	Tidal Height Score
T_{max}	Mean daily temperature maxima
T_{min}	Mean daily temperature minima
T_{range}	Mean daily temperature range
UKHMA	UK Harbour Masters' Association
UPV	Ultrasonic Pulse Velocity
vp	Propagation Velocity

Section 1.

Research Context and Design



Marine wildlife on a historic masonry wall
Drawn by Hope Calloway

Chapter 1.

Introduction

1.1 Maritime built heritage and marine wildlife

Historic masonry walls represent an important component of cultural heritage in marine and coastal environments around the world. Valued as unique heritage assets as well as structural components of larger heritage sites (e.g. historic harbours, breakwaters), walls with traditional block-masonry designs have important historic, scientific, aesthetic, economic, and cultural values, in addition to functional benefits (e.g. coastal protection) associated with their use (Cork and Chamberlain, 2015). As well as being tangible heritage assets, historic masonry walls provide context to intangible aspects of culture such as traditional practices, skills, stories, and languages associated with the coast and the structures they are integrated within (Carmichael et al., 2018; Claesson, 2011; Firth, 2015; Howard and Pinder, 2003). As noted by Brabec and Chilton (2015, p268), "…objects of tangible heritage have meaning only because of the intangible values societies place on them, and intangible heritage almost always has an expression in tangible products…".

As with other aspects of maritime built heritage (e.g. shipwrecks), stone-built heritage is intrinsically related to its surrounding environment (Richards et al., 2019). For instance, the environment modifies masonry walls through deteriorative weathering processes, provides materials for their construction and repair (e.g. quarried stone), and contributes to the values associated with them (e.g. aesthetics). At the same time, historic masonry walls modify the environment by altering habitat composition and connectivity (e.g. Bishop et al., 2017) and by influencing environmental processes and dynamics (e.g. sediment transportation, hydrodynamics, microclimates; Dafforn et al., 2015). Given the complexity of these two-way interactions, the effective interpretation, conservation, engagement, and sustainable long-term management of historic masonry walls and

other aspects of maritime built heritage can only be realised by viewing them within the context of their surrounding environment (Richards et al., 2019).

One aspect of the environment that interacts with built heritage assets, but that has been generally overlooked in the context of stone-built heritage, is marine wildlife. The age, traditional design, and decay mechanisms associated with historic masonry walls means they may provide important, but largely unrecognised, benefits to marine wildlife (Ferraby, 2007). For instance, crevices found between adjacent stones in mortared and drystone configurations may provide cryptic habitat space (i.e. the interstitial space between blocks) and refugia for a range of sessile and mobile species (e.g. Chapman and Blockley, 2009; Dugan et al., 2011; Johnson et al., 1998; Moreira, 2006; Moreira et al., 2007). At the same time, colonising wildlife may either enhance or retard deteriorative weathering processes acting on a structure (e.g. Bone et al., 2022b; Coombes, 2014; Davidson et al., 2018; Naylor et al., 2012b), and/or contribute to the value of a heritage site through the provision of additional benefits and services (e.g. ecosystem services; Burdon et al., 2017; Potts et al., 2014). As of yet, however, the two-way interactions and feedbacks between historic masonry walls and marine wildlife are relatively understudied (López, 2019). Furthermore, there is limited understanding of how marine growth is perceived by those responsible for managing stone-built heritage sites. Such attitudes are important to understand as they will shape how marine growth is managed on historic masonry walls, which in turn may influence biodiversity and built heritage conservation and any associated values (Coombes and Viles, 2021).

Given the potential ecological benefits of maritime built heritage and the uncertainty surrounding the net impact of marine growth on the conservation of these structures, there is an urgent need to investigate the interrelationships between historic masonry walls and marine wildlife as well as practices and attitudes towards marine growth, and any values, services, and benefits associated with wildlife-heritage interactions. Considering that both maritime built heritage and marine wildlife is increasingly threatened by future effects of climate change (e.g. coastal erosion, sea level rise,

habitat destruction) and coastal urbanisation (e.g. Harkin et al., 2020; Hayhow et al., 2019; Hunt, 2011; Murphy et al., 2013; Sesana et al., 2021; Wyatt and Prizeman, 2018), understanding the two-way interactions between historic masonry walls and the wildlife it supports is more important than ever.

Research on wildlife-heritage interactions can, in particular, draw on methods and understanding from geomorphology, heritage science, and marine ecology. Geomorphology studies the origin and evolution of landforms and landscapes (Goudie, 2004) and encompasses the sub-discipline of biogeomorphology that focuses on understanding the contribution of organisms (i.e. plants, animals, microorganisms) to landscape evolution as well as the impacts of geomorphological processes and landforms on the distribution and dynamics of biodiversity (Viles, 1988). Over the last few decades, analytical approaches and understandings from geomorphology (and biogeomorphology) have increasingly been used to study cultural and natural heritage, contributing to the emergence of heritage science as an interdisciplinary domain of scientific enquiry (Naylor et al., 2002; Viles, 2019). For example, methods used in geomorphology to study the impact of environmental factors on rock breakdown have increasingly been used to investigate drivers of deterioration on built heritage assets constructed of natural materials, such as quarried stone or rammed earth (e.g. André et al., 2012; Coombes et al., 2018; Richards, 2020; Richards et al., 2020). Consequently, many concepts (e.g. spatial and temporal scale, magnitude and frequency) and methods (e.g. field-based research) associated with geomorphology—and especially those related to biogeomorphology and heritage science—are highly relevant for understanding how marine wildlife modifies built heritage assets, including historic masonry walls.

Marine ecology, on the other hand, studies marine wildlife and its interactions with the surrounding environment. This includes the impact of abiotic (e.g. non-living physical and chemical factors) and biotic factors (e.g. interactions associated with living organisms) on ecological processes and dynamics (Hall-Spencer, 2020). Over the last few decades, the proliferation of marine infrastructure

(e.g. coastal defences, offshore wind farms) in response to coastal urbanisation and the threats associated with climate change (e.g. sea-level rise) has led to growing concern regarding the ecological impacts of artificial structures (Firth et al., 2016b). Consequently, marine ecology research has increasingly focused on developing new ways of investigating the impacts of human activities on marine ecosystems (see Firth et al., 2016b for a recent review) as well as solutions for enhancing the biodiversity of artificial structures (referred to as "ecological engineering"; MacArthur et al., 2019; Naylor et al., 2017a; O'Shaughnessy et al., 2019; Strain et al., 2018). Although the ecological communities associated with historic masonry walls have, so far, been overlooked, recent advances in methods and understanding relating to the impact of modern structures on marine communities makes marine ecology highly applicable for investigating wildlife-heritage interactions in marine and coastal environments.

1.2 Overview of thesis

This thesis uses an interdisciplinary approach drawing on methods and understanding from geomorphology, heritage science, and marine ecology to investigate the two-way interactions and feedbacks between stone-built heritage and marine wildlife as well as potential opportunities for joint heritage-ecology conservation.

To ensure the outcomes of my research are relevant to both researchers and practitioners, this thesis directly addresses gaps in evidence and understanding identified through a literature review (Section 1, Chapter 2) and a preliminary survey of marine managers responsible for conserving maritime built heritage and marine wildlife (Section 2, Chapter 4, Paper 1). Despite focusing on wildlife-heritage interactions along UK coastlines, the methodologies and findings discussed are applicable to other heritage sites in marine and coastal environments around the world.

This thesis is article-based; the main body of work is presented as a series of academic papers that have been published in peer reviewed journals (Sections 2–4; Fig. 1.1). These papers are

accompanied by an introductory section which provides an overview of the literature and outlines the research context and design (Section 1, Chapter 2), and a final discussions and conclusions section that reflects on the main findings of the papers as well as their implications within a wider research context (Section 5, Chapter 8). Each paper is presented in its submitted/published format, and includes its own introduction, methods, results, discussion, and conclusions. A statement of author contribution for each paper is provided in Appendix A.

Section 1 provides an overview of the current understanding of wildlife-heritage interactions and feedbacks in marine and coastal environments from which the aims and objectives of the thesis were derived. A literature review is provided at the beginning of this section (Chapter 2), which is structured as follows: (i) Marine human development; (ii) The ecological impacts of built heritage; (iii) Coastal biogeomorphology; (iv) Broader conceptual frameworks for wildlife-heritage interactions: ecosystem services and values; (v) Research methods and challenges. While this section reviews the current research landscape, due to the paper-based format of this thesis, relevant contextual material is also given in the introductory parts of each paper in Sections 2-4. For instance, factors associated with historic masonry walls that may favour colonisation by marine wildlife are discussed in detail in the introductions of Paper 3 (Section 3, Chapter 6) and Paper 4 (Section 4, Chapter 7).

Section 2 establishes current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage. Paper 1 uses a perception study to determine the perceived gaps in research, evidence, and guidance relating to the management of marine growth. The findings of the perception study were used in combination with the literature review (Section 1, Chapter 2) to help develop and guide subsequent research presented in Sections 3 and 4.

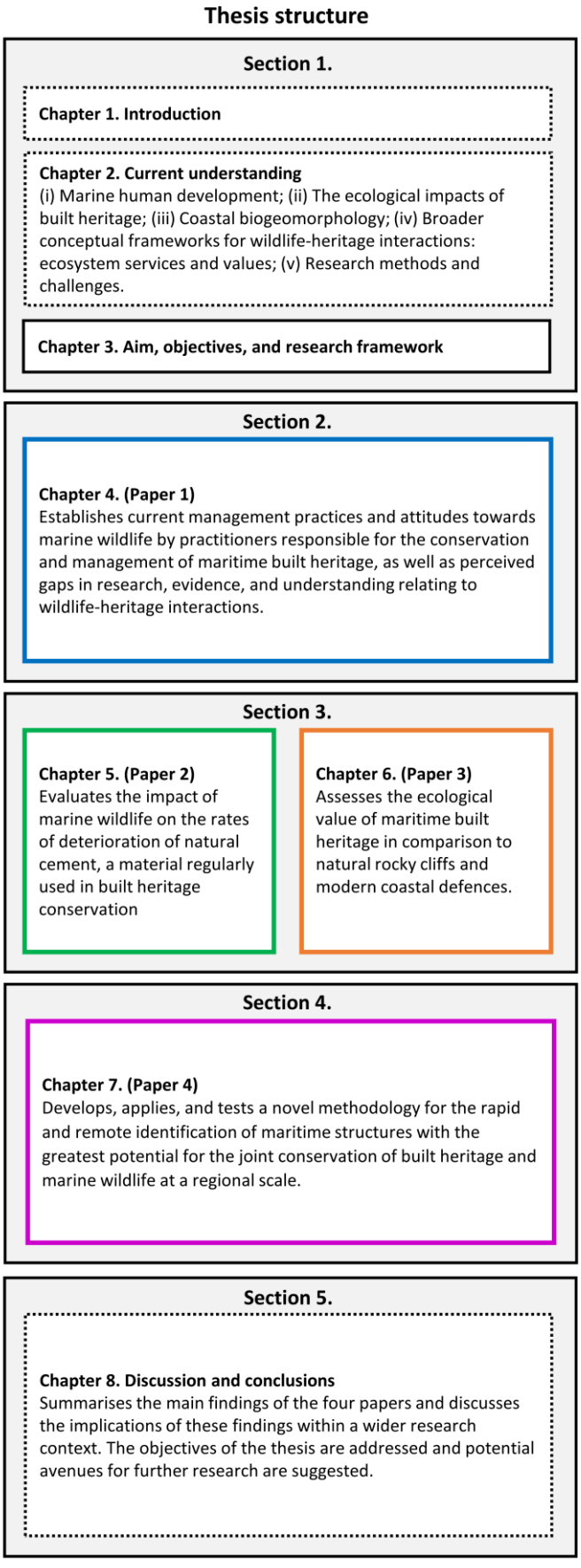


Fig. 1.1. Thesis structure.

Section 3 investigates the interactions and feedbacks between historic masonry walls and marine wildlife using field experiments and complementary laboratory analysis. Paper 2 (Chapter 5) uses a field block exposure trial to evaluate the impact of marine wildlife on the rates of deterioration of natural cement, a material regularly used in the construction and repair of maritime built heritage. Paper 3 (Chapter 6) uses ecology surveys and physical habitat assessments to compare the ecological value of historic masonry walls to concrete walls and natural rocky cliffs at several locations across the UK.

Section 4 presents a novel methodology for the rapid and remote identification of maritime structures with the greatest potential for the joint conservation of built heritage and marine wildlife at a regional scale. Paper 4 (Chapter 7) develops, applies, and tests this methodology on the Isles of Scilly using desk-based research that is validated through ground truthing to (i) create a full inventory of maritime structures along the entire coastline of the archipelago, (ii) evaluate the ecological potential and heritage value of each structure, (iii) identify 'conservation priority structures' for both heritage and marine biodiversity, and (iv) provide an initial assessment of intervention opportunities for enhancing joint heritage and biodiversity conservation.

Lastly, Section 5 summarises the main findings of the four papers and discusses the implications of these findings within a wider research context. The objectives of the thesis are addressed and potential avenues for further research are suggested. In addition, three opportunities for advancing research in wildlife-heritage interactions and the practical conservation of maritime heritage and marine wildlife are discussed. Specifically, these opportunities relate to: (i) the application of this research to other heritage sites; (ii) using an interdisciplinary, multi-method approach to advance understanding of wildlife-heritage interactions, and; (iii) developing practical solutions for joint wildlife-heritage conservation. Finally, potential future effects of coastal urbanisation and climate change on wildlife-heritage interactions are considered. Appendices containing supplementary

work are included at the end of the thesis, which are referenced throughout the main text where appropriate.

1.3 Funding and supporting partners

The research has been undertaken within the EPSRC SEAHA (Science and Engineering in Arts, Heritage, and Archaeology) Centre for Doctoral Training in collaboration with Historic England and Artecology. Historic England is an executive non-departmental public body of the British Government responsible for protecting and championing the historic environment in England, and Artecology is the research and development department of Arc Biodiversity and Climate, an environmental consultancy group based on the Isle of Wight. Both collaborators have provided expertise and guidance on the project to ensure that findings have the potential to inform the conservation management strategies of stone-built heritage and biodiversity in marine environments.

Chapter 2.

Current understanding

This chapter reviews current understanding of wildlife-heritage interactions and feedbacks in marine and coastal environments. It starts with an overview of human development influences on the marine environment, with a particular focus on modern artificial structures (i.e. built pre-1900), and then considers the likely ecological responses to built heritage by reviewing existing evidence from both terrestrial and marine environments. This is followed by a review of biogeomorphological concepts relevant to the interactions between stone-built structures and marine organisms. The broader implications of structure colonisation, including those of heritage and amenity value, are then considered. The final section reviews the benefits and challenges associated with methods used to investigate ecological processes and dynamics, biogeomorphological interactions, and how these processes are interpreted or perceived. Throughout this chapter, specific gaps in knowledge are identified and used to formulate research objectives.

2.1 Marine human development

Human populations have built artificial structures in marine and coastal environments for millennia (Bugnot et al., 2020). Throughout history, marine infrastructure has been developed to support maritime transport and trade, resource exploitation (e.g. aquaculture, fishing, offshore energy production), and to protect against coastal flooding (Fig. 2.1). Over the last few decades, there has been a rapid expansion of maritime structures around the world (Airoldi et al., 2021; Bugnot et al., 2020; Claassens et al., 2022; Firth et al., 2016b; Halpern et al., 2015). For example, it is estimated that over 50% of natural shorelines in parts of Europe, North America, Asia, Australia, and New Zealand have been replaced by seawalls, breakwaters, and other hard structures (Airoldi and Beck, 2007; Chapman and Bulleri, 2003; Davis et al., 2002; Floerl et al., 2021; Gittman et al., 2015). Termed ‘ocean sprawl’ (Bishop et al., 2017; Dafforn et al., 2015; Duarte et al., 2013; Firth et al., 2016b; Heery et al., 2017), the proliferation of maritime structures is predicted to increase into the twenty-first

century in response to burgeoning coastal populations, expanding coastal cities, and the threats associated with climate change, such as sea level rise and increased storm frequency (Bulleri and Chapman, 2010; Dugan et al., 2011; Floerl et al., 2021; Thompson et al., 2002). Growing concern over rapidly expanding marine and coastal infrastructure has driven an increase in research investigating the ecological impacts of ocean sprawl (Firth et al., 2016b) as well as strategies to mitigate these impacts and improve the overall sustainability of coastal developments (i.e. ecological engineering; Chapman and Underwood, 2011; Dyson and Yocom, 2014; Naylor et al., 2017a; O'Shaughnessy et al., 2019; Strain et al., 2018). With a few exceptions, research has predominantly focused on investigating the ecological processes and dynamics associated with modern infrastructure built from concrete and other engineering materials (e.g. metal and natural rock armour) since the beginning of the twentieth century (e.g. Airoldi et al., 2015; Bacchiocchi and Airoldi, 2003; Momota and Hosokawa, 2021; Vaselli et al., 2008).

Artificial structures modify marine habitats through (i) direct physical disturbance during construction, (ii) the addition of artificial habitats that alters habitat composition (e.g. substrate material, complexity, etc.) and connectivity, (iii) indirect physical disturbance caused by changes in water movement, sediment transportation, and altered turbidity, and (iv) changes in noise and light pollution (Dafforn et al., 2015). Once established within marine environments, a combination of dynamic, complex, and interacting biotic and abiotic factors influences marine communities on artificial structures (Firth et al., 2016b). In addition to community interactions and dynamics, these factors relate to environmental and anthropogenic factors as well as structure design and age as summarised in Fig. 2.2.

Although artificial structures have previously been considered as surrogates for natural habitats (e.g. Bulleri and Chapman, 2004; Hawkins et al., 1983; Holloway and Field, 2020; Thompson et al., 2002), comparative studies repeatedly show distinct differences in community structure and functioning between artificial structures and natural rocky shores/reefs (Firth et al., 2016b; Megina et al., 2012;

Momota and Hosokawa, 2021). In some cases, artificial structures have been shown to increase diversity and abundance (Chou and Lim, 1986; Connell and Glasby, 1999; Munsch et al., 2014; Wehkamp and Fischer, 2013) and provide habitats for taxa that are not found on natural rocky reefs (Andersson et al., 2009; Bulleri and Chapman, 2004; Chapman, 2003). In general, however, artificial structures are considered to be ecologically poor compared to natural habitats (Aguilera et al., 2014; Chapman and Bulleri, 2003; Moschella et al., 2005; Pister, 2009) as they alter ecological connectivity (Bishop et al., 2017), attract and promote the spread of non-native and invasive species (Airoldi et al., 2015; Bulleri and Airoldi, 2005; Glasby et al., 2007; Mineur et al., 2012; Vaselli et al., 2008), and typically support younger, less diverse assemblages of marine organisms (Connell and Glasby, 1999; Moschella et al., 2005; Pister, 2009). Furthermore, compared to natural shores, marine organisms associated with artificial structures have also been shown to be smaller in individual size (Diaz-Agras et al., 2010), male dominated (Earp et al., 2023), at greater risk of dislodgement (Drakard et al., 2021), and have lower genetic diversity (Fauvelot et al., 2009; Sammarco et al., 2012) and reduced reproductive output (Drakard et al., 2021; Moreira, 2006).

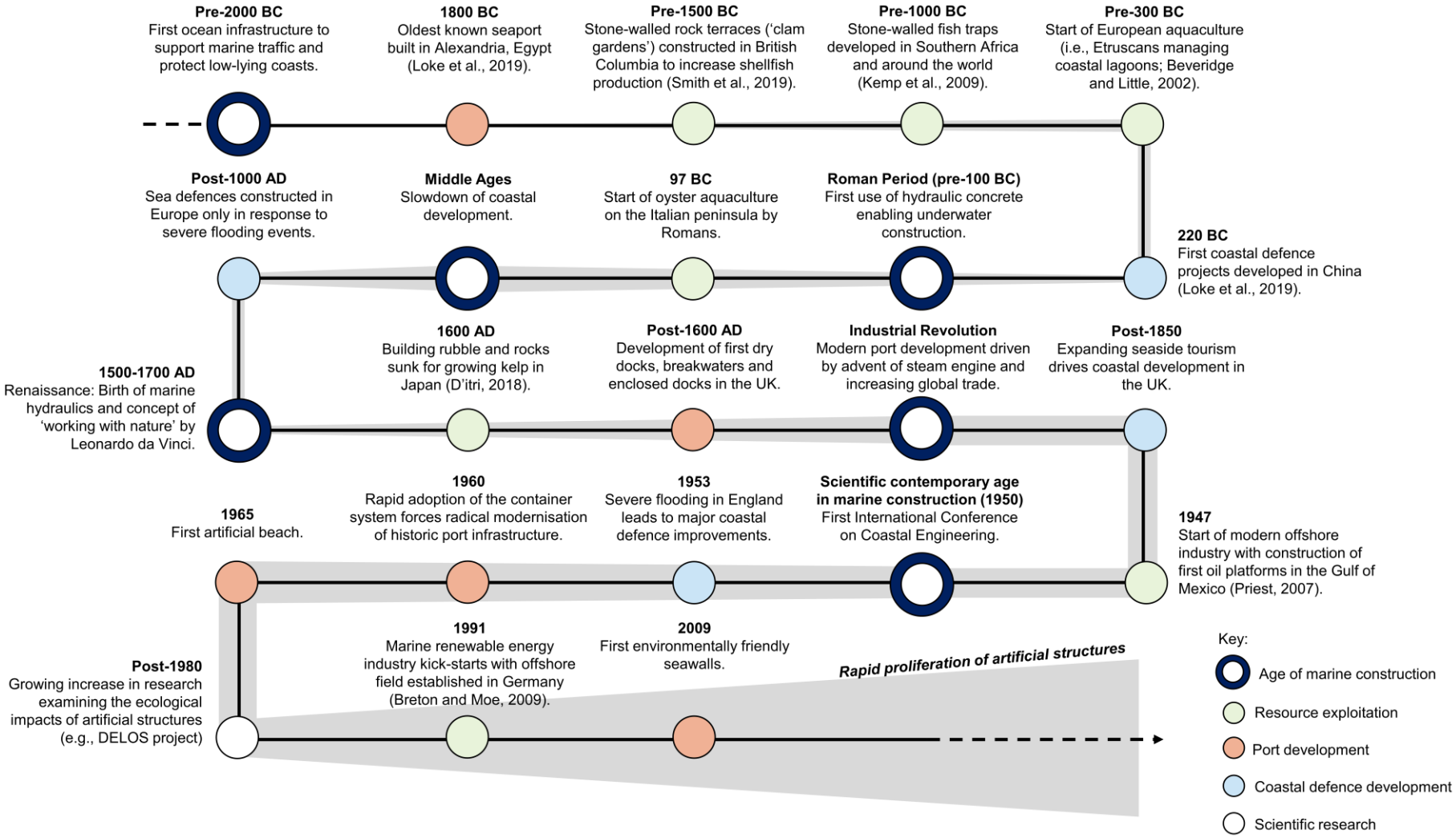
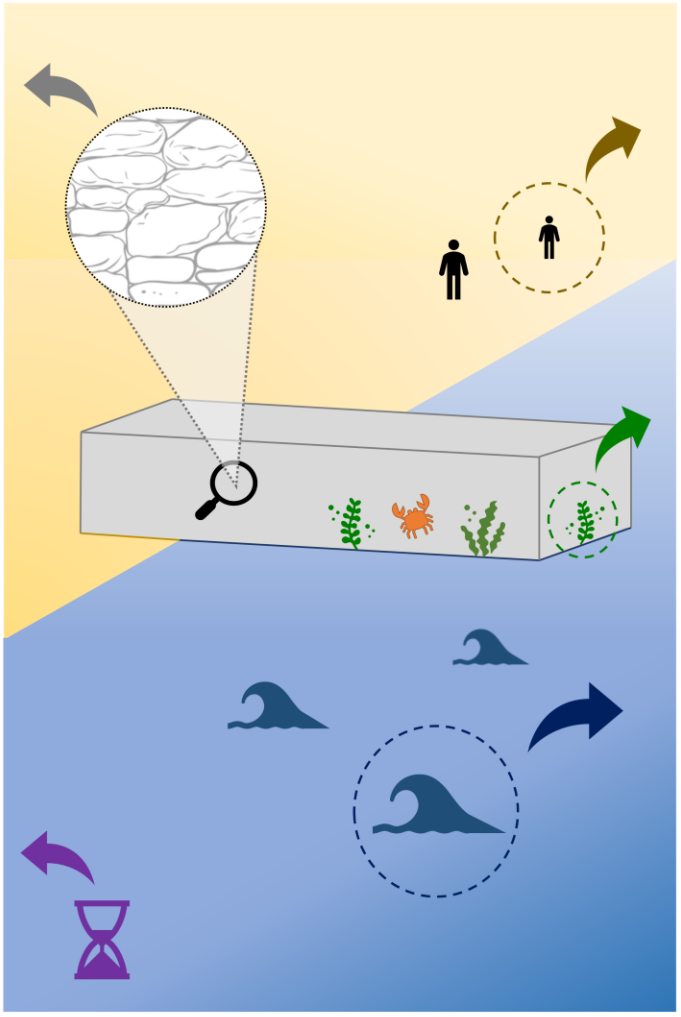


Fig. 2.1. Timeline of marine human development. This thesis focuses on pre- and post-1900 time periods, as a distinction between 'historic' and 'modern' structures. Adapted from Bugnot et al. (2020), Box 2.

Structure Design	Example References
Substrate type	Connell and Glasby, 1999 Coombes et al. 2011 Dodds et al. 2022 Herbert and Hawkins, 2006 Sempere-Valverde et al. 2018
Fine-scale surface texture	Coombes et al. 2015 MacArthur et al. 2019 Naylor et al. 2011
Habitat complexity	Aguilera et al. 2014, 2019 Loke et al. 2016 Moreira et al. 2007 Moschella et al. 2005 Naylor et al. 2011 Firth et al. 2013 Sherrard et al. 2015
Surface orientation and inclination	Chapman and Underwood, 2011 Connell, 1999 Firth et al. 2015b Hanlon et al. 2018 Knott et al. 2004 Perkol-Finkel et al. 2006 Lam et al. 2008 Langhamer et al. 2009

Structure Age	Example References
Age	Burt et al. 2011 Butler and Connolly, 1999 Holloway and Field, 2020 Knott et al. 2004 Perkol-Finkel et al. 2005 Pinn et al. 2005a



Anthropogenic	Example References
Maintenance regimes	Airoldi and Bulleri, 2011 Moschella et al. 2005 Sherrard et al. 2015
Other anthropogenic disturbance events (e.g., harvesting, trampling)	Airoldi et al. 2005 Crowe et al. 2000

Biotic	Example References
Larval supply and recruitment regimes	Bulleri, 2005a, b Cacabelos et al. 2016 Iveša et al. 2010
Community interactions	Ferrario et al. 2016 Iveša et al. 2010 Marzinelli et al. 2011 Miller et al. 2009

Environmental	Example References
Exposure (e.g., waves, abrasion, insolation)	Blockley and Chapman, 2006 Davis et al. 2002 Glasby, 1999 Moschella et al. 2005 Pister, 2009 Pardal-Souza et al. 2017 Southward and Orton, 1954
Location within the tidal frame	Bilkovic and Mitchell, 2013 Bozek and Burdick, 200 Dugan et al. 2008 Glasby, 1999 Moreira, 2006

Fig. 2.2. Factors that influence marine communities on artificial structures, including biotic, environmental, and anthropogenic factors, structure design and age.

2.2 The ecological impacts of built heritage

Despite growing concern regarding the ecological impact of maritime infrastructure, relatively few studies have examined how assemblages of marine organisms respond to artificial structures over time. The few studies which have been conducted suggest that: (i) older structures support more diverse communities than newer structures (Pinn et al., 2005a); (ii) the communities they support continue to change after decadal timescales (Burt et al., 2011; Butler and Connolly, 1999); (iii) the communities become more similar to those found on natural shores with age (Burt et al., 2011; but also see Aguilera et al., 2022), and yet; (4) they remain distinct (Gacia et al., 2007; López, 2019). Despite this evidence, only a handful of studies have examined ecological communities on heritage structures more than 100-years old (e.g. López, 2019). Consequently, in comparison to modern infrastructure (post-1901), relatively little is known about the impacts of built heritage assets on marine wildlife. This includes historic masonry walls with traditional block-masonry designs that were used to construct a significant proportion of coastal infrastructure in the UK and around the world (e.g. harbours, breakwaters, seawalls, etc.) before concrete and other engineering materials (e.g. rock armour, steel piles, etc.) became more widely available during the 19th century (Historic Scotland, 2013; Mackley and Buckley, 1977).

2.2.1 Terrestrial built heritage

In terrestrial environments, the impacts of stone-built heritage on biodiversity are more widely recognised (Ferraby, 2007). Research suggests that the design (i.e. masonry configuration), material, and decay mechanisms of historic masonry structures, including decommissioned and/or ruined sites, all contribute to the ecological communities they support to varying extents (Caneva et al., 2002; Ferraby, 2007; Juřičková, 2005). For example, in urban environments, old masonry walls (Brandes, 1992; Francis, 2010; Huang et al., 2019; Jim, 1998, 2010, 2013, 2014; Jim and Chen, 2010; Li et al., 2016), archaeological sites (Caneva et al., 2018), and ancient monuments, such as the Colosseum in Rome (Caneva et al., 2002), support diverse communities of vascular plants. Dry stone

walls, which are common in rural landscapes around the world (Paterson, 2015), are also important habitats for diverse communities of wildlife, including rare and endemic species of plants and animals (Collier, 2013; Manenti, 2014; Ruas et al., 2022; Stoll, 2004). Notably, unique structural features (e.g. interstitial space between stones) and environmental conditions (e.g. external and internal temperature and moisture regimes) associated with drystone walls and ruined masonry provide refuges for a range of species (Stoll, 2004), especially in areas of high exposure or where conditions do not favour biodiversity (e.g. agricultural land; Hollingsworth and Collier, 2020). In some cases, the ecological communities hosted by dry stone walls may differ drastically from the surrounding landscape in terms of species richness, abundance, and composition (Hollingsworth and Collier, 2020). Indeed, the unique environmental conditions and assemblages of wildlife associated with dry stone walls has led to their recognition as 'novel' anthropogenic ecosystems (e.g. Collier, 2013, 2015; Morse et al., 2014), whereby human intervention has resulted in the crossing of an ecological threshold (Hobbs et al., 2009). Additionally, the ecological communities associated with dry stone walls have been described as examples of 'biological cultural heritage' (e.g. Grove et al., 2020), a term used to describe the "biological manifestations of culture, reflecting indirect or intentional effects, or domesticated landscapes, resulting from historical human niche construction" (Eriksson, 2018, p1). Given that stone-built heritage assets in marine environments are comparable in terms of design (e.g. dry-jointed, mortared) and material (e.g. quarried stone) to historic structures found in urban and rural settings, they may provide similar ecological benefits and biocultural value. However, this remains relatively untested.

2.2.2 Shipwrecks

In marine environments, underwater aspects of cultural heritage are increasingly being recognised for the benefits they provide ecological communities (e.g. Firth et al., 2018; Lengkeek et al., 2013; Meyer-Kaiser and Mires, 2022; Meyer et al., 2017; Wessex Archeology, 2008; Zintzen et al., 2006). Shipwrecks, for example, support diverse assemblages of marine wildlife in both shallow waters (e.g.

Price et al., 2020; Walker et al., 2007) and at greater depths (e.g. Hamdan et al., 2021; Hampel et al., 2022; Johnson et al., 2020). In soft sediment environments, shipwrecks increase habitat heterogeneity, forming unique patches of habitat on the seabed (Balazy et al., 2019). In this way, many shipwrecks function as island-like habitats, hosting novel microbial communities (Hamdan et al., 2021; Moseley et al., 2022; Price et al., 2020) as well as assemblages of fish and sessile invertebrates where they would not otherwise exist (Meyer-Kaiser et al., 2022; Sanderson et al., 2014). Interacting biological, environmental, and anthropogenic processes influence the formation of ecological communities on shipwrecks once they arrive on the seafloor (Heyes, 1994). This includes, for example, a shipwreck's material and structural features (González-Duarte et al., 2018; Moseley et al., 2022; Perkol-Finkel et al., 2006), depth and orientation (Balazy et al., 2019; Walker et al., 2007), and distance to source populations (Gravina et al., 2021; Walker and Schlacher, 2014) as well as environmental conditions such as wave exposure and sedimentation (Baynes and Szmant, 1989; González-Duarte et al., 2018; Pinto et al., 2021) and anthropogenic activities that disturb and/or damage a shipwreck and the communities it supports including deep-water trawling (Brennan et al., 2012, 2013, 2016; Kingsley, 2009, 2015), cable laying (Kingsley, 2011), and oil spills (Hamdan et al., 2018; Mugge et al., 2019). Communities hosted by shipwrecks tend to become more diverse over time (Paxton et al., 2018; Simon et al., 2013) and, in some cases, increasingly similar to the surrounding seabed (e.g. Perkol-Finkel et al., 2005). For example, benthic assemblages associated with a 2000-year-old Bronze naval ram in the Mediterranean were recently found to have strong similarities with nearby coralligenous reefs and circalittoral habitats (Gravina et al., 2021). Wooden shipwrecks also provide habitat that resembles natural organic falls, such as the carcasses of whales or naturally occurring woody debris that has settled on the seabed (Hampel et al., 2022).

Despite some older shipwrecks hosting benthic communities similar to those found on nearby natural reefs (e.g. Genzano et al., 2011; Pinto et al., 2021), in general, shipwrecks tend to support species assemblages that differ from the surrounding environment in terms of trophic structure, species interactions, and/or community composition. For example, although shipwrecks can host

high densities of fish (Johnson et al., 2020; Paxton et al., 2019b, 2021) including large reef-associated predators, such as sharks (Paxton et al., 2019a, 2020), fish assemblages associated with shipwrecks often differ to those found on natural reefs, even after hundreds of years (Simon et al., 2013). Benthic wildlife, coral, and microbial communities also differ between shipwrecks and the surrounding sediment and aquatic environment (Price et al., 2020; Work et al., 2008). Furthermore, some shipwrecks pollute the seafloor with toxic compounds, heavy metals, or other contaminants (Carter et al., 2021; Mancini et al., 2019; Monfils et al., 2006; Work et al., 2008) and can cause long-term shifts in benthic community composition that may persist even after the shipwreck has been removed (Casoli et al., 2020; Work et al., 2018). In addition, by expanding the geographic ranges of species (e.g. Paxton et al., 2019b), shipwrecks can act as stepping-stones for invasives (Soares et al., 2016, 2020).

Given the ecological impacts of submerged shipwrecks, it is surprising that few studies have examined the communities of intertidal wildlife supported by shipwrecks in the littoral zone. In general, marine growth is viewed negatively as it is thought to contribute to the gradual deterioration of shipwrecks in intertidal environments (see discussion of 'bioerosion' in Section 2.3.1; Price et al., 2014). Recently, however, the ecological value of intertidal shipwrecks has been examined, with preliminary research suggesting higher levels of biodiversity than surrounding sedimentary environments (Evans and Davidson, 2019). As with submerged shipwrecks, differences in community structure between intertidal shipwrecks and areas of soft sediment appear to be associated with differences in habitat complexity (Evans and Davidson, 2019).

2.2.3 Stone-built maritime heritage

In addition to metal and wooden shipwrecks, underwater stone-built heritage also supports diverse assemblages of marine organisms (Table 2.1, Fig. 2.3). This includes, for example, several 1000-year-old marble statues salvaged from a Roman-era shipwreck near Antikythera, Greece (Calcinai et al., 2019; Davidde et al., 2017; Ricci et al., 2018), mortared stonework from a submerged roman villa

(Sacco Perasso and Ricci, 2019), and the remnants of a centuries-old breakwater off the coast of St. Eustatius, eastern Caribbean (Hill et al., 2021; Lymperaki et al., 2022). As with some shipwrecks, structural differences between underwater stone-built heritage and the surrounding seabed may explain differences in species richness, composition, and competitive interactions, even after many decades of community development (Hill et al., 2021; Lymperaki et al., 2022).

In intertidal environments, research investigating the biodiversity of stone-built heritage has been relatively limited, with the majority of studies focusing on a small subset of historic structures (Fig. 2.4). This includes ancient rock-walled terraces or 'clam gardens' used by Indigenous People of the Northwest Coast of North America for at least 3500 yrs to extend and augment soft-sediment beaches for shellfish production (Deur et al., 2015; Groesbeck et al., 2014; Lepofsky et al., 2017; Smith et al., 2019). The soft-sediment environments associated with clam gardens are considered culturally and biologically rich habitats as they support diverse assemblages of marine wildlife that differ from unmodified mudflats and sandy beaches (Cox et al., 2019; Jackley et al., 2016). In addition, the rock walls that enclose clam gardens provide novel habitat space for intertidal species, supporting greater invertebrate diversity than adjacent non-walled areas of natural rocky substrate (Holmes et al., 2020; Irons et al., 2016; Mathews et al., 2016). The greater structural complexity associated with clam gardens is thought to contribute to differences in the ecological communities supported by these structures relative to unmodified shores (Holmes et al., 2020).

Ancient fish traps and tidal weirs represent other examples of stone-built heritage increasingly recognised for their contributions to marine biodiversity. These specialised stone structures designed for catching fish are one of the earliest forms of maritime built heritage and are found along coastlines around the world, including North America (e.g. Costa-Pierce, 1987; Elder et al., 2014; Garduño Argueta and Caballero Pinzón, 1998), South America (e.g. Favier Dubois et al., 2018; Torres, 2009), Oceania (e.g. Hunter-Anderson, 1981; Rowland and Ulm, 2011; Stockton, 1982), Europe (e.g. Bathgate, 1949; Chadwick and Catchpole, 2010; Gandois et al., 2018; Jones, 1983;

Montgomery et al., 2015), Asia (e.g. Luo et al., 2019; Yu et al., 2015), and Africa (e.g. Kemp et al., 2009; Pattrick et al., 2022). Like clam gardens, the stone walls associated with fish traps provide novel habitat space and refuge for marine organisms during low-tide periods (Favier Dubois et al., 2018; Hunter-Anderson, 1981). For example, in Pembrokeshire, western Wales (UK), semi-submerged prehistoric fish traps act as functioning reefs, supporting dense carpets of red algae and sea anemones as well as protected species, such as *Sabellaria spinulosa* (Otto, 2014). Further along the Welsh coastline in the Menai Straits, stone-walled fish traps support high abundances of seaweed (e.g. *Ascophyllum nodosum*) and other intertidal species (Bannerman and Jones, 1999; Jones, 1983), while in France, fish traps in Normandy and Brittany provide hard substrate for extensive assemblages of *Sabellaria* spp. and beds of maerl, such as *Phymatolithon purpureum* (Gandois et al., 2018; Gruet, 1986). In southern Africa, stone-walled fish traps (or 'vywers' as they are locally known) up to two or three millennia old support ecological communities with greater species richness than adjacent areas of natural rocky substrate (Kemp, 2006), with similar effects reported in Taiwan (Jeffery, 2013; Yu et al., 2015) and Japan (Kakuma and Kamimura, 2011; Yanagi, 2013). Furthermore, ancient fish traps act as nurseries for coastal fishes and invertebrates by providing stable environmental conditions (i.e. pools of permanent non-stagnant water) and reducing exposure to marine predators and dynamic wind and wave regimes (Pattrick et al., 2022).

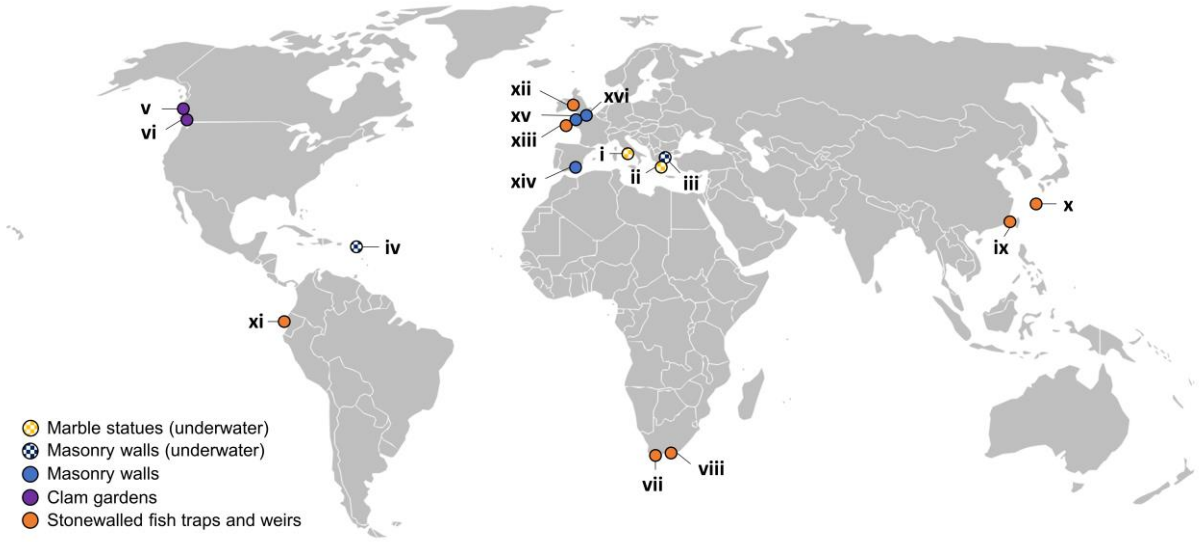


Fig. 2.3. Locations of studies in Table 2.1 that have investigated the biodiversity of stone-built heritage assets.

Table 2.1. Examples of studies examining the biodiversity of maritime stone-built heritage.

Environment	Habitat Type	Age	Location	Impact on Biodiversity	Reference	Fig. 2.3 ID
Underwater	Marble statues	~2000 yrs. bp*	Italy	Substrate supports diverse communities of euendolithic sponge communities.	Calcinai et al. (2019)	i
		~1000 yrs. bp*	Greece	Substrate supports diverse communities of epilithic micro- and macro-organisms.	Calcinai et al. (2019) Davidde et al. (2017) Ricci et al. (2018)	ii ii ii
	Masonry walls	~1500 yrs. bp*	Greece	Substrate supports high abundances of epilithic organisms.	Sacco Perasso and Ricci (2019)	iii
		1829	Caribbean	Diverse communities of coral and coral-associated fauna supported, however, these remain distinct to those found on nearby natural reef.	Hill et al. (2021) Lymperaki et al. (2022)	iv iv
Intertidal	Clam gardens (terraces)	~3500 yrs. bp	Canada	Terraces support novel and distinct types of soft sediment communities, including culturally important species.	Cox et al. (2019) Jackley et al. (2016) Groesbeck et al. (2014)	v v vi
	Clam gardens (stone walls)	~3500 yrs. bp	Canada	Rock walls provide novel habitat, supporting greater invertebrate diversity than non-walled beaches.	Holmes et al. (2020) Irons et al. (2016) Mathews et al. (2016)	vi - -
	Fish weirs (stone walls)	~100–3500 yrs. bp	South Africa	Stone walls support greater biodiversity than nearby rocky shores, however, communities remain distinct.	Kemp (2006) Kemp et al. (2009)	vii vii
	Fish weirs (pools)	~100–3500 yrs. bp	South Africa	Pools of non-stagnant water that form behind the walls of fish traps provide nurseries to fish and invertebrate larvae.	Pattrick et al. (2022)	viii
	Stone fish traps	~1644–1911	Taiwan	Stone weirs support more diverse fish and invertebrate communities than non-stone weir areas.	Yu et al. (2015)	ix
	Stone fish traps	Unknown	Japan	Fish traps enhance biodiversity as the crevices between the rocks creates novel habitat space.	Kakuma and Kamimura (2011) Yanagi (2013)	x x
	Stone fish traps	~750–1532	Ecuador	Stone walls and pools that form behind the structure host diverse intertidal communities.	Favier Dubois et al. (2018)	xi
	Stone fish traps	~2000–1500 yrs. bp	UK	Stone walls support high abundances of seaweed and other intertidal species.	Jones (1983) Bannerman and Jones (1999)	xii xii
	Stone fish traps	7000–4000 yrs. bp	France	Fish traps provide hard substrate for extensive assemblages of *Sabellaria* spp. and beds of meal.	Gandois et al. (2018) Gruet (1986)	xiii
	Masonry seawall	1914	Spain	Annelid assemblages differ significant to those on nearby natural rock substrate.	López (2019)	xiv
	Masonry breakwater	1818	UK	Endangered mollusc species observed within crevices of masonry harbour wall.	Hine et al. (2015)	xv
	Blockwork breakwater	1841	UK	Eroded limestone blocks replicate natural water-retaining features that are favourable to biodiversity, such as rockpools.	Firth et al. (2013)	xvi

* Approximate date of submersion.

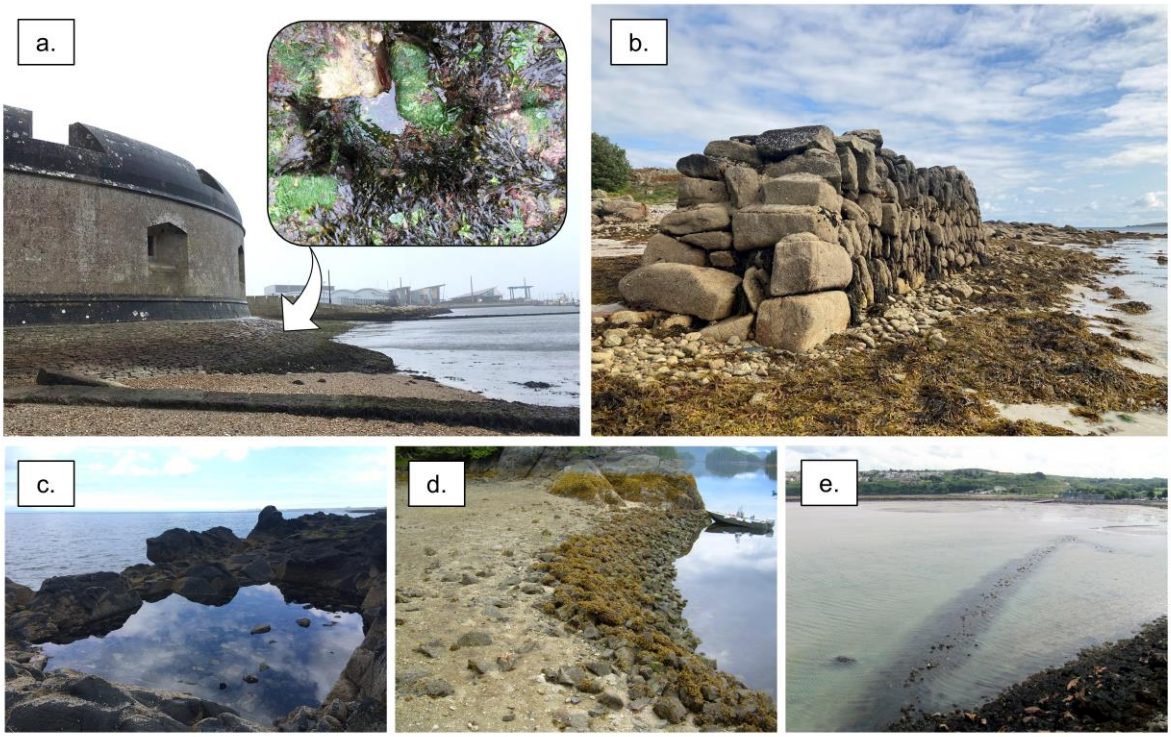


Fig. 2.4. Examples of maritime built heritage constructed from or carved out of stone: (a) sixteenth century Portland Castle and (inset) water retaining features that mimic natural rockpools caused by missing brickwork on the revetment; (b) seventeenth century historic masonry quay on the island of St Martin's, Isle of Scilly, Cornwall; (c) eighteenth century rock-cut seawater holding tank for salt pans in Cockenzie, Scotland; (d) clam garden in the Broughton Archipelago, Canada (Photo © John Harper - CC BY 2.0); (e) submerged stone-walled fish trap in Fishguard Harbour, Wales (Photo © Natasha Ceridwen de Chroustchoff - CC BY 2.0).

2.2.4 Research gaps and opportunities

Despite this evidence of the potential ecological value of stone-built heritage assets, surprisingly few studies have examined the ecological communities supported by traditional masonry walls associated with historic coastal infrastructure (e.g. seawalls, breakwaters, jetties, etc.). López (2019) found that annelid assemblages on a centuries-old masonry wall on the southeastern coast of Spain were significantly different to those found on nearby rocky shores, with higher species richness and abundance on the natural substrate. In the UK, harbour walls with traditional masonry configurations have been reported to provide habitat for a range of benthic organisms (Evans, 2016), including endangered species of mollusc (Hine et al., 2015). Furthermore, unintentional structural features created by eroded and/or dislodged material on historic blockwork structures, such as the 200-year-old Plymouth Breakwater in Devon (UK), resemble natural water-retaining

features, such as rockpools (Coombes, 2011a; Firth et al., 2013). Although these studies indicate the potential importance of historic masonry walls for marine biodiversity, as of yet, the ecological value of these structures in comparison to modern infrastructure and natural rocky substrate has not been adequately assessed. As such, this thesis addresses the following objective in Section 3, Chapter 6 (Paper 3):

Objective: To determine whether communities of marine wildlife supported by historic maritime structures differ to those found on natural rocky cliffs and modern concrete

As with other forms of stone-built heritage, historic masonry walls may possess a number of characteristics relating to their traditional design (i.e. masonry configuration), material, age and decay mechanisms, maintenance regimes, and protected status that makes them favourable for marine wildlife colonisation. A summary of these influences is provided in Table 2.2, and these are further discussed in detail in the introductions of Chapter 6 (Paper 3) and Chapter 7 (Paper 4).

Understanding the contribution of stone-built heritage to marine biodiversity may help identify mutually beneficial opportunities for the conservation of cultural heritage and marine wildlife. For instance, if historic structures are shown to support priority species or act as hotspots for marine biodiversity (particularly along heavily urbanised shores), it may boost arguments for their continued protection and conservation. This would not only benefit the conservation of these structures but also the marine wildlife they support, offering potential 'win–win' conservation outcomes (Coombes and Viles, 2021). Furthermore, determining the ecological benefits of built heritage may encourage the use of ecologically friendly management practices that are compatible with national legislation on marine biodiversity conservation (e.g. the Environment Act 2021, the Water Framework Directive, etc.). In addition, if particular design features associated with historic masonry structures (e.g. blockwork configuration) benefit marine wildlife, this can inform the design of modern coastal infrastructure as well as eco-engineering solutions aimed at enhancing the biodiversity of existing structures (Naylor et al., 2017a; O'Shaughnessy et al., 2019).

Table 2.2. Factors associated with maritime structures that influence the colonisation of marine wildlife, and the hypotheses tested in this thesis.

Factor	Effect on marine communities	Explanation	Example Reference	Hypotheses tested in this thesis
Age	Older structures tend to support more diverse communities than newer structures. With age, these communities become increasingly similar to those found on nearby natural shores/reefs.	Over time, structures develop weathering features that favour marine colonisation. Ecological succession will gradually lead to the development of diverse marine communities via facilitation/ community-level effects.	Burt et al. (2011) Butler and Connolly (1999) Perkol-Finkel et al. (2005) Pinn et al. (2005a)	Due to their age, historic masonry walls have a greater density of weathering features and support more diverse marine communities than structures more recently built (**Papers 3 and 4)**.
Material	Natural rock tends to support greater abundances of marine species than artificial materials.	Natural rock typically has rougher surfaces than artificial materials, which is beneficial to ecology. The weathering of calcareous materials (e.g. limestone) can create favourable water-retaining microhabitats.	Connell and Glasby (1999) Coombes et al. (2011) Dodds et al. (2022) Herbert and Hawkins (2006) Sempere-Valverde et al. (2018)	Historic masonry walls constructed of natural rock have rougher surfaces and support greater abundances of marine species compared to modern coastal infrastructure constructed of concrete (**Paper 3**).
Surface texture	Surfaces with fine scale topographic features (<1 cm) will typically colonise faster and support more abundant and diverse communities than smooth surfaces.	Textured surfaces provide shade, increase water retention, and aid organism settlement, recruitment, and attachment.	Coombes et al. (2015) MacArthur et al. (2019) Naylor et al. (2011)	Given that they have experienced years of degradation due to weathering and erosional processes, the availability of fine-scale surface features is higher on historic walls compared to other forms of coastal infrastructure (**Paper 3**).
Structural complexity	Species richness and diversity typically increase with the availability of meso-scale topographic features (>1 cm) such as rockpools and crevices.	Water-retaining features can provide refuge from physical and biotic stress.	Aguilera et al. (2014) Moreira et al. (2007) Moschella et al. (2005) Naylor et al. (2011)	The availability of meso-scale habitat features is greater on walls with traditional masonry configurations compared to other forms of coastal infrastructure (**Paper 3**).
Availability of cryptic habitats	Porous structures with internal habitats typically support more diverse ecological communities than those without.	Voids within structures can provide functional habitat space for marine organisms not found elsewhere.	Moreira (2006) Sherrard et al. (2016)	The availability of (internal) cryptic habitat space is greater on historic masonry walls compared to other forms of coastal infrastructure. These features provide novel habitat for marine organisms (**Paper 3**).
Maintenance regime	Structures that are regularly maintained tend to support less diverse ecological communities than those that are not.	Maintenance practices can result in the disruption, removal or destruction of habitats and marine organisms, and create opportunities for opportunistic and invasive species to colonise.	Airoldi and Bulleri (2011) Moschella et al. (2005) Sherrard et al. (2016)	Marine wildlife is managed differently on historic masonry walls compared to other forms of coastal infrastructure (**Paper 1**). This affects the types of ecological communities that form on these structures (**Paper 3**).

Many historic structures, including those with traditional masonry construction, already exist within coastal regions designated to protect marine species and habitats. Consequently, in some locations, culturally important heritage assets spatially overlap with highly valued components of marine and coastal ecosystems. Practical tools for identifying heritage sites with the greatest potential to support diverse ecological communities would allow conservation managers to prioritise areas for the joint conservation of cultural heritage and marine biodiversity. Unfortunately, however, these tools do not currently exist. Given that maritime built heritage faces increasing threats associated with climate change, coastal urbanisation, and neglect (Harkin et al., 2020; Hunt, 2011; Sesana et al., 2021; Wyatt and Prizeman, 2018), and the majority of UK coastal species are either in long term decline or threatened with extinction (Hayhow et al., 2019), identifying joint wildlife-heritage conservation opportunities is more important than ever. Therefore, to address a lack of practical approaches for identifying areas of joint biodiversity and heritage value, this thesis focuses on the following objective in Section 4, Chapter 7 (Paper 4).

Objective: To develop and apply a methodology for identifying joint priority areas for biodiversity and maritime heritage conservation at a regional scale.

2.3 Coastal biogeomorphology

Plants, animals, and microorganisms contribute to the formation of landforms and landscapes through a series of complex, two-way interactions (Naylor et al., 2002). Known collectively as biogeomorphological processes, these include: (i) bioturbation, the disturbance and reworking of soils and sediments by plants and animals (e.g. lugworm casts, Fig. 2.5a; Meysman et al., 2006); (ii) bioerosion, the direct or indirect breakdown of hard substrata by living organisms (e.g. rock-boring molluscs, Fig. 2.5b; Davidson et al., 2018); (iii) bioprotection, the active or passive role of organisms in reducing the efficiency of deteriorative weathering or erosional processes (e.g. sand-binding algae, Fig. 2.5e; Carter and Viles, 2005); and (iv) bioconstruction, the production of sedimentary deposits, accretions, or accumulations by organic means (e.g. *Sabellaria* reefs, Fig. 2.5d; Viles, 1988).

The relationships between biogeomorphological processes are often varied and complex, with organisms often exhibiting more than one function concurrently in the same environment (e.g. Mottershead et al., 2003; Pappalardo et al., 2018; Viles et al., 2011b). Furthermore, the dominance of each process may depend on the spatial and temporal scales at which they are considered and the environment in which they are acting in (Carter and Viles, 2005).

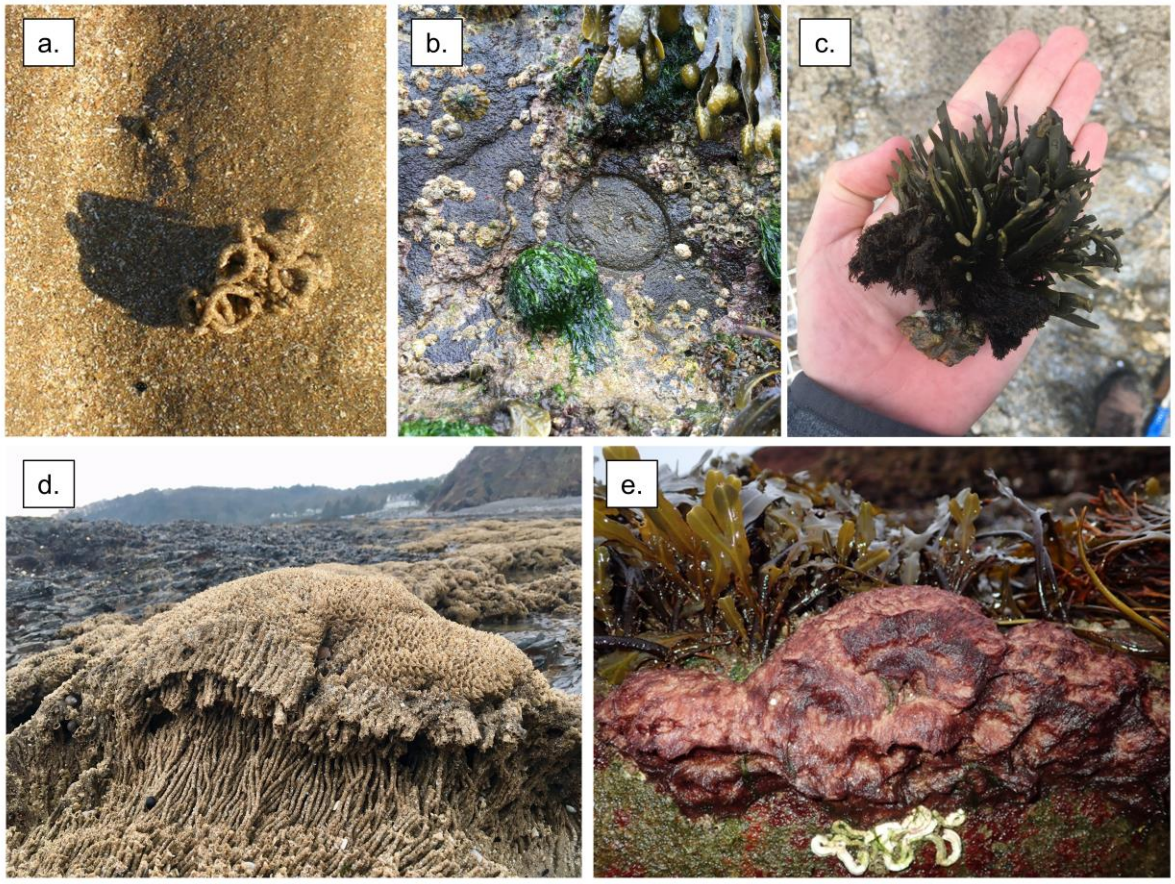


Fig. 2.5. Biogenic features on the coast: (a) coiled casts formed by burrowing lugworms (*Arenicola marina*), Isle of Anglesey, Wales (Photo © Keith Williamson - CC BY 2.0); (b) ringed shaped hollows or 'home scars' caused by limpets excavating rock using the edges of their shells on a masonry wall, Tenby, Wales; (c) indirect bioerosion of rock by seaweed (*A. nodosum)* following rough sea conditions, Falmouth, Cornwall; (d) biogenic reefs formed by the tube-dwelling honeycomb worm (*S. spinulosa*), Amroth, Wales; (e) sand bound together by seaweed (*Rhodothamniella floridula*), Scapa Flow, Scotland (Photo © Derek Mayes - CC BY 2.0).

In addition to contributing to the geomorphic evolution of natural environments, biogeomorphological processes alter built environments, including heritage assets. For instance, biological agents may cause undesirable changes to historic buildings (i.e. biodeterioration) by altering (Cutler et al., 2013) or obscuring their appearance (i.e. bio-obscuration; Pardela et al., 2022;

Viles et al., 2011b), or by facilitating the physical and chemical breakdown of building materials (Caneva et al., 2009; Negi and Sarethy, 2019; Ortega-Calvo et al., 1991; Warscheida and Braams, 2000). Alternatively, wildlife may contribute to the conservation of heritage assets through bioprotective processes (e.g. André et al., 2012, 2014; Gadd and Dyer, 2017; Jang and Viles, 2021), and/or enhance the value of heritage sites through the provision of additional services and benefits (e.g. carbon stock, aesthetics, biodiversity, pollution removal, microclimate regulation; Coombes and Viles, 2021). In some cases, biological agents that colonise heritage assets may exhibit both bioerosive and bioprotective functions (Bartoli et al., 2014; Liu et al., 2022). For instance, in terrestrial environments, ivy (*Hedera* spp.) can cause the deterioration of archaeological sites (Bartoli et al., 2016) but can also protect historic masonry walls by regulating near-surface microclimates (Coombes et al., 2017a; Sternberg et al., 2011; Thornbush, 2013; Viles et al., 2011b) and reducing the risk of damage from frost action (Coombes et al., 2018) and airborne pollution (Sternberg et al., 2010).

In marine environments, biogeomorphological processes contribute to the geomorphic evolution of rocky shores and the degradation and/or protection of artificial structures (Bone et al., 2022b; Coombes, 2014; Davidson et al., 2018; Naylor et al., 2012b). The net bioprotective or bioerosive effects of a given marine species or assemblage is spatially and temporally dynamic, and dependent on many complex and interacting biotic and abiotic factors (Bone et al., 2022b). These include: (i) substrate type, slope, and orientation (e.g. Coombes et al., 2017b; Pomar et al., 2012, 2017), (ii) exposure (e.g. wave abrasion, insolation; Mottershead et al., 2003; Pomar et al., 2012, 2017), (iii) other abiotic factors that influence the distribution of marine organisms and the efficiency of biologically moderated decay processes (e.g. tidal regimes, local climatic conditions, distance to the coast; Palmer et al., 2003), (iv) the morphology of the biological covers (e.g. canopy/encrustation thickness and organism density; Coombes et al., 2013b), (v) disturbance regimes (Coombes et al., 2013b; Spencer and Viles, 2002; Viles et al., 2008); (vi) ecological interactions and dynamics (e.g. predation, competition, etc.); and (vii) longer-term climatic changes that may influence community

functioning and dynamics (e.g. Coombes et al., 2018; Viles and Coombes, 2022; Viles and Cutler, 2012).

The following sub-sections (2.3.1–2.3.2) provide an overview of bioerosive and bioprotective processes that operate on natural rock and engineered materials (i.e. quarried stone, concrete) in marine environments followed by a more focused review of biogeomorphological research on marine/coastal stone-built heritage assets. Research gaps and opportunities that emerge throughout this review are then discussed in Section 2.3.4.

2.3.1 Bioerosion

Bioerosion can be conceptualised as two distinct processes: biomechanical erosion (or bioabrasion) and biochemical erosion (or biocorrosion). Biomechanical erosion involves the direct removal of substratum by physical or mechanical forces that are initiated and/or enhanced by biological interactions (e.g. the rasping and grinding activities of grazers and rock-boring organisms), whereas biochemical erosion includes biologically driven and/or assisted solution and corrosion (Coombes, 2014). While biomechanical erosion causes the breakdown of rock into its constituent parts (i.e. mineral sediment), biochemical erosion produces solutional product. Both processes operate directly (actively) or indirectly (passively), and often occur in combination, with individual organisms capable of altering rocky substrates through both biomechanical and biochemical means.

2.3.1.1 Direct bioerosion

In marine and coastal environments, direct (active) bioerosion includes the breakdown of substrate by rock-boring organisms. Several species of molluscs, annelid worms, echinoids (e.g. sea urchins), and sponges bore into the surfaces of rock via biomechanical and/or biochemical means, rendering the material more susceptible to wave action and contributing to its gradual breakdown (Scott et al., 1988; Trudgill, 1987, 1988; Trudgill and Crabtree, 1987). This includes, for example, piddocks (*Pholadidae* sp.), which have been shown to significantly increase the erosion of soft rock habitats

(Pinn et al., 2005b; Pinn et al., 2008). At the micro-scale, holes created via biochemical erosion by rock-boring microorganisms can form at considerable densities on rock surfaces (Coombes et al., 2011; Naylor et al., 2012b; Pomar et al., 2017). The bioerosive activities of rock-boring microorganisms may weaken the surface of rock (Coombes et al., 2011, 2013a) facilitating subsequent bioerosion by grazing organisms (Schneider and Torunski, 1983) and enhancing the efficiency of mechanical and chemical breakdown through weathering (e.g. wetting–drying, salt weathering, solution, etc.) and erosional (e.g. abrasion) processes (Trudgill, 1976a, b, 1987). In some cases, µm–cm scale bioerosive features created by rock-boring microorganisms and marine animals may facilitate meso-scale erosional processes, such as the loosening of boulders on rocky shore platforms (Naylor et al., 2012b).

On soft rock types (e.g. chalk), grazing molluscs (limpets, snails, and chitons) rasp away fragments of rock as they feed on epilithic and endolithic microbial biofilms (Trudgill, 1988). This not only causes direct bioerosion (Gómez-Pujol et al., 2006) but also facilitates deeper penetration by rock-boring microorganisms (Golubic et al., 1981; Spencer, 1988; Trudgill, 1985, 1988). There is also evidence to suggest that limpets use the edges of their shells (i.e. biomechanical erosion) or dissolution (i.e. biochemical erosion) to excavate ring shaped hollows or 'home scars' that they return to after grazing (Andrews and Williams, 2000; Bromley and Heinberg, 2006; Trudgill, 1988; see Fig. 2.5b). Certain species of piddock and clam are thought to use a similar mechanism to burrow mechanically into rock (Bone et al., 2022b).

Although generally considered a superficial process (e.g. Coombes, 2014), macro-algae holdfast growth has been observed to cause the mechanical disintegration of natural rock (i.e. limestone and granite) to a depth of up to 10 mm (Morrison et al., 2009). Similar observations have been made for marine concrete; for instance, algal filaments (e.g. *Ulva* sp.) can penetrate concrete surfaces and adhere to the exposed particles of fine aggregate (Hughes et al., 2013a, b). Mussels can also contribute to the deterioration of hard substrate through the invasive nature of their attachment

structures (Bone et al., 2022b); for example, the byssal threads that are produced by mussels have been shown to penetrate concrete surfaces (Perez et al., 2003). Surface features (e.g. fissures) caused by erosive modes of attachment may reduce the compressive strength of substrates colonised by marine organisms (Yao et al., 2017) and can increase water ingress, potentially enhancing chemical weathering processes, such as dissolution (Bone et al., 2022b).

2.3.1.2 Indirect bioerosion

In addition to direct forms of bioerosion, some marine organisms contribute to the breakdown of rocky substrate through indirect (passive) biomechanical and biochemical erosion. For example, organisms that preferentially grow within confined spaces on rocky shores, such as mussels and barnacles, may induce mechanical stresses within surface discontinuities or void spaces (Coombes, 2014). Alternatively, the swelling and shrinking of organisms in response to wetting–drying may facilitate mechanical breakdown. For instance, field and laboratory experiments suggest that the expansion and contraction of biofilms in response to microclimatic changes may contribute to rock decay and accelerated rates of breakdown on supratidal rocks (Gómez-Pujol et al., 2007; Mayaud et al., 2014; Moses and Smith, 1993; Yuan et al., 2018, 2019). Through a similar mechanism, the desiccation and subsequent contraction of biofilms can cause the removal of mineral grains from substrate surfaces, as observed on building materials under laboratory conditions (Guillitte and Dreesen, 1995).

On vertical and near-vertical substrate, macro-algae, and other dense agglomerations of marine biota (e.g. barnacles, mussels, oysters) increase static load making the surfaces they colonise more susceptible to failure (Wang et al., 2014). During storm events, drag forces acting on these biotic covers can also increase the susceptibility of material to being removed due to plucking (see Fig. 2.5c), particularly in the case of large species of macro-algae, such as kelp (*Laminaria* spp.), that form strong holdfasts and have extensive fronds (Bromley and Heinberg, 2006; Garden and Smith, 2011, 2015; Smith and Bayliss-Smith, 1998; Trenhaile, 1980). The backwards and forwards sweeping

motion of seaweed due to waves has also been suggested as a cause of erosion on rocky shore platforms (Brew, 2004).

On carbonate shores, intertidal organisms contribute to the solution and pitting of rock surfaces by enhancing the acidity of surface waters (Trudgill, 1987, 1988). These biochemical processes can cause the development and extension of surface depressions and enclosed basins and are particularly influential at higher tide levels where grazers and rock-boring organisms tend to be scarce (Coombes, 2014; Fornós et al., 2006; Gómez-Pujol et al., 2006; Palmer et al., 2003; Pomar et al., 2017). Furthermore, on concrete structures, seaweed secretions have been shown to cause biochemical decay (Jayakumar et al., 2010; Jayakumar and Saravanane, 2009).

On rocky substrate, biotic covers alter near-surface microclimatic regimes by moderating the absorption of solar radiation and water retention at the surface, creating wetter conditions at the rock-air interface. These influences are generally considered to be most relevant for protecting rocks from temperature- and moisture-driven modes of breakdown, however, in some cases, they may also enhance deterioration (Coombes, 2014). For instance, biotic covers with a low albedo (e.g. dark-coloured lichen and biofilms) may enhance heat absorption by coastal rocks, increasing the efficiency of mechanical decay processes associated with fluctuations and extremes in rock surface temperature and thermal gradients (Carter and Viles, 2005; Mayaud et al., 2014). By enhancing moisture retention at the surface, biotic covers may equally enhance chemical forms of rock breakdown (Baxter et al., 2022), although direct evidence for this remains limited.

2.3.2 Bioprotection

Marine organisms that form dense canopies and encrustations on the surfaces of natural rock and engineered materials (e.g. concrete, quarried stone) can reduce the efficiency of certain forms of mechanical weathering through the dampening of near-surface microclimatic regimes. For instance, dense assemblages of mussels (Baxter et al., 2022; Gonzalez et al., 2021; Jurgens and Gaylord, 2018; Zardi et al., 2023), barnacles (Coombes et al., 2017b), oysters (McAfee et al., 2017, 2018, 2022), and

seaweed (Coombes et al., 2013b; Gowell et al., 2015) moderate extremes and fluctuations in near-surface rock temperatures over diurnal and/or minute-hour timescales. Shading effects as well as enhanced moisture retention and evaporative cooling have been linked to the thermal-dampening effects of these biotic covers (Coombes, 2014; Coombes and Naylor, 2012).

The surface-cooling effects of marine organisms have been shown to translate to reduced internal (i.e. subsurface) rock thermal cycling and dampened thermal gradients. For example, laboratory experiments suggest that encrustations of mussels and barnacles may reduce thermal gradients by up to 0.1°C per 1-cm depth of rock compared to bare/uncolonised surfaces (Baxter et al., 2022; Coombes et al., 2017b). Comparable laboratory experiments show that encrustations of vermetid worms (*Dendropoma* spp.) have a similar dampening effect on internal rock temperatures in addition to reducing potentially damaging salt ingress (La Marca, 2017).

As mechanical weathering processes are influenced by surface and subsurface temperature regimes, the stabilising effects of biotic covers may translate to a reduction in the efficiency of mechanical decay associated with repeated heating (e.g. thermal fatigue, thermal shock) and drying (e.g. wetting–drying) as well as salt crystallisation (Gonzalez et al., 2021; Mottershead et al., 2003; Moura et al., 2012; Stephenson and Kirk, 2000; Trenhaile, 1980, 1987). For instance, the thermal buffering effects of seaweed have been shown to moderate rock breakdown via salt crystallisation under laboratory conditions (Gowell et al., 2015). In the field, similar thermal effects associated with mussels have been linked to erosion rates on hard and cohesive rock platforms (Baxter et al., 2022; Gonzalez et al., 2021).

During cold weather, seaweed canopies have also been shown to have a thermal insulating effect, reducing the frequency, severity, rate, and duration of potentially damaging frost events affecting underlying substrates (Scrosati and Ellrich, 2018). Species of mussels and other types of biotic covers that have evolved local adaptations to survive freezing temperatures may also protect intertidal

rocks from the damaging effects of freeze–thaw weathering, although this remains largely untested (Gonzalez et al., 2021).

Encrusting organisms, such as barnacles and mussels, and the calcareous deposits of coralline algae (e.g. *Lithothamnion* spp.) and tube-building annelid worms (e.g. *Polychaeta* spp.) modulate near-surface water flows and can physically armour rock surfaces making them less susceptible to physical (e.g. wave impact, abrasion, etc.) and biological-driven erosional processes (Coombes, 2014; Trenhaile, 1980). For instance, mussel beds have been shown to attenuate hydrodynamic and abrasive forces on hard and cohesive rock platforms, thereby moderating deteriorative processes associated with turbulence (e.g. abrasion, dissolution, wave impact) and sediment-laden waves and tidal flows (Baxter et al., 2022; Gonzalez et al., 2021). Encrusting organisms and organically produced calcareous deposits may also limit the bioerosive effects of other organisms (e.g. grazers, rock-borers) by reducing the area of air-exposed rock (Trudgill, 1987). For example, on intertidal rock platforms along the Yorkshire coastline, UK, the calcareous deposits of red coralline algae (e.g. *Lithophyllum incrustans*) are thought to protect substrate from rock-boring cyanobacteria and biologically cement/reattach loose boulders to the platform surface, thereby increasing the shear stress required to initiate boulder movement (Kennedy et al., 2019).

Oyster cementation improves the durability of marine concrete by reducing water absorption and enhancing resistance to chemical forms of material breakdown, such as carbonation and corrosion (Lv et al., 2015a, 2021). By sealing microcracks and limiting chloride ion penetration, encrustations of barnacles can provide similar bioprotective effects on marine concrete (Chlayon et al., 2018; Lv et al., 2022). On the other hand, field experiments along the northwest coast of Italy suggest that barnacles can simultaneously act as bioprotective and bioerosive agents on carbonate shore platforms; sub-surface rock hardness was found to be higher under areas of colonised rock compared to bare substrate, while barnacles also contributed to rock-surface breakdown via biocorrosion (Pappalardo et al., 2016, 2018).

Seaweed may also dampen the impact of waves on rocky shores (Brew, 2004; Kirk, 1977; Trenhaile, 1980), with research suggesting that macro-algae limits downwearing rates on carbonate platforms in southern Portugal (Moura et al., 2012). There is also evidence to suggest that, in some cases, seaweed growth can limit the bioerosive effects of cyanobacteria; for example, Naylor and Viles (2002) found an inverse relationship between macroalgal abundance and bioerosion of experimental limestone blocks after seven months of colonisation on the western coast of Crete, Greece. At the microbial scale, biofilms can also act as a physical barrier, inhibiting the access of aggressive salts and bioerosive organisms to rock surfaces (Mottershead et al., 2003). Furthermore, biofilms may reduce the frequency of salt crystallisation as well as the efficiency of weathering by thermal cycling and wetting–drying by enhancing water absorption, retention, and evaporative cooling during low tide periods (Coombes and Naylor, 2012). Microorganisms also contribute to the development of biochemical crusts on marine concrete that can seal pores and reduce rates of leaching, thereby limiting damage caused by seawater penetration (Coombes et al., 2011, 2013a; Gao and Tang, 2018; Lv et al., 2015b).

2.3.3 Biogeomorphology on maritime built heritage

In comparison to natural rocky shores and engineered materials used to construct modern infrastructure (e.g. concrete) the biogeomorphological impacts of marine organisms on built heritage assets have received relatively little attention. Given that historic masonry walls are typically constructed of stone, biogeomorphological processes operating on these structures likely resemble those acting on natural rocky shores, as reviewed in the previous sections. However, relatively few studies have directly examined the biogeomorphological roles of marine organisms on built heritage assets (including historic masonry walls) despite the potential implications for the conservation of these structures.

The few studies that have investigated the biogeomorphological impacts of wildlife on maritime built heritage have tended to focus on the biodeterioration of submerged artifacts and structures.

This includes, in particular, damage caused to shipwrecks and other historic assets constructed of timber (e.g. piers) by wood-degrading microorganisms (Björdal, 2012) alongside boring crustaceans and molluscs (Pournou, 2020). However, microborers (algae, fungi, and cyanobacteria) and macroborers (sponges, bivalves, polychaetes, sipunculids, and echinoids) have also been shown to cause the deterioration of culturally significant prehistoric organic materials (Antonelli et al., 2019; Fischer, 2011) and underwater aspects of stone-built heritage (Ricci et al., 2013, 2015; Sacco Perasso et al., 2022), including roman mosaics (e.g. Antonelli et al., 2015; Gravina et al., 2019; Ricci et al., 2008, 2016), marble statues, and other stone artifacts (e.g. Calcinai et al., 2019; Davidde et al., 2010, 2017; La Russa et al., 2013; Ricci and Davidde, 2013; Sacco Perasso et al., 2015, 2022). Mortars used to construct Roman-era masonry walls are thought to be particularly susceptible to the bioerosive effects of rock-boring organisms, such as endolithic bivalves (e.g. *Lithophaga lithophaga*) and sponges (e.g. *Cliona* spp.), and the rasping activities of echinoderms, such as sea urchins (e.g. *Paracentrosus lividus*; Sacco Perasso and Ricci, 2019).

In terms of bioprotection, biofilms can enhance the preservation of submerged heritage assets, such as shipwrecks, by forming protective surfaces that decrease access by agents of abiotic corrosion (Beech and Cheung, 1995; Mugge et al., 2019; Price et al., 2020). Through a similar mechanism, biofilms can protect stone-built heritage located in the supra-tidal zone by mediating surface and subsurface microclimatic variations and by forming layers (i.e. 'rock varnishes') that inhibit the access of aggressive salts and bioerosive organisms (Gadd and Dyer, 2017), as observed by Mottershead et al. (2003) on Fort Perch Rock, a Grade II listed building constructed of sandstone on the northwest coast of England. Furthermore, the natural and human-cultivated colonisation of coralline algae and tube-building worms (e.g. *Pomatoleios kraussii*) on ancient stone-walled fish traps in Hawai'i, southern Africa, and Ecuador is thought to cause the consolidation and strengthening of these walls over time, as the calcareous deposits associated with these organisms naturally cement the stones together (e.g. Costa-Pierce, 1987; Favier Dubois et al., 2018; Keala et al., 2007; Kemp, 2006, 2009).

2.3.4 Research gaps and opportunities

An improved understanding of the biogeomorphological processes that operate on built heritage assets would allow conservation managers to make more informed decisions about how best to conserve historic sites while, at the same time, preserving their biodiversity (Cicinelli et al., 2017). In terrestrial environments, management practices designed to exploit the bioprotective functions of colonising wildlife on stone-built heritage assets have already been developed (Jroundi et al., 2017). This includes examples of 'nature-based' solutions to heritage conservation (Coombes and Viles, 2021), such as the 'soft capping' of ruins with soil and grass (Hanssen and Viles, 2014; Z. Lee et al., 2009; Lim et al., 2013; Miller, 2018; Morton et al., 2011; Naylor et al., 2017a; Wood et al., 2018) and managing ivy on historic walls (Coombes et al., 2017a, 2018; English Heritage, 2010; Sternberg et al., 2011; Viles et al., 2011b). In comparison, the biogeomorphological role of marine organisms on maritime stone-built heritage has received little attention. For instance, a relatively recent report on 'Old Waterfront Walls' by the Construction Industry Research and Information Association (CIRIA) fails to mention the potential impacts of marine organisms on the conservation of masonry walls or other maritime heritage assets constructed of stone (Cork and Chamberlain, 2015). Furthermore, in the coming century, changes in microbial, plant, and animal life as a result of climate change will likely have consequential effects on the deterioration and conservation of heritage sites as processes of bioerosion and bioprotection transform (Davidson et al., 2018; Viles and Cutler, 2012). Given the current lack of understanding of biogeomorphological processes operating on maritime stone-built heritage assets, particularly in comparison to understanding of these processes on natural shores and modern infrastructure, there is an urgent need to investigate wildlife-heritage interactions in marine and coastal environments. As such, this thesis focuses on the following objective in Section 3, Chapter 5 (Paper 2):

Objective: To evaluate the impact of marine wildlife on the rates of deterioration of a material regularly used in the construction and repair of maritime built heritage.

2.4 Broader conceptual frameworks for wildlife-heritage interactions: ecosystem services and values

Biogeomorphological processes, including in heritage contexts, have previously been studied within an Earth System Science framework (e.g. Coombes et al., 2018; Sternberg et al., 2011). Within this framework, built heritage and marine wildlife are considered as interacting components of the environment; built heritage modifies ecological processes and dynamics, and wildlife modifies built heritage through biogeomorphological processes (Richards et al., 2019). Complementary to these approaches, wildlife-heritage interactions can be understood within an Ecosystem Services framework (Comberti et al., 2015; Ehrlich and Mooney, 1983; Millennium Ecosystem Assessment, 2005; UK National Ecosystem Assessment, 2011) or alternative frameworks focusing on human-nature relationships (e.g. 'Nature's Contributions to People'; Díaz et al., 2015, 2018; Kadykalo et al., 2019; Pascual et al., 2017; Peterson et al., 2018).

Ecosystem services are defined as the direct and indirect outputs of the environment that benefit people and society (UK National Ecosystem Assessment, 2011). Within an ecosystem services framework, the bioprotective effects of marine organisms on heritage assets can be considered as a regulatory service; that is, colonising biota regulates near-surface microclimatic conditions, thereby reducing the efficiency of mechanical forms of material breakdown and aiding building conservation (Naylor et al., 2017a). In addition to regulating microclimatic conditions, marine wildlife is associated with several other regulatory services, including erosion prevention and carbon sequestration, as well as provisioning services (e.g. food), cultural services (e.g. recreational and educational opportunities, aesthetics), and supporting services (e.g. habitat provision, carbon sequestration) that benefit human well-being (Austen et al., 2011; Burdon et al., 2017; Fletcher et al., 2012; Jones et al., 2011; Potts et al., 2014; Turner et al., 2014). Marine organisms have even been recognised as delivering services related to cultural heritage, as they are associated with

cultural practices and spiritual traditions (Beaumont et al., 2007; Garcia Rodrigues et al., 2017; Millennium Ecosystem Assessment, 2005; Tengberg et al., 2012).

At the same time, marine wildlife is also associated with several functions that negatively impact society (Friess et al., 2020; Limburg et al., 2010; Riisager-Simonsen et al., 2020; Willis et al., 2018). In the context of stone-built heritage conservation, these 'ecosystem disservices' include biodeteriorative processes that cause undesirable changes to a structure's appearance or the breakdown of building materials (Lyytimäki and Sipilä, 2009). Other disservices related to marine growth on built heritage assets might include the negative impacts of colonising organisms on health and safety (e.g. slippery marine algae on slipways), odour and aesthetics, threats to local biodiversity (e.g. invasive species), and the cost and implementation of maintenance regimes (Lyytimäki et al., 2008). In some cases, marine organisms may both positively and negatively impact human wellbeing, concurrently (Limburg et al., 2010); for example, bioerosive species may cause physical damage to heritage assets while, at the same time, enhancing local biodiversity.

As with heritage sites, the values associated with marine organisms are broad, flexible, and in constant evolution; perceptions of wildlife-heritage interactions may vary over time and space, with attitudes varying between individuals and populations. For instance, in the built environment, the impact of biological growth on the aesthetic value of heritage assets has been viewed both positively and negatively (English Heritage, 2010). On the one hand, biological growth is perceived to negatively alter the appearance of structures through 'greening' or by reducing the visibility of architectural features of interest (Antunes et al., 2015; Pardela et al., 2022; Viles et al., 2011b). On the other hand, biological growth may contribute to a structure's sense of 'authenticity' and 'age' or provide texture and colour to otherwise dull and homogenous surfaces, thereby enhancing its appeal (Brimblecombe and Grossi, 2005; English Heritage, 2010). In marine and coastal environments, wildlife has been shown to impact upon aesthetic preferences and self-reported interest levels (Fairchild et al., 2018; Tribot et al., 2018). For example, Fairchild et al. (2022) recently

found that facets of biodiversity (e.g. species richness) strongly enhance the aesthetic appeal of seawalls and other artificial structures. These values and perceptions likely affect how structures are managed (e.g. maintenance regimes and conservation practices; Dahdouh-Guebas et al., 2020; Ferraby, 2007), although these effects remain understudied. For example, while the services and disservices associated with marine wildlife have been broadly considered (e.g. Burdon et al., 2017; Potts et al., 2014), research is lacking in the specific context of maritime built heritage (although see Evans and Davidson, 2019). Therefore, in order to address this gap in understanding, this thesis focuses on the following objective in Section 2, Chapter 4 (Paper 1):

Objective: To identify current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage

By investigating the services and disservices associated with marine growth on heritage assets (e.g. Paper 1–2) and the potential for historic structures to provide ecological benefits to marine wildlife (e.g. Papers 3–4), this research contributes to a growing number of attempts to integrate heritage within frameworks that focus on human-nature relationships (e.g. Evans and Davidson, 2019; Firth, 2020; Fluck and Holyoak, 2017; Powell et al., 2018).

2.5 Research methods and challenges

A range of laboratory- and field-based methods have been used to investigate the impacts of maritime structures on ecological processes and dynamics (Taormina et al., 2022) as well as biogeomorphological interactions on natural rock and engineered materials in marine and coastal environments (Moses et al., 2014; Pappalardo et al., 2016). Qualitative techniques have also been used to understand the values and benefits people associate with marine wildlife, including organisms found on artificial structures (e.g. Fairchild et al., 2022). Despite some inherent limitations, when used in combination, these methods can help identify and address research questions relating to wildlife-heritage interactions and feedbacks.

The following section reviews several methods that can be used to investigate interactions between marine wildlife, built heritage, and asset/conservation managers, including: (i) qualitative methods, such as interviews and questionnaires; (ii) laboratory experiments; (iii) field experiments, with a particular focus on test walls and exposure trials, and; (iv) ecology surveys. Given the scope of my research and the range of methods available, this section does not attempt to review all possible methods. Instead, by considering the benefits and challenges associated with several techniques commonly used in heritage science and coastal research (i.e. marine ecology, coastal biogeomorphology), this section provides contextual information that is used to justify the suite of methods used in this thesis.

2.5.1 Qualitative methods

Qualitative approaches are used in ecology and heritage science to gather information on management practices and identify the opinions and priorities of a target population (e.g. Mukherjee et al., 2015; Richards et al., 2018; Sutherland et al., 2018; White et al., 2005). Questionnaires and interviews represent the most frequently used methods for collecting qualitative data, with both approaches previously used to investigate public and stakeholder perceptions towards marine ecosystems (e.g. Fairchild et al., 2018, 2022; Hynes et al., 2014; Jefferson et al., 2014; Tribot et al., 2019). Each of these methods has its own unique set of advantages and disadvantages, and as such, are often used in combination (i.e. a multi-method approach) with the aim of providing a holistic understanding of attitudes and perceptions (e.g. Evans et al., 2017).

Questionnaires—especially those conducted online—provide a practical, robust, and cost-effective way of gathering data from a large or geographically dispersed population (McGuirk and O'Neill, 2016; Newing, 2011). For instance, questionnaires have successfully been used in perception studies to determine attitudes towards marine wildlife and associated management practices (e.g. eco-engineering strategies) at a national (e.g. Jefferson et al., 2014; White et al., 2017) and international

scale (e.g. Kienker et al., 2018; Strain et al., 2019). However, several problems are associated with using questionnaires and these include: (i) low response rates, (ii) superficial responses that do not provide wider context (i.e. lack of nuance/insight), (iii) incorrect feedback caused by interpretation issues or survey fatigue, and (iv) dishonest answers. As such, data obtained through questionnaires are often used to provide a framework for more intensive forms of qualitative research, such as interviews and focus groups, that allow key themes, concepts, and meanings to be teased out and developed (McGuirk and O'Neill, 2016). Although interviews can be time-consuming and costly, they can provide valuable context that can help situate potentially differing perspectives and practices (Richards et al., 2018). Importantly, in the context of this thesis, qualitative methods provided a means of identifying gaps in evidence and understanding that could be used to formulate pertinent research questions for subsequent field-based analyses (White et al., 2005).

2.5.2. Methods in coastal biogeomorphology

2.5.2.1 Laboratory experiments

Laboratory studies have commonly been used in biogeomorphological research to investigate the bioprotective and/or biodeteriorative effects of wildlife on natural rock and engineered materials, including those used to construct and repair stone-built heritage assets (e.g. Coombes and Naylor, 2012; Z. Lee et al., 2009; Wood et al., 2018). For example, simulated weathering experiments have been used to assess the influence of different types of marine biotic covers on surface and subsurface microclimatic regimes (Baxter et al., 2022; Coombes et al., 2017b; La Marca, 2017), microtopographic fluctuations (Yuan et al., 2019) and rates of material breakdown (Coombes et al., 2018; Gowell et al., 2015). Laboratory weathering simulations offer several advantages over field experiments when investigating the biogeomorphological impacts of biotic covers. First, particular variables of interest can be isolated and precisely controlled during weathering simulations (Coombes et al., 2018). This includes substrate type and environmental regimes (e.g. temperature, moisture, insolation, etc.) that can be designed to reflect field conditions (Coombes, 2011b;

Coombes and Naylor, 2012; Warke and Smith, 1998) as well as the type and morphology (e.g. thickness) of the biotic cover (Baxter et al., 2022; Gowell et al., 2015). The application of specialist monitoring equipment (e.g. Tinytags®, iButtons) on pre-prepared sample blocks also allows the study of variables that may be difficult to measure directly in the field—and especially in dynamic tidal environments—including subsurface (internal) rock thermal regimes (Baxter et al., 2022; Coombes et al., 2017b; Warke and Smith, 1998). Second, accelerated weathering simulations that subject sample blocks to deteriorative processes at artificially enhanced magnitudes/frequencies allow the study of 'fatigue' modes of breakdown (e.g. wetting–drying, salt crystallisation, freeze–thaw) over relatively short (and manageable) time periods that are not feasible in the field (Coombes et al., 2018; Gowell et al., 2015; Ruedrich et al., 2010).

Despite the advantages of using weathering simulations to investigate the bioprotective and/or biodeteriorative effects of biotic covers, concern exists over how representative these experiments are of wildlife-substrate interactions in the field. For instance, it is not known whether processes of rock breakdown monitored during accelerated weathering simulations are representative of deteriorative processes that naturally operate over longer time periods. Laboratory studies also tend to use small samples that are uniform in size and shape (i.e. cuboid), and this is associated with several problems, including: (i) an overemphasis of edge effects and the impact of this on subsurface (internal) temperature and moisture regimes; (ii) a failure to differentiate the effects of mineralogical and structural variations (e.g. bedding) that typically operate at larger scales in the field; (iii) the small size of sample blocks in comparison to many weathering features observed on natural rock; and (iv) a failure to replicate the confining pressures to which larger rock masses are subject (Smith et al., 2005; Smith and Warke., 1996). Furthermore, compared to the lifespan of many stone-built heritage assets and natural rocky shores, sample blocks used in weathering simulations are typically exposed to environmental drivers for a relatively short amount of time (Richards, 2020). Challenges associated with using living organisms in laboratory experiments—and especially marine organisms that require saltwater to survive—means they are rarely used in weathering simulations.

Instead, artificial materials or 'non-living' biogenic structures (e.g. shells) that are more manageable have been used to simulate living organisms; for example, Gowell et al. (2015) used chemically inert black foam to simulate live seaweed, whereas Coombes et al. (2017a) and Baxter et al. (2022) used empty shells to simulate encrustations of barnacles and mussels, respectively.

The inherent uncertainties associated with laboratory simulations means these studies can face upscaling issues, particularly when relating findings taken from small (cm-scale) sample blocks measured over a period of weeks to months to large (m-scale) stone-built heritage assets or km-scale natural rocky shores that have been exposed to environmental conditions for hundreds to thousands of years (Richards, 2020; Smith and Warke., 1996; Viles, 2001).

2.5.2.2 Field experiments

Undertaking biogeomorphological research in the field removes some of the uncertainties associated with laboratory experiments. Field-based research can be done *in situ* using a variety of techniques (see Pappalardo et al., 2016, and Moses et al., 2014, for reviews). In summary, these include: (i) direct observations and measurements of bioprotective and bioerosive features, such as boreholes (e.g. Healy, 1968; Kennedy et al., 2019; Mottershead et al., 2003; Naylor et al., 2012b; Trudgill, 1987; Trudgill and Crabtree, 1987; Trudgill et al., 1987); (ii) indirect estimations of bioerosion rates through the analysis of faecal pellets from grazing organisms (e.g. Abensperg-Traun et al., 1990; Andrews and Williams, 2000; Fornós et al., 2006; McLean, 1967, 1974; North, 1954; Schneider and Torunski, 1983; Swantesson et al., 2006; Torunski, 1979); (iii) electronic microclimate monitoring equipment, such as using temperature and humidity loggers (e.g. Baxter et al., 2022; Coombes et al., 2013b; Gonzalez et al., 2021; McAfee et al., 2017, 2018, 2022; Scrosati and Ellrich, 2018) and infra-red cameras (e.g. Jurgens and Gaylord, 2016, 2018; Lathlean et al., 2017; McAfee et al., 2018); (iv) rock and plaster weight-loss tablets used to assess water flow, abrasion, and bio-dissolution rates (e.g. Baxter et al., 2022; Gonzalez et al., 2021; Krklec et al., 2021; Trudgill, 1975; Trudgill, 1976a, b); (v) micro-erosion meters (MEM), traversing micro-erosion meters (TMEM), and

alternative methods for measuring the downwearing of shore platforms (e.g. Foote et al., 2006; Gómez-Pujol et al., 2007; Gonzalez et al., 2021; Mayaud et al., 2014; Moura et al., 2012; Schneider and Torunski, 1983; Spencer, 1985a, b; Stephenson and Kirk, 1998; Trudgill, 1976a, b; Yuan et al., 2018); (vi) methods used to measure surface hardness and compressive strength, such as the Equotip and Schmitt Hammer (e.g. Baxter et al., 2022; Coombes et al., 2013a; Gonzalez et al., 2021; Pappalardo et al., 2016, 2018; Pinn et al., 2008); and (vii) various techniques used to measure surface roughness, such as profile gauges and laser scanning (e.g. Abensperg-Traun et al., 1990; Gómez-Pujol et al., 2006; Pinn et al., 2008).

While collecting data in the field has its advantages, it also associated with several challenges. For instance, field measurements can only be collected using portable devices. In most cases, when conducting research at heritage sites, non-destructive data collection methods are also preferred to avoid any unnecessary damage (English Heritage, 2008; Moropoulou et al., 2013). In dynamic coastal environments, safe access to a field site may only be possible at low-tide or during calm weather conditions. Access may be further restricted when conducting research at heritage sites as permissions from the owner or managing authority are required. Travelling to field sites—and especially remote coastal locations—may also be expensive, both in terms of time and capital. Furthermore, practical and financial constraints associated with fieldwork may be exacerbated by unpredictable circumstances. This includes short-term travel disruption caused by industrial action (e.g. striking rail staff) or adverse weather as well as longer-term disruptions, such as those associated with the COVID-19 pandemic (e.g. nation-wide lockdowns).

As an alternative to the *in situ* analysis of biogeomorphological processes, many of the techniques previously outlined can be performed on samples that are removed from the field (i.e. site specimens). This approach allows for more intensive laboratory-based analysis, such as the identification of bioerosive features through microscopy (e.g. Gómez-Pujol et al., 2007; Hughes et al., 2013b; Morrison et al., 2009; Pomar et al., 2017; Yuan et al., 2019), subsurface salt content

analysis using ion chromatography (e.g. Gonzalez et al., 2021), water absorption tests, and microstructure analysis (e.g. Lv et al., 2015b, 2022). However, removing samples from the field may not always be possible. For instance, permissions are required to take samples from protected heritage sites. In addition, several challenges associated with fieldwork may not be overcome by removing samples from the field. Notably, it can be difficult to determine how long substrata has been exposed to environmental conditions and/or covered with biota unless it is experimentally cleared of any colonising wildlife at the start of an experiment (e.g. Gonzalez et al., 2021; Pappalardo et al., 2018). It may also be difficult to disentangle the contribution of bioerosion from that of other weathering processes (Pappalardo et al., 2016).

2.5.2.3 Exposure experiments

Test walls have previously been used in biogeomorphological research to overcome some of the issues associated with field experiments (e.g. Coombes et al., 2017a, 2018; Hanssen and Viles, 2014; Sternberg et al., 2010; Wood et al., 2018). Made to replicate built heritage structures by using traditional materials, designs (i.e. configuration of masonry), and construction methods, test walls can be exposed to the same environmental conditions as heritage sites (Richards, 2020). However, unlike most built heritage structures, the age of any colonising wildlife that establishes itself on a test wall will be known. Furthermore, materials can be removed from test walls to allow analysis through laboratory-based methods. The use of destructive/semi-destructive techniques that are generally not permitted on built heritage structures (e.g. Schmitt hammer) are also possible.

However, test walls are expensive and time consuming to construct, and it may also take several months or years for wildlife to become established on them (Viles, 2012). Specialist expertise is also required to ensure test walls are constructed properly and safely maintained. Consequently, the construction of test walls is generally more suited to long-term research projects that have greater access to resources (e.g. Coombes et al., 2017a; Wood et al., 2018; but also see Fusade, 2018, and Richards, 2020). In marine and coastal environments, practical and financial constraints associated

with building and maintaining test walls are exacerbated by access issues and harsh weather conditions. Furthermore, in comparison to terrestrial wildlife, it may be particularly challenging to encourage the colonisation of specific types of intertidal wildlife (e.g. barnacles, seaweed, etc.) as they often occupy narrow environmental niches.

Field block exposure trials provide an alternative method to using test walls in biogeomorphological research in marine and coastal environments (Moses, 2000). Exposure trials involve exposing pre-prepared samples to environmental conditions in the field before they are removed for subsequent analysis. Field block exposure trials have been used alongside complementary techniques to determine the bioprotective and/or bioerosive effects of marine wildlife including microscopy (e.g. Coombes et al., 2011; Donn and Boardman, 1988; Hughes et al., 2013a; Jayakumar et al., 2010; Jayakumar and Saravanane, 2009; Naylor et al., 2012b; Naylor and Viles, 2002), laboratory weathering simulations (e.g. Coombes et al., 2017b), surface hardness analysis (e.g. Equotip; Naylor et al., 2012b), compressive strength tests (e.g. Georges et al., 2021; Naylor et al., 2012b), subsurface salt content analysis through ion chromatography (e.g. La Marca et al., 2014), carbonation tests and microstructure analysis (e.g. Lv et al., 2021), and electron probe microanalysis and chloride migration tests (e.g. Chlayon et al., 2018, 2020). The advantages and disadvantages of using field block exposure trials are similar to those associated with using test walls; however, compared to constructing test walls, field block exposure trials are often cheaper and less time consuming to set up. As such, they are more suited to short-term research projects, such as a PhD (e.g. Naylor, 2001). Samples used in exposure trials can also be attached under pre-existing biotic covers (e.g. seaweed canopies) or deliberately positioned in the tidal zone where colonisation by a particular organism is more likely. However, one of the disadvantages of using test walls that is potentially enhanced when using field block exposure trials is that test walls/samples are generally much younger and smaller than historic structures. As such, results can suffer from spatial upscaling issues, especially when comparing cm-scale exposure samples to historic walls that may span several metres. Temporal upscaling issues may also exist when comparing observations of samples exposed for relatively short

periods of time (e.g. months) to surfaces exposed for hundreds and thousands of years (e.g. historic structures, natural shores), thereby failing to account for variable process rates. Combining short term field-based exposure experiments with observations of exiting, *in-situ* structures may therefore provide the best approach for addressing upscaling issues (e.g., English Heritage, 2010; Wood et al., 2018).

2.5.3 Ecology surveys

Various approaches have been used to examine the impact of artificial structures on marine ecology. This includes studies examining the impact of artificial structures on: (i) the biological structure (e.g. taxonomic identity) or (ii) functional structure (e.g. properties/ biological traits) of marine communities, (iii) single-species or (iv) multi-species dynamics, and (v) ecosystem-scale dynamics (e.g. marine-food-web structure and functioning) using holistic approaches, such as Stable Isotopic Analysis (SIA) and trophic-web modelling (see Taormina et al., 2022, for a recent review). Of these approaches, the most common involves examining the biological structure of marine communities associated with maritime infrastructure (Bortone and Kimmel, 1991; Bortone et al., 2000; Taormina et al., 2022).

The data used in previous studies tends to derive from an inventory of recorded taxa and associated quantitative information (e.g. number of individuals, density, biomass, percentage cover, etc.), which can be used calculate univariate indices and define community characteristics in terms of diversity and evenness (e.g. species richness, Shannon index H', etc.). Standard similarly indices (e.g. Bray–Curtis) and multivariate community analyses (Clarke, 1993) can then be used to evaluate the similarities between different communities over time and space in greater detail (Taormina et al., 2022). This may include, for example, comparing communities before and after intentional or unintentional anthropogenic disturbances (e.g. harvesting, pollution, construction, conservation strategies, clearing experiments, etc.) or between artificial structures and natural substrate

(Aguilera et al., 2014, 2019, 2022; Bulleri, 2005b; Cacabelos et al., 2018; Holloway and Field, 2020; Lam et al., 2008; Pister, 2009).

Various destructive and non-destructive methods are used to record inventories of taxa ranging from relatively low-cost *in situ* visual censuses and imagery (Bortone et al., 2000) to relatively time-consuming destructive sampling techniques that allow subsequent analysis in the laboratory (e.g. microscopy). When conducting visual censuses in the field, line transects and quadrats are the most common sampling units used to survey ecological communities. These plot-based methods allow the sampling of populations with a variety of spatial patterns and densities, and although they can be time/labour intensive and are biased towards slow-moving and stationary taxa, they represent a relatively robust and inexpensive means of collecting occurrence and distribution data (Ambrose, 2002). Quadrat sampling has previously been used to investigate communities of marine wildlife on a variety of maritime structures, including modern coastal defences (e.g. Aguilera et al., 2014; Moschella et al., 2005; Pister, 2009), older artificial structures with limited heritage value (e.g. Burt et al., 2011; Hill et al., 2021; Lymperaki et al., 2022; Pinn et al., 2005a), and heritage assets (e.g. Cox et al., 2019; González-Duarte et al., 2018).

Ecology surveys are typically conducted in combination with other data-collection methods used to record environmental conditions and/or other biotic and abiotic variables of interest that may influence community composition (e.g. wave exposure, salinity, substrate type, etc.). This includes various techniques used to record microclimatic conditions (e.g. temperature and humidity loggers, infra-red cameras) and topographic complexity (Frost et al., 2005) including relatively low-cost, coarse (i.e. >1 mm resolution) analogue methods, such as the 'chain method' (e.g. Aguilera et al., 2014, 2019, 2022; Beck, 1998; Hall et al., 2018; Luckhurst and Luckhurst, 1978; Sherrard, 2017; Simon et al., 2013) and a profile gauge (e.g. McCormick, 1994; Pinn et al., 2008; Underwood and Chapman, 1989), and more advanced, digital techniques including structure-from-motion (SfM)

photogrammetry and laser scanning (e.g. D'Urban Jackson et al., 2020; Evans et al., 2021; Lawrence et al., 2021), which can be used to map relatively fine-scale (i.e. <1 mm) surface complexity.

2.5.4 Mixed-method approach

Each method discussed in Section 2.5 is capable of providing valuable information on the interactions and feedbacks between maritime built heritage and marine wildlife or, in the case of qualitative techniques, how these are managed by asset managers. However, mixed-method approaches that combine quantitative and qualitative data collection techniques can bring more understanding than can be gained through one method alone, particularly when investigating complex systems that involve dynamic biophysical processes that are influenced by humans (Hattam et al., 2015; Kinnebrew et al., 2021). While challenging to achieve, adopting a mixed-method approach can make conservation planning and implementation more effective; as noted by Castelló y Tickell (2021, p18), "…such interdisciplinary research allows for the incorporation of social context into conservation plans, reflecting what is locally feasible and important to the community, while working within an understanding of ecological processes".

Given the interdisciplinary nature of my research, this thesis adopts a mixed-method approach to answer research questions relating to wildlife-heritage interactions. Social surveys and desk-based research are combined with field-based experiments and ecological surveys of species presence and abundance. To ensure the findings of my research reflect wildlife-heritage interactions operating in natural systems, field-based research is preferred over laboratory-based experiments. Furthermore, given the time and financial constraints of conducting a PhD, a field-block exposure trial is used instead of a test wall to investigate the impacts of marine growth on the deterioration of materials regularly used to construct and repair stone-built heritage assets.

Chapter 3.

Aim, objectives, and research framework

3.1 Aim and objectives

The work presented in this thesis aims to improve understanding of the two-way interactions and feedbacks between maritime built heritage and the marine wildlife it supports. In doing so, it aims to address the concerns of practitioners responsible for managing heritage sites while also highlighting potential opportunities for joint wildlife-heritage conservation. The overall objectives of the research are shown in Table 3.1.

Table 3.1 Overall thesis objectives

O1. (Paper 1)	To identify current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage.
O2. (Paper 2)	To evaluate the impact of marine wildlife on the rates of deterioration of a material regularly used in the construction and repair of maritime built heritage.
O3. (Paper 3)	To determine whether communities of marine wildlife supported by historic maritime structures differ to those found on natural rocky cliffs and modern concrete infrastructure.
O4. (Paper 4)	To develop and apply a methodology for identifying joint priority areas for biodiversity and maritime heritage conservation at a regional scale.

These objectives aim to directly address the gaps in understanding identified in the literature review (Section 1, Chapter 2) and a survey of practitioners that is detailed below and presented in Section 2, Chapter 4 (Paper 1). By addressing these objectives and the overall aim, this thesis:

(i) Contributes to the fields of biogeomorphology and heritage science by examining the bioprotective and/or bioerosive effects of biotic covers on a material commonly used in built heritage conservation;

(ii) Contributes to the fields of marine ecology and eco-engineering by investigating the ecological value of design features characteristic of historic masonry structures, and;

(iii) Addresses some of the concerns of practitioners concerning wildlife-heritage interactions and informs practical conservation through the identification of joint-priority conservation areas and potential win–win conservation strategies.

The thesis findings are, therefore, intended to be relevant to researchers from a range of disciplines (i.e. heritage science, geomorphology, marine ecology) as well as practitioners responsible for managing maritime heritage assets and marine wildlife conservation.

3.2 Methodology

3.2.1 Overarching framework

The research was structured using a novel conceptual framework of the interactions and feedbacks between built heritage, marine wildlife, and practitioners responsible for managing cultural heritage and biodiversity in marine and coastal environments (Fig. 3.1). The framework was developed by reviewing existing literature and methodological approaches to understanding geomorphology-ecology interactions as well as stakeholder perceptions and management practices (Chapter 2). The framework responds to a range of connections/challenges discussed in the literature review (e.g. Table 2.2), including several that are directly investigated/addressed in the thesis, notably: (i) the values, benefits, and services as well as disservices associated with marine growth on heritage assets (Chapter 4, Paper 1), (ii) the influence of marine wildlife on geomorphological processes operating on built heritage assets (Chapter 5, Paper 2), (iii) the influences of heritage assets on ecological processes and dynamics (Chapter 6, Paper 3), and (iv) methods for identifying win–win conservation priorities (Chapter 7, Paper 4). Other connections illustrated in Fig. 3.1, such as the influence of environmental controls on marine ecosystems and the deterioration of stone-built heritage assets, were not directly studied given that extensive research already exists on these topics (e.g. Doehne and Price, 2010; Kunze et al., 2021; Smith et al., 2008). This ensured my research remained relevant to practical conservation and focused on those connections with the least evidence and understanding.

To ensure the outcomes of the thesis addressed the concerns of those responsible for managing marine wildlife and maritime built heritage, attitudes towards the colonisation and growth of marine wildlife were first evaluated; a perception study was undertaken to identify perceived gaps in evidence and advice relating to the management of marine growth on historic maritime structures (Paper 1). The outcomes of the perception study were then used to develop field experiments (i.e. a field-block exposure trial) and on-site assessments (i.e. ecology surveys and environmental assessments) aimed at addressing some of these concerns, namely the impact of marine growth on the deterioration of materials used to construct and repair historic masonry structures (Paper 2), and the ecological value of heritage assets compared to other maritime structures (Paper 3). Site-specific field data from these experiments/assessments were then used to inform the development of a novel methodology for quantifying the full extent of marine engineering structures (including heritage assets) at a regional scale, and for identifying priority structures for joint biodiversity and heritage conservation (Paper 4). Figure 3.2 shows how the four papers presented in this thesis map onto the research framework.

3.2.2 Study sites and methods

To address the aims of the thesis, a mixed-method approach was used, drawing on the methods used in a range of disciplines across the social and natural sciences, as detailed in Table 3.2. The following section provides a summary of the methods used during each phase of the project, with further details provided in the methods sections of the relevant papers. A variety of field sites from across the UK were used to address the research objectives (Fig. 3.3), which were selected for various reasons including their appropriateness for addressing specific research objectives and ease of access (i.e. safety and permissions).

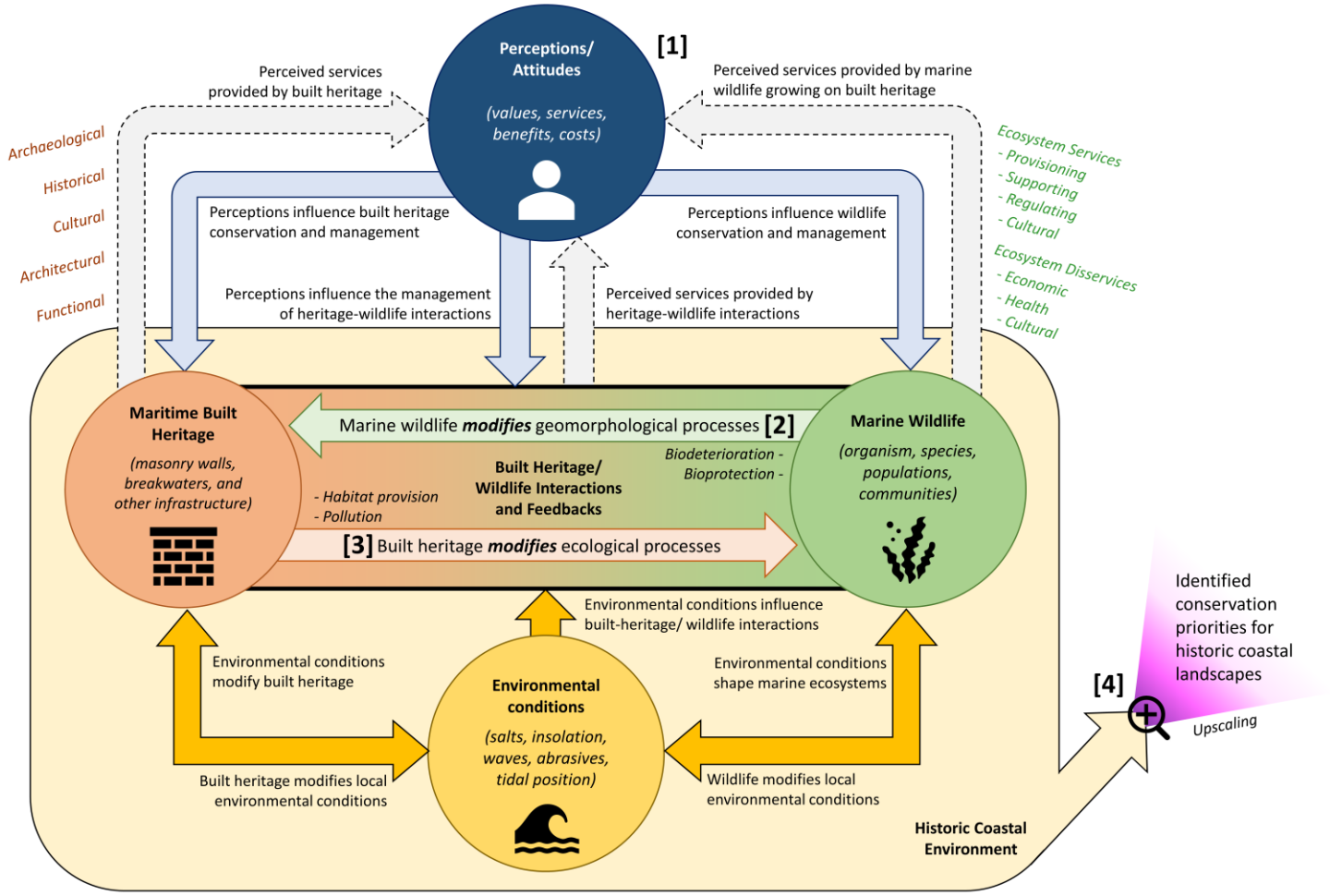


Fig. 3.1. Thesis conceptual framework of the interactions and feedbacks between built heritage, marine wildlife, and marine asset managers in intertidal environments. [1] Paper 1 (Chapter 4, p62) establishes current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage; [2] Paper 2 (Chapter 5, p98) evaluates the impact of marine wildlife on the rates of deterioration of a material regularly used in the construction and repair of maritime built heritage; [3] Paper 3 (Chapter 6, p123) provides an assessment of the ecological value of maritime built heritage by comparing the biodiversity and physical habitat characteristics of these structures to natural rocky cliffs and modern concrete infrastructure; [4] Paper 4 (Chapter 7, p152) presents a novel methodology for identifying joint wildlife-heritage conservation priorities at a regional-scale.

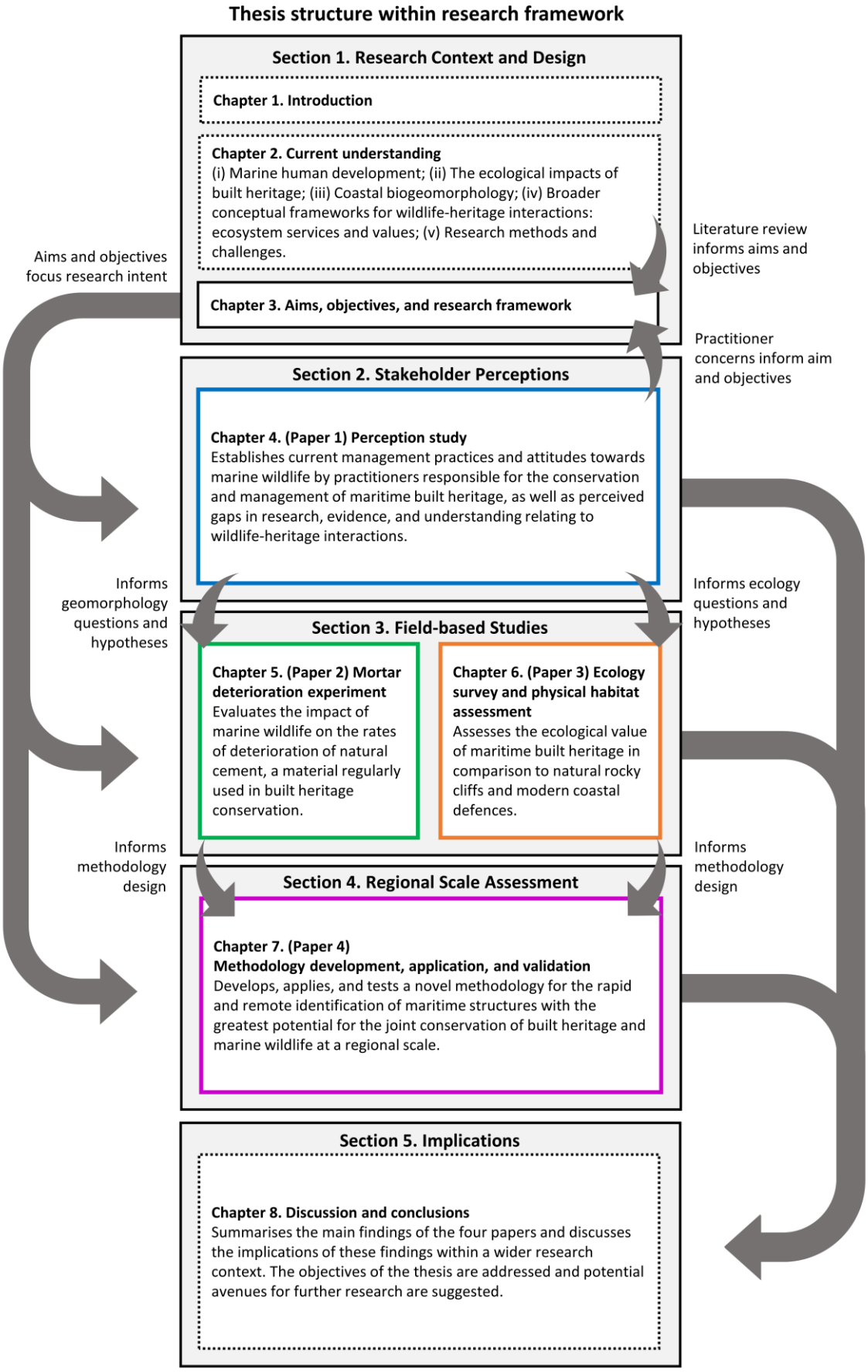


Fig. 3.2. Research framework and thesis structure. Developed from Fig. 1.1.

3.2.2.1 Qualitative research

In Paper 1 (Chapter 4) qualitative methods were used to establish current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage. In addition, data were collected on the perceived gaps in evidence and advice relating to managing marine growth on heritage assets to guide subsequent research during the later phases of the project (e.g. Papers 2–4). An online questionnaire was used to collect data on the attitudes and practices of the target group, and semi-structured interviews were used to gain valuable context to help situate potentially differing perspectives. The perception study was conducted at a national scale (i.e. Great Britain and Northern Ireland) so that local and regional differences in management practices and perceptions could be identified. Distributing the questionnaire online and conducting the interviews remotely (i.e. via video communication platforms) was the safest and most practical way of collecting data from a geographically dispersed target group, especially during the COVID-19 pandemic, which is when this part of the project was conducted.

3.2.2.2 Field-based methods

Research described in Section 3 (Papers 2–3) was specifically designed to address some of the concerns arising from the perception study (i.e. Paper 1); field experiments were developed to test the perception that (i) colonising wildlife damages materials used to construct and repair maritime built heritage, and (ii) heritage assets provide unique habitats for marine wildlife. A multi-method approach was used to collect data in the field, drawing on research methods used in coastal geomorphology and marine ecology studies. In Paper 2 (Chapter 5), a field block exposure trial was used to evaluate the impact of marine wildlife (i.e. seaweed) on the rates of deterioration of natural cement-based mortar, a material regularly used in built heritage conservation. Using microclimate monitoring and three different indicators of weathering and material breakdown (surface hardness, surface roughness, and ultrasonic pulse velocity), samples of mortar with and without a cover of

seaweed were compared after 6 months of exposure to intertidal conditions. The trial was conducted at Portland Port, Dorset, England because: (i) the site had an existing cover of algae; (ii) the port is closed to the public and, therefore, the risk of the experiment being disturbed was reduced, and; (iii) permissions for regular access were successfully obtained.

In Paper 3 (Chapter 6), ecology surveys and physical habitat assessments were used to compare the biodiversity and habitat provision of historic (pre-1900s) masonry walls, concrete walls, and natural rocky cliffs at seven locations across the UK (Table 3.2). At each study location, three habitat types (i.e. masonry wall, concrete wall, and natural cliff) are found less than 200 m apart and are broadly comparable in terms of gradient (steep/vertical, 60–90°), aspect, position within the tidal zone (mid-to-high intertidal), the Marine Life Information Network (MarLIN) wave exposure category, and surrounding habitat (i.e. rocky, sandy, or mixed). On the outer, seaward-facing surfaces of the walls/cliffs, quadrat sampling was used to analyse differences in species richness and community composition, and SfM photogrammetry was used to analyse differences in fine-scale topography. The topographic surveys were complemented by physical habitat assessments to compare the provision of cryptic microhabitats associated with internal void space on the walls and cliffs. In addition, an inventory (presence/absence) of taxa found within these microhabitat features was recorded to determine the contribution of cryptic microhabitats to the overall ecological value of the different structure types.

3.2.2.3 A methodology for regional-scale joint-conservation assessment

In Paper 4 (Chapter 7) historical datasets (e.g. heritage records) and findings from Papers 1–3 were used alongside remote-sensing data and records of modern coastal defences to develop and test a methodology for (i) the rapid and remote mapping of maritime structures (including heritage assets) at a regional scale, (ii) predicting the ecological potential of structures based on key features including construction type and tidal position, and (iii) identifying priority structures for joint biodiversity and heritage conservation. The Isles of Scilly were used as a geographically confined

case study due to their long history of human marine development that dates from the Neolithic to the present day. By evaluating the ecological potential and heritage value of structures using a novel and ground-truthed scoring system, priorities for joint heritage and biodiversity conservation and other managed interventions were identified.

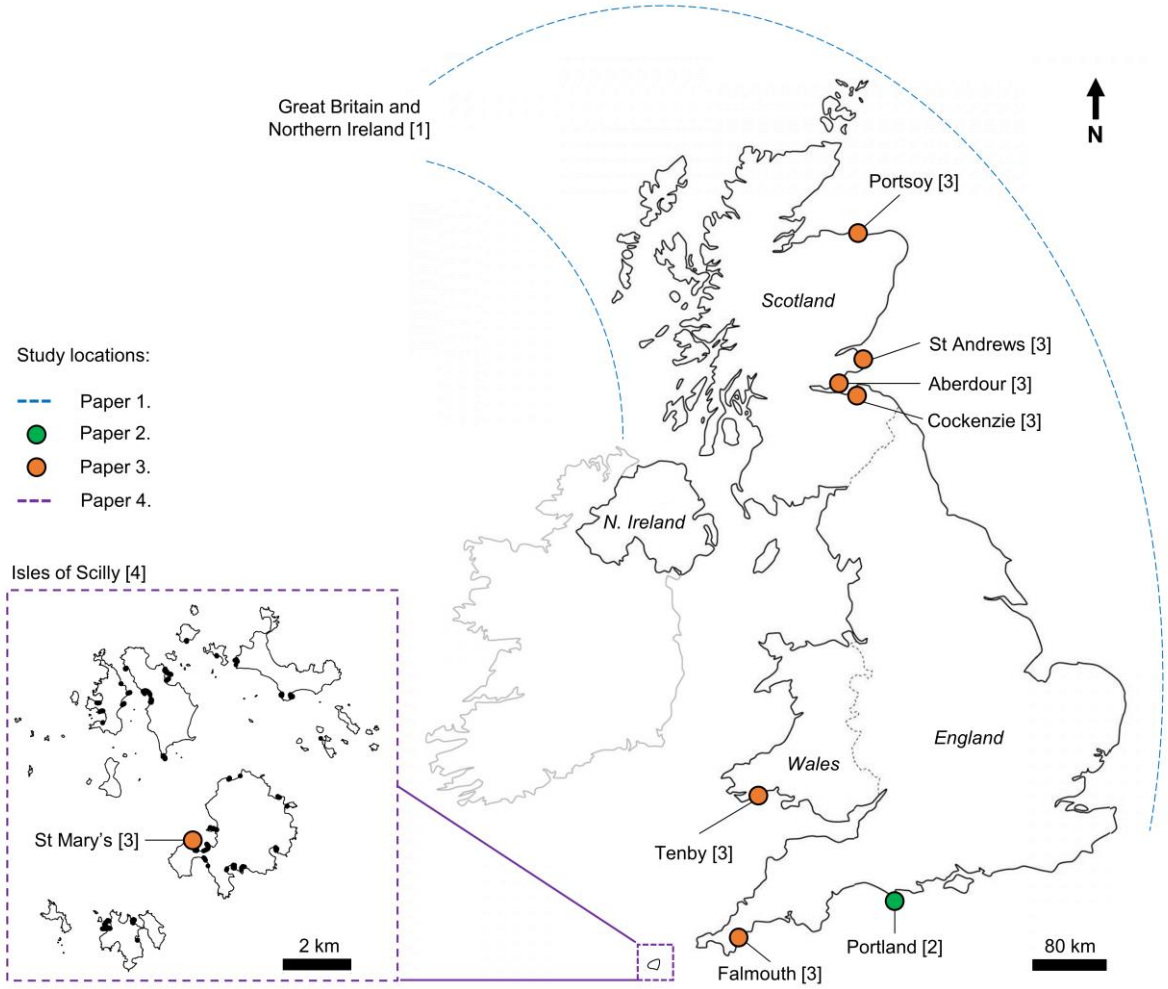


Fig. 3.3. Study locations for different phases of the project. Paper 1—A survey of harbour masters and marine managers from Great Britain and Northern Ireland; Paper 2—A field-block exposure trial conducted at Portland Port, Dorset (green dot); Paper 3—Ecology surveys and physical habitat assessments at seven locations around the UK (i.e. St Mary's, Falmouth, Tenby, Cockenzie, Aberdour, St Andrews, and Portsoy; orange dots); Paper 4—The development, application, and ground-truthing of a methodology to identify priority conservation areas on the Isles of Scilly (enlarged purple box).

Table 3.2. Study locations and methods used in each phase of the project. Further details on these methods are found in the respective papers.

	Study Locations		Methods		
Objective	**Location**	**Rationale**	**Methods**	**Rationale**	**Page**
To establish management practices and practitioner attitudes towards marine wildlife (Paper 1).	Great Britain and Northern Ireland (i.e. Over 310 individuals, organisations, coastal partnerships, and professional bodies contacted remotely via email from across the country)	By contacting potential participants at a national scale, local and regional differences in management practices and perceptions can be identified. A representative sample is also likely to be achieved.	Online questionnaire (analysed using Nvivo software) Semi-structured interviews. Conducted remotely via telephone or online using video communication platforms. (analysed using Nvivo software)	Provides an overview of perspectives and attitudes of a large and geographically dispersed target group. Provides context to help situate differing perspectives. Remote interviews allow data to be collected when face-to-face contact is not possible (e.g. during the COVID-19 pandemic)	p62
To evaluate the impact of marine growth on the rates of deterioration of a conservation material (Paper 2).	Portland Port, Dorset, England (50°33'49"N, 02°25'31"W)	Portland Port is a private port and therefore there is no public access. This reduces the risk of members of the public disturbing an experiment. Ease of access and permissions. Existing cover of algae. History of biogeomorphology research at the study site (e.g. Coombes et al., 2013b)	Six-month field-block exposure trial and subsequent laboratory analysis: • Surface hardness (Equotip Piccolo 2, D-Type) • Surface roughness (3D microscopy, optical profilometer) • Ultrasonic pulse velocity (Portable Ultrasonic Non-destructive Digital Indicating Tester, PUNDIT)	Allows the assessment of biotic covers on three indicators of material breakdown (i.e. surface hardness, roughness, and ultrasonic pulse velocity).	p98

Table 3.2. Continued.

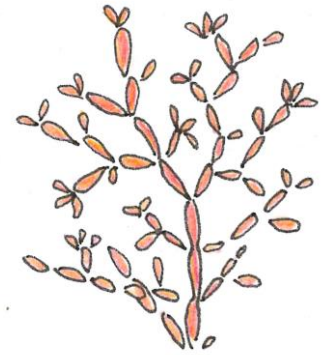
	Study Locations		Methods		
Objective	**Location**	**Rationale**	**Method**	**Rationale**	**Page**
To determine the communities of marine wildlife supported by historic maritime structures (Paper 3).	St Mary's, Isles of Scilly, England (49°54'57"N, 06°18'56"W) Falmouth, Cornwall, England (50°09'44"N, 05°03'37"W) Tenby, Pembrokeshire, Wales (51°40'25"N, 04°41'52"W) Cockenzie, East Lothian, Scotland (55°58'13"N, 02° 58'00"W) Aberdour, Fife, Scotland (56°03'06"N, 03°17'42"W) St Andrews, Fife, Scotland (56°20'23"N, 02°46'55"W) Portsoy, Aberdeenshire, Scotland (57°41'06"N, 02° 41'27"W)	Each location has a (i) historic (pre-1900) masonry wall, (ii) modern concrete wall, and (iii) a rocky cliff habitat less than 200 m apart and broadly comparable in gradient (steep/vertical, 60–90°), aspect, position within the tidal zone (mid-to-high intertidal), MarLIN wave exposure category, and surrounding habitat (i.e. rocky, sandy, or mixed).	Ecology survey (analysed in PRIMER-e) • Quadrat sampling on outer, seaward facing surfaces of walls/cliffs. • Presence/absence survey of taxa found in cryptic microhabitat features. Topographic complexity analysis • SfM photogrammetry (analysed using Agisoft Metashape, CloudCompare and ArcGIS). • Physical habitat assessment. Thermal regime sampling • Temperature loggers (i.e. iButtons) • Infra-red imagery	Provides occurrence and/or percentage cover data of colonising taxa used to determine species richness and/or community composition. Provides mm-scale surface topography data. Provides data on cryptic microhabitat provision (i.e. dimensions, type, density). Provides data on the temporal and spatial variability of thermal regimes.	p123
To develop a tool to identify priorities for the joint conservation of biodiversity and maritime built heritage (Paper 4).	Isles of Scilly, England (49°54'57"N, 06°18'56"W) (With a focus on the island of St Mary's for ground-truthing surveys)	The Isles of Scilly archipelago has a long history of marine human development and can be used as a geographically confined case-study.	Desk-based analysis of historical databases, infrastructure reports, and environmental data used in combination with ArcGIS. Ecology survey (quadrat sampling, data analysed in PRIMER-e) and on-site environmental assessments.	Allows the identification and mapping of maritime structures, including those with historical value. Allows the ground-truthing of assumptions of a desk-based assessment relating to the ecological value of different structures.	p152

Section 2.

Current Management Practices and Attitudes Towards Marine Growth on Heritage Assets

Section 2 addresses objective 1: identify current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage.

In Chapter 4 (Paper 1), an online questionnaire and a series of semi-structured interviews are used to determine the practices and attitudes of asset managers towards marine growth, and to identify perceived gaps in research, evidence, and guidance relating to wildlife-heritage interactions. Paper 1 is written for a broad scientific audience interested in the views of practitioners and gaps in understanding that would benefit from future research.



Bunny-eared bead-weed (Lomentaria articulata).
Drawn by Hope Calloway.

Chapter 4.

Managing marine growth on historic maritime structures: An assessment of perceptions and current management practices

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Abstract

Maritime built heritage (e.g. historic harbours, breakwaters, etc.) is found widely along the coastlines of Europe. Due to its age and traditional construction, built heritage may represent important and largely unidentified hotspots of biodiversity in marine and coastal environments. At the same time, marine growth (e.g. seaweed, mussels, barnacles, etc.) found on these structures may provide both deteriorative and protective functions. To ensure future research focusing on the two-way interactions between marine growth and built heritage addresses the concerns of those responsible for their management, attitudes towards the colonisation and growth of marine wildlife must first be evaluated. Such attitudes will shape how marine growth is managed at these sites, which in turn may influence biodiversity and built heritage conservation and any associated values. This study assesses how the growth of sessile species and other surface-colonising organisms is currently perceived and managed by those responsible for maintaining maritime built heritage, with a particular focus on historic structures constructed of natural stone. Responses from a semi-quantitative online questionnaire of harbourmasters, coastal engineers, environmental officers, and

* Minor changes have been made to this manuscript to aid the readability and continuity within the thesis. For instance, British English is used instead of American English, and figure and table numbers have been changed. The published journal article is available at: https://doi.org/10.3389/fmars.2022.913972

heritage managers from around the UK (n = 132) were analysed alongside a series of semi-structured interviews (n = 29). Our results demonstrate that attitudes towards marine growth are generally in agreement among practitioners irrespective of their occupation or the historic maritime structures they are responsible for managing. Perceptions of marine growth are mostly positive, but concerns exist regarding its impacts on maintenance regimes, the condition of mortar, and health and safety. As well as highlighting opportunities for a more integrated approach to biodiversity and built heritage conservation, the concerns identified require further research attention to help address potential barriers and conflicts that may arise in practice.

4.1 Introduction

Historic maritime structures including harbours, quays, and breakwaters, provide essential functions to coastal communities (e.g. access to the sea for maritime activities, flood defence, tourism, etc.). In the United Kingdom, many of these structures are valued as heritage assets and are protected through designations as listed buildings or Scheduled Monuments (Fulford et al., 1997). The age, traditional construction, historic value, and location of these structures within dynamic coastal environments mean they often require careful management (Wyatt and Prizeman, 2018). One component of managing these sites involves the growth of marine wildlife, including epilithic marine algae and benthic organisms such as barnacles and limpets, which often colonise the surfaces of these structures. Where still in use, responsible authorities (e.g. harbour authorities, marine facilities, and the Environment Agency) are required to manage marine growth to ensure structures remain safe and operational (e.g. The Port Marine Safety Code,[1] The National Flood and Coastal Erosion Risk Management Strategy[2]), and to meet obligations that promote and protect biodiversity and a healthy marine environment (e.g. The Natural Environment and Rural Communities Act 2006[3]).

Research concerning the interactions between maritime structures and colonising wildlife has tended to focus on (i) the impacts of structures and associated maintenance regimes on marine ecosystems (e.g. Airoldi and Bulleri, 2011; Firth et al., 2016a; Moschella et al., 2005; Sherrard et al., 2016), (ii) the impacts of marine wildlife on the deterioration of engineering materials used in maritime structures, such as natural stone and concrete (e.g. Chlayon et al., 2018; Coombes et al., 2013b, 2017a; Lv et al., 2015b; Mottershead et al., 2003), and (iii) techniques for encouraging the colonisation of marine wildlife on the surfaces of structures as a way of improving local marine biodiversity, termed 'ecological enhancement' (Firth et al., 2016a; O'Shaughnessy et al., 2019; Strain

[1] Accessed at: https://www.gov.uk/government/publications/port-marine-safety-code
[2] Accessed at: https://www.gov.uk/government/publications/national-flood-and-coastal-erosion-risk-management-strategy-for-england--2
[3] Accessed at: https://www.legislation.gov.uk/ukpga/2006/16/contents

et al., 2018). As of yet, however, there is limited understanding of how marine growth is perceived by those responsible for managing these sites, and whether colonisation by marine wildlife (i.e. sessile organisms) is viewed positively or negatively by practitioners. Perception studies have previously been used to understand the opinions and priorities of stakeholders involved in the management of maritime infrastructure in order to guide future research into the development of strategies for implementing multi-functional coastal defences (Evans et al., 2017). An improved understanding of attitudes towards marine growth is essential to ensure that future research focusing on the two-way interactions between marine organisms and maritime structures, including those with heritage value, addresses the concerns of those responsible for their management. Such attitudes may shape maintenance regimes that directly influence the marine wildlife these structures support alongside conservation measures and any associated values. For example, the willingness of harbourmasters to implement eco-enhancement techniques (e.g. retrofitting artificial rockpools to existing walls) or environmentally friendly management practices aimed at encouraging marine colonisation, may, to some extent, be influenced by how they perceive marine growth and its associated impacts. This includes the impact of marine growth on factors relating to the specific responsibilities of managers, such as health and safety, but also other services and values associated with maritime structures and the ecological communities they support (e.g. aesthetic, educational, recreational, etc.).

To address this research gap, we carried out a perception study with more than 130 practitioners involved in the conservation and management of historic maritime structures and marine wildlife in the UK using an online, semi-quantitative questionnaire and a series of semi-structured interviews. As part of a larger project exploring the interrelationships between marine wildlife and historic maritime structures, we designed this study to gain an insight into three areas: first, the perceived impacts of marine growth on the conservation and management of historic maritime structures; second, the perceived advantages and disadvantages of marine growth beyond any supposed impact on the condition of structures; and third, current practices used to remove, manage, and

conserve colonising organisms, and the perceived barriers to the effective implementation of these techniques. By focusing on these three areas, we aimed to identify the dominant perceptions and practices among the respondents as well as any areas of disagreement. We also sought to identify perceived gaps in research, evidence, and advice relating to the management of marine growth on historic maritime structures. The findings from our questionnaire provide the first overview of the attitudes and practices of the target group, whilst our interviews provide valuable context to help situate potentially differing perspectives.

4.2 Methods

4.2.1 Questionnaire

The online questionnaire was designed to maximise engagement among appropriate respondents (Toepoel and Dillman, 2012). Initially, a pilot questionnaire was tested on a group of 20 people to check several design aspects (e.g. language clarity, question format and order). The questionnaire was then modified according to recommendations provided in the feedback (Parfitt, 2005; Toepoel, 2016). Before respondents were asked to participate they were provided with precursory information about the questionnaire, including its broad aims and approximately how long it would take to complete. In order to focus their answers, respondents were also asked to consider "historic blockwork or masonry maritime structures…built pre-1960 that are regularly submerged and exposed by the tide" when responding to the questionnaire.

The final questionnaire contained 17 questions. This included an introductory question that was intended to increase interest and encourage respondents to consider different types of marine wildlife found growing on artificial structures when responding to later questions. As the sole purpose of this question was to encourage engagement and to set the scene, responses to this question were not analysed. The remaining 16 questions were associated with one of four broad themes: (i) five questions on the impacts of marine growth on the conservation and management of historic maritime structures, (ii) three questions on the additional advantages and disadvantages

associated with marine growth on historic maritime structures, (iii) five questions on current practices used to manage and conserve colonising organisms and any associated barriers, and (iv) three questions used to collect attribute data (e.g. occupation) and any final comments (Table 4.1). Four types of questions were used in the questionnaire:

- Rating Scale—Pairs of antonyms (e.g. negatively–positively, encouraged–discouraged) were placed at the left and right ends of a bipolar scale that ranged from 1 to 7. These questions were presented as standalones or within a matrix when consecutive questions had the same response options.
- Likert-type Scale—Respondents were asked how much they agreed or disagreed with a single statement. The horizontal scale ranged from 1 (strongly disagree) to 7 (strongly agree) with 4 as neutral (neither agree nor disagree).
- Open-ended questions.
- Multiple Choice—Respondents were asked to select one or more options from a list of answers depending on the question. Where deemed appropriate, an "other" answer option and comment field were provided.

The design of the scalar questions was carefully considered to reduce the chance of inconsistent answering behaviour and measurement error (Toepoel, 2016). This included using a seven-point scale rather than a five-point scale, providing numbers for every option on the scale (1 to 7), and not using negative numbers or colour (De Beuckelaer et al., 2012; Toepoel and Dillman, 2012).

Attribute data collected during the questionnaire included the occupation of respondents and the names of structures they were responsible for managing. Additional information about the structures including age, material, location, heritage designation, and structure type was determined from analysing publicly accessible databases including the National Heritage List for

England (NHLE),[4] Canmore[5] (the national record of the historic environment in Scotland), and Cof Cymru[6] (an online record of Designated Historic Assets in Wales). To aid analysis, data for each of these attributes was categorised into logical groups. For instance, structure location was categorised according to country (i.e. England, Scotland, Wales, or Northern Ireland), and structure age was categorised according to Cultural Periods defined by Historic England. Occupation was differentiated into five groups according to the primary responsibilities of respondents: (i) Harbourmasters and Managers (i.e. harbourmasters, managers, trustees, and chairpersons), (ii) Engineers (i.e. coastal and/or structural engineers, asset managers, etc.), (iii) Environmental/Biodiversity Officers, (iv) Heritage/Conservation Managers (i.e. National Trust managers, archaeological officers or advisors, etc.), and (v) Other (i.e. any other interested party).

Appropriate questionnaire respondents were recruited using a targeted sampling method. Respondents were identified through email addresses listed on online directories (e.g. the South West Regional Ports Association Directory) and the websites of councils, port associations, harbour authorities, engineering companies, and heritage organisations. Overall, 270 individuals, companies and organisations were directly contacted with personalised emails and invited to respond to the questionnaire. In addition, over 40 coastal partnerships and professional bodies were contacted and asked to disseminate the questionnaire among their members. Of these, 27 responded and shared the questionnaire, including the UK Harbour Masters' Association (UKHMA).

The questionnaire was hosted by JISC Online Survey (formerly Bristol Online Survey) and was made available between 4th June 2020 and 2nd February 2021. All respondents were provided with a participant information sheet before agreeing to respond to the questionnaire. Ethical approval for this research, including the questionnaire and interviews, was obtained following standard procedures of the University of Oxford (ethics approval reference number: SOGE1A2020-162).

[4] Accessed at: https://historicengland.org.uk/advice/hpg/heritage-assets/nhle/
[5] Accessed at: https://canmore.org.uk/
[6] Accessed at: https://cadw.gov.wales/advice-support/cof-cymru

There were 132 responses to the questionnaire from around the UK (Appendix B1), and on average, it took participants 12–15 minutes to complete the questionnaire. At the time of completing the questionnaire, the respondents were responsible for the management and/or maintenance of at least 270 maritime structures, including over 230 harbours, quays, and breakwaters. Of these 270 structures, 16 are registered as Scheduled Monuments and 150 are listed buildings.

Table 4.1. Questions and possible answers included in the questionnaire.

Question Type	Question		Factor/ Perception Assessed	Possible Answers
Multiple Choice	1.		Observed marine wildlife on structures	Multiple
Rating Scale	2.		Impact of marine wildlife on:	
(matrix)		2.1.	- Blockwork/ masonry	1 (Damages) –7 (Protects)
		2.2.	- Mortar/ joints	1 (Damages) –7 (Protects)
		2.3.	- Appearance	1 (Diminishes) –7 (Enhances)
		2.4.	- Overall condition	1 (Damages) –7 (Protects)
Open	3.		The most damaging marine wildlife	Open
Open	4.		The most protective marine wildlife	Open
Multiple Choice, (Single answer)	5.		Whether contractors are employed to conduct maintenance	Yes, No, Unsure, Prefer not to say, Not applicable
Rating Scale	6.		Impact of marine wildlife on:	
(matrix)		6.1.	- Inspections	1 (More difficult) – 7 (Easier)
		6.2.	- Maintenance work	1 (More difficult) – 7 (Easier)
		6.3.	- Maintenance and repair costs	1 (More costly) – 7 (Cheaper)
Rating Scale	7.		Whether the conservation of habitats is considered during maintenance work	1 (Never) – 7 (Always)
Multiple Choice	8.	8.1.	Whether marine wildlife is removed	Yes, No, Unsure, Prefer not to say
(Single answer)		8.2.	Reasons for removing marine wildlife	Invasive species, Maintenance, Health and Safety, Other, Unsure, Prefer not to say
		8.3.	Methods to remove marine wildlife	Pressure washing, Mechanical scrubbers, Cleaning agents, Other, Unsure, Prefer not to say
Open		8.4.	Guidance used for maintenance regimes	Open
Likert-type Scale	9.		Whether there is sufficient guidance	1 (Disagree) – 7 (Agree)
Rating Scale	10.		Impact of marine wildlife on:	
(matrix)		10.1.	- Safety issues	1 (Negatively) – 7 (Positively)
		10.2.	- Water quality	1 (Negatively) – 7 (Positively)
		10.3.	- Recreational and educational activities	1 (Negatively) – 7 (Positively)
		10.4.	- Tourism and commercial activities	1 (Negatively) – 7 (Positively)
		10.5.	- Appearance	1 (Negatively) – 7 (Positively)
		10.6.	- Odour	1 (Negatively) – 7 (Positively)
		10.7.	- Local biodiversity	1 (Negatively) – 7 (Positively)
Open	11.		Additional advantages and disadvantages of marine wildlife	Open
Likert-type Scale	12.		Whether the benefits of marine wildlife outweigh the negatives	1 (Strongly disagree) – 7 (Strongly Agree)
Rating Scale	13.		Whether the growth of marine wildlife should be encouraged or discouraged	1 (Strongly discouraged) – 7 (Strongly Encouraged)
Multiple Choice	14.		Reasons that would make respondents more likely to encourage the growth of marine wildlife	The cost of eco-friendly management techniques was reduced; There was more information on how to conduct eco-friendly management; Evidence of marine wildlife providing various benefits
Open	15.		Structures associated with respondents	Open
Open	16.		Respondents' occupation	Open
Open	17.		Final comments	Open

4.2.1.1 Questionnaire data analysis

The strength of opinions from scalar questions was assessed using Relative Importance Index (RII) analysis. RII is a non-parametric technique for analysing ordinal data from structured questionnaire responses (Richards et al., 2018; Sodangi et al., 2014). The index ranges from 0 to 3. A high RII value suggests respondents predominantly selected answers towards the extremes of the scale (i.e. 1, 2, 6, or 7), indicating a strong preference/opinion or the importance of a factor. A low RII value, on the other hand, suggests respondents predominantly selected answers within the middle of the scale (i.e. 3, 4, or 5), indicating ambivalence or neutrality.

An agreement index (AI), adapted from Richards et al. (2018), was used to show the overall directionality of responses and to test for the agreement between the opinions of the respondents. The index ranges from -1 to 1. An AI value close to 1 indicates that responses were predominantly on the right-hand side of the scale (e.g. 5, 6, or 7); an AI value close to -1 indicates that responses were predominantly on the left-hand side of the scale (i.e. 3, 2, or 1). An AI value close to 0 indicates that there was low agreement among the respondents. Neutral responses were not included in the calculations of AI values as they showed no preference to either side of the scale (Richards et al., 2018). For each scalar question, responses to the questionnaire were pooled (n = 132). Single values of RII and AI representative of all respondents were then determined. In addition, RII and AI values were calculated and compared between respondents categorised into different groups (e.g. by occupation, location, etc.) so that between-group variability in the responses could be analysed.

Visual representations were produced in R (R Core Team, 2021) using the 'ggplot2' package (Wickham, 2016) to determine the overall responses of the target group and any relationships between responses and attribute data (e.g. occupation). Spearman's rank correlation coefficients were used to determine the statistical relationship between responses to different scalar questions. This non-parametric test was used because assumptions of normality, assessed using Shapiro-Wilk tests, were not met.

Open-ended questions were analysed and coded into primary and secondary themes (Table 4.2) using the NVivo software (Release 1.5.1, QSR International (UK) Limited, Daresbury, Cheshire, UK). Responses were further differentiated for certain open-ended questions depending on the subject of the response. For example, for Question 3 (i.e. 'What type of marine wildlife do you consider the most damaging?') responses were differentiated depending on the type of organism mentioned. Organisms with distinct taxonomic classifications that were easily distinguished by respondents (e.g. barnacles) could be differentiated in the analysis to a greater level than those within polyphyletic groups (i.e. organisms grouped together based on similar characteristics rather than a shared common ancestor), such as 'algae', which were necessarily treated in the analysis as encompassing a broader range of species (e.g. macro-algae to unicellular micro-organisms). By grouping responses in this way, patterns within the data were easier to identify, and the chance of misrepresenting the types of marine growth the respondents were referring to was minimised.

Table 4.2. List of primary and secondary themes used to code open-ended questionnaire questions and interviews.

Primary Coding	**Secondary Coding**
Wildlife impacts on the conservation of structures	Damaging Negligible Protective Comparisons to other threats Maintenance regimes
Additional advantages and disadvantages of wildlife	Health and safety Environment and biodiversity Education and recreation Aesthetics
Wildlife management practices	Non-disturbance Removal Conservation Structures as habitats Barriers Guidance and future research

4.2.2 Interviews

Interview participants were primarily recruited through the online questionnaire. Respondents who agreed that they could be contacted at the end of the questionnaire were sent a personalised email inviting them for an interview. One participant who did not want to complete the questionnaire approached us directly to request an interview. All of the interviews were held between June and December 2020, and were conducted remotely via the telephone or online using video communication platforms (e.g. Zoom or Skype). In person, face-to-face interviews were not possible because of travel restrictions imposed by the UK government during national lockdowns in response to the COVID-19 pandemic. During the interviews, participants were invited to expand on themes presented in the questionnaire as well as several new topics including the role of historic maritime structures as habitats for marine wildlife (Table 4.3). Although the structure of the interviews was prepared in advance, the order (and breadth) of questions varied according to the expertise of the participants (Sesana et al., 2019). With permission from the participants, all of the interviews were audio recorded.

Table 4.3. Interview questions.

Theme	**Question**
Background Information	- What is your role? - What types of maritime structures are you responsible for? (functional use, construction type, material, age, etc.)
Structures as habitats	- What kinds of marine wildlife do you find on these structures? (type, rare or threatened, invasive or non-native). - Do any structural features provide habitats for marine wildlife? - How do you manage unintended structural features that provide habitats for marine wildlife?
Wildlife impacts on the conservation of structures	- What impact does marine wildlife have on the condition of structures? How does this compare to other threats? - Are there any other advantages or disadvantages of marine growth that you haven't already mentioned?
Wildlife Management Practices	- When, why, and how is marine growth removed, managed, or encouraged/conserved on the structures you manage? - Is there sufficient guidance concerning how to best manage marine wildlife on maritime structures? What are the research gaps?
Final Comments	- Is there anything else you would like to comment on?

In total, 29 interviews were conducted, with the average interview taking approximately 30 minutes. The interview participants had diverse specialisms related to the management of historic maritime structures and marine wildlife (Appendix B1), and between them, worked with or were responsible for at least 97 historic maritime structures from across the UK.

4.2.2.1 Interview data analysis

The interviews were transcribed, analysed, and coded using the NVivo software (Release 1.5.1, QSR International (UK) Limited, Daresbury, Cheshire, UK) according to the same primary and secondary themes used to code the open-ended questionnaire questions (Table 4.2). Illustrative quotes from each theme were then identified to provide context to the views that emerged during the questionnaire and throughout the study.

4.3 Results

The results are presented based on the primary and secondary themes from the NVivo coding (Table 4.2). The results are supported by illustrative quotes and the analysis of quantitative data derived from responses to scalar questions in the questionnaire.

4.3.1 Impacts of marine growth on the condition of structures

Questionnaire respondents tended to indicate either a neutral or negative perception of the impact of marine growth on the condition of structures (Fig. 4.1, Q2). More than half (55%) considered the effects of marine growth on stonework to be insignificant, although a considerable minority (27%) viewed marine growth as a cause of damage. Most respondents held negative perceptions of the impact of marine growth on the condition of mortar, with 57% suggesting damaging effects. This is further indicated by an AI value close to -1 for Question 2.2 (Fig. 4.1). Interview participants generally perceived the impacts of marine growth on the overall condition of historic maritime structures as “negligible” or minimal (17 out of 29), with several commenting on the “passive” or “benign” nature of marine growth. In general, respondents who worked as environmental officers

perceived the impacts of marine growth more positively than harbourmasters, engineers, or heritage managers, although the variability in opinions between different groups was relatively small (Fig. 4.2a). Furthermore, responses indicated that the perceived risk of damage to a structure was dependent on the type of structure being considered. For instance, several respondents stressed the susceptibility of wooden and metal structural elements to direct and indirect damage caused by marine growth compared to stonework.

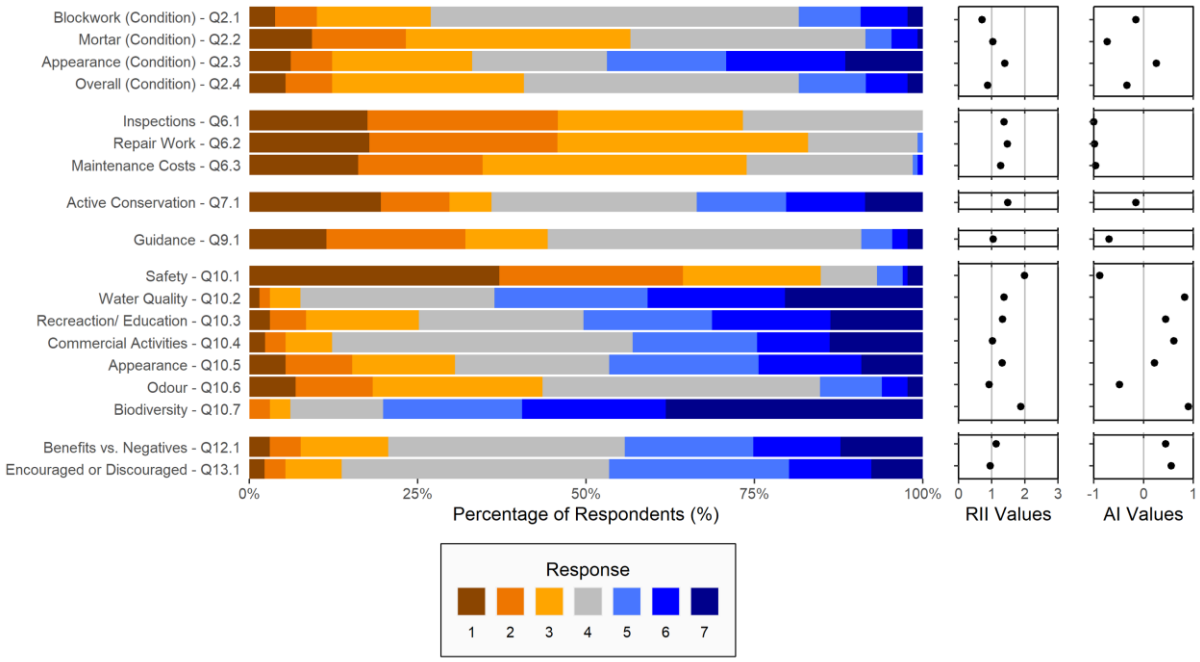


Fig. 4.1. Responses to scalar questions in the questionnaire as a percentage of total respondents with their corresponding RII and AI values. See Table 4.1 for question number and description.

4.3.1.1 Damaging types of marine growth

The type of marine growth that was mentioned the most in relation to damaging affects was marine algae (Fig. 4.3). Questionnaire responses indicated two dominant opinions as to why marine algae were considered damaging (Table 4.4). Firstly, algae holdfasts were perceived to "root" or penetrate material causing cracks to expand (i.e. active damage). Secondly, algae were perceived to increase the susceptibility of material to being removed during storm events due to their fronds increasing drag on the surfaces they are attached to (i.e. passive damage). Other forms of active biodeterioration mentioned by respondents included damage caused by boring worms in mortar

and timber, the rasping of limpets on stone surfaces, and the undermining of structures by burrowing tubeworms (e.g. *Ficopomatus enigmaticus*). Respondents also commented on the perceived damage caused by passive forms of biodeterioration associated with marine growth, including bio-chemical weathering processes facilitated by the enhanced retention of surface moisture by barnacles, and increases in mechanical strain caused by the build-up of organic matter on structures (i.e. the accumulation of oysters and/or seaweed on harbour walls).

Cleaning processes associated with the removal of surface marine growth were identified by several questionnaire respondents and interviewees as a cause of damage. For some, the removal of marine growth through pressure washing, scraping (barnacle removal), pulling (macro-algae removal), and smashing and chiselling (oyster removal) were perceived to be a cause of more damage than the wildlife itself.

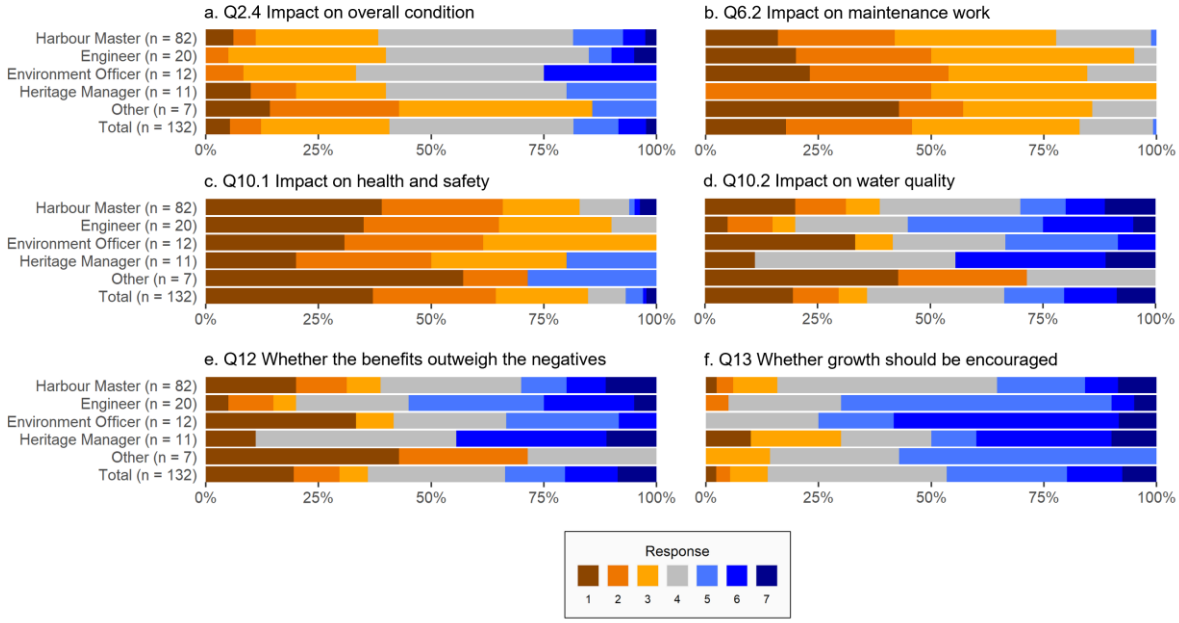


Fig. 4.2. Responses to a selection of scalar questions in the questionnaire differentiated by occupational group. The questions relate to the impact of marine growth on (a) the overall condition of a structure, (b) maintenance work, (c) health and safety, (d) water quality, and whether (e) the benefits of marine growth outweigh the negatives and (f) whether marine growth should be encouraged or discouraged.

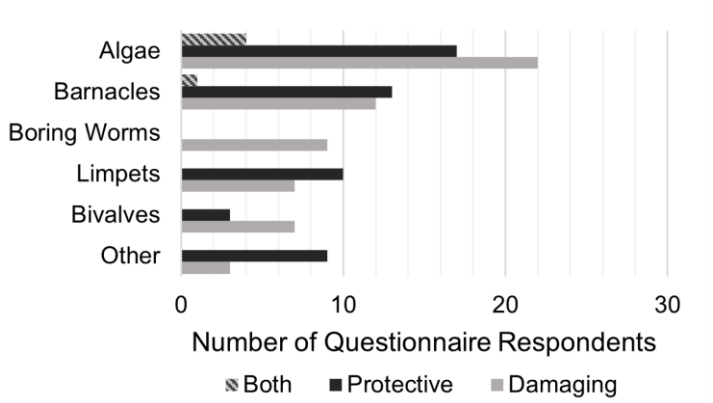


Fig. 4.3. Types of marine wildlife identified by questionnaire respondents as the most damaging and most protective to historic maritime structures.

4.3.1.2 Protective types of marine growth

Marine growth was perceived to contribute to the direct and indirect protection of maritime structures in several ways. The most commonly held perception was that canopy forming marine algae and encrusting species reduced the susceptibility of structures to damage from wave action, abrasion, and boat collisions through the provision of a physical barrier (Table 4.4). For example, respondents commented on how macro-algae (seaweed) protects "…mortar from being washed out by wave action…" and "…improves mechanical impact strength…", and how barnacles "…break up the wave forces…" and "…aid the physical dissipation of waves". Several respondents commented on the perceived ability of marine growth, including macro-algae, barnacles, and lichen, to "seal", "plug", and "fill" cracks in stonework and mortar, while one respondent emphasised the ability of barnacles to "…bind loose masonry…" preventing it from being dislodged.

Marine growth was also perceived to indirectly protect structures by reducing the efficiency of rock weathering processes and steel corrosion through the regulation of near-surface temperature, moisture, and salt accumulation. For example, one respondent commented that barnacles "…thermally protect the substrate…" onto which they attach. Questionnaire respondents and interviewees also emphasised the unintentional, indirect protection afforded to historic maritime structures through marine species that are protected by UK wildlife legislation (i.e. the Wildlife and

Countryside Act 1981). It was suggested that protected species "…help prevent unsympathetic or damaging repair/maintenance to historic structures…" as legislation prohibits the unnecessary disturbance and destruction of their habitats, which in some cases may include the structures themselves.

In addition to being perceived as destructive, marine algae were the type of marine growth most mentioned in relation to its protective properties (Fig. 4.3). Mechanisms of algal attachment that were perceived as damaging by some respondents were, in contrast, perceived by others as non-existent or having limited or no impact. For instance, the perception of one respondent that macro-algae cause damage by attaching through "large roots" contrasts directly with the perception of another respondent who believed that macro-algae only attach to the surfaces of structures. The contrasting viewpoints surrounding the effects of marine algae is highlighted best through four questionnaire respondents who commented on the ability of marine algae to impact both positively and negatively on the condition of a structure.

Table 4.4. Illustrative quotes concerning the perceived impact of marine growth on the condition of historic maritime structures.

Theme	Quotes
Damaging	*"…holdfasts are strong so strong tidal/current conditions can cause weed to be pulled off and chunks of structure to be taken with them."* Environmental Officer
	"Some seaweed can try to put in large roots making small cracks grow bigger." Harbourmaster
	"North Pacific Oysters as a non-native, invasive species are particularly damaging to wall works largely due to sheer numbers that accrue on blockwork." Harbourmaster
	"…wildlife itself does not cause the most damage to the structures…I believe it is the cleaning processes (pressure washing) which actually causes more damage to the structures including the mortar and joints." Harbour Manager
Negligible Effect	*"After working for 47 years at harbours I cannot say I have seen any damage caused by marine wildlife."* Harbourmaster
	"I doubt if marine wildlife is beneficial. Their effect on the integrity of the structure is likely to be neutral." Harbour Trustee
Protective	*"Marine growth can protect structures—less abrasion, less salt in and egress."* Engineer
	"Barnacles can help to protect masonry. They can aid with the physical dissipation of wave energy and also thermally protect the substrate." Engineer (contractor)
	"Seaweed could help to protect mortar from being washed out by wave action as it just attaches to a structure rather than any root structures prizing it apart." Conservation Manager
	"…there were two [threatened] species of mollusc that had been observed in these quite big holes and gaps in the stones. And they were another reason that was added to the fact that this structure had to be saved, in situ…" Engineer
Varied Effect	*"There is a balance here, whilst seaweed roots can have a very minor impact on structures, they also have a minor role in creating protection—it is probably a balance overall."* Environmental Officer

4.3.1.3 Comparison to other threats

Although not directly asked, comparisons between the impacts of marine growth and other threats posed to historic maritime structures were provided by several questionnaire respondents (Table 4.5). For these individuals, wave action and weathering processes were often of greater concern than the effects of colonising wildlife. This view was supported by the interviewees, with more than a third emphasising that the magnitude of damage caused by natural, weather-driven processes was greater than that caused by marine growth. Collisions from boats, inappropriate maintenance techniques, and the damaging effects of rooting (non-marine) vegetation were also mentioned as significant causes of deterioration by both the questionnaire respondents and interviewees.

Table 4.5. Illustrative quotes comparing the impacts of wildlife growth to other natural threats and human activity.

Theme	Quotes
Comparisons to other threats	*"…the problems I have dealt with have not been caused by marine growth or marine wildlife. It is the physical environment…and/or human activity…that have caused the majority, if not all of the problems I have had to address."* Engineer
	"I think most of the damage that occurs to our assets is physical damage caused by storm events, rather than by anything particularly to do with marine overgrowth" Environmental Officer
	"Heavy rain on top of the surface…might wash out some of the infill…so then you get a collapse. So, it's maybe not always wave action as opposed to some rain action…" Harbourmaster
	"It what's in the intertidal that suffers the most damage. Though that's probably more to do with the wetting–drying cycle than any biota" Sustainability Manager
	"Most time my problems I've had are not due to…marine growth or wildlife, it's all about the structures had some impact from a ship or a fishing boat" Engineer
	"…it is not always marine weed or animals that effect the harbour. It is coastal plants that can grow on the dry areas and cracks of non-pointed harbour walls and quays." Harbour Trustee and Archaeological Advisor

4.3.2 Impacts of marine growth on maintenance work

Questionnaire responses collectively indicated that marine growth is perceived to have a negative impact on structural inspections, and the cost and implementation of maintenance work (Fig. 4.1, Q6). This is highlighted by AI values equalling or close to -1 for the three parts of Question 6. The negative perception of marine growth on maintenance work was found to be relatively consistent among subsets of respondents differentiated by location (e.g. England, Scotland, Northern Ireland, and Wales), occupation (e.g. harbourmaster, environmental officer, etc.; Fig. 4.2), and the structures they were responsible for managing (e.g. structure type, age, material, or heritage designation). The

perception that marine algae “obscure” or “hide” structural defects from visual inspections and underwater assessments was the issue most mentioned by questionnaire respondents. This view was echoed by several interview participants who were negative about the impact of marine growth on assessments of stonework and mortar in the intertidal zone. While the majority of respondents expressed the view that marine growth negatively impacts maintenance work, the perceived severity of these impacts differed among individuals. For example, some respondents commented on marine growth as “awkward” or a “nuisance” rather than a serious threat to the maintenance of structures. In contrast, several other respondents emphasised the negative impact of marine growth on the restoration of coastal heritage assets, such as Scheduled Monuments, and the safety and legal implications associated with accidents or structural failures due to inadequate inspections caused by marine growth. The protective properties associated with some marine species viewed in combination with the perceived negative impacts of colonising wildlife on structural assessments led one interviewee to view marine growth as a “double-edged sword” (Table 4.6).

Table 4.6. Illustrative quotes concerning the perceived impacts of marine growth on maintenance regimes.

Theme	Quotes
Inspections	*“It isn't that the algae is the cause of the damage as that is due to many contributing factors, the difficulty can be that algae can hide the damage from inspection.”* Coastal Asset Manager *“Biofouling can hide defects from visual inspection and can impede the performance of assets…”* Engineer *“…kelp on sea walls makes it difficult to survey as kelp reflects the sonar signal.”* Harbourmaster *“…asset management approaches would encourage wanting to see a clean structure so the condition (and consequential safety) of the structure can be objectively assessed.”* Engineer *“…it’s a bit of a double-edged sword because the seaweed or the build-up of organic materials on a structure can protect it from the harsh wave action, but then also it can hide any damage which is being caused by that marine wildlife.”* Engineer

4.3.3 Additional advantages and disadvantages associated with marine growth

Responses indicate a shared negative perception towards the impact of marine growth on health and safety (Fig. 4.2c); over 85% of respondents emphasised the negative impacts of marine growth on health and safety compared to 7% who viewed it as having a positive influence (Fig. 4.1, Q10.1). The overall strength of this negative perception among respondents is highlighted by an RII value close to 2 for Question 10.1, the highest for any of the scalar questions. Marine algae were most

frequently identified as posing a risk to health and safety, followed by invasive Pacific oysters (*Magallana gigas*) and barnacles. Specifically, respondents commented on the tendency of marine algae to increase the slipperiness of surfaces, reducing safe access (i.e. to stairs, ladders, slipways, etc.) and increasing the risk of accidental slips and falls. The sharp surfaces of barnacles and Pacific oysters were identified as a potential cause of scrapes and cuts, and damage to inflatable craft. In contrast, several interview participants commented on the perceived ability of barnacles to reduce the risk of falls and increase safety by impeding the growth of slippery algae and increasing surface roughness, thereby enhancing overall grip (Table 4.7).

Marine growth was consistently perceived to positively influence the environment surrounding maritime structures (Fig. 4.2d). There was an overall perception that marine growth enhances local biodiversity and that filter feeders, such as oysters and mussels, provide valuable ecosystem services by regulating and improving the local water quality, as indicated by AI values close to 1 for Questions 10.2 and 10.7 (Fig. 4.1). As well as being a unique component of ecosystems, marine growth was perceived to contribute to biodiversity by supporting and/or attracting other sessile species and mobile organisms by providing shelter (i.e. canopy forming species) and food. The only cases where marine growth was perceived to negatively impact biodiversity related to non-native invasive species, with concerns relating to the impacts of Pacific oysters most frequently mentioned. Marine growth was also identified as providing educational and recreational benefits including “harvesting”, “angling”, and “wildlife tourism”. However, respondents also discussed the “stink” of algae and the negative effects of marine growth and associated “pests” on boat and harbour operations, such as when algae or bird droppings obscure navigation aids or tidal gauges. A shared negative perception of the smell of marine growth is indicated by an AI value below 0 for Question 10.6 (Fig. 4.1).

Table 4.7. Illustrative quotes concerning the perceived advantages and disadvantages of marine growth.

Theme	Quotes
Health and Safety	*"Algae is the only problem. It has to be removed. Safety will always be the most important issue."* Harbourmaster
	"We have a particular issue with the colonisation of Pacific Oysters…They are classified as an invasive non-native marine species and have a detrimental effect on native marine species. There is also a considerable safety concern…as their shells are sharp and can cause harm to people and damage to property such as inflatable boats." Environmental Officer
	"Barnacles actually improve grip." Conservation Manager
Education and Recreation	*"Opportunities for recreational and educational activities—depends on the species, if just barnacle probably not much value."* Engineer
Biodiversity and Environment	*"Inhabitation by crab and other scavenging species are of particular benefit as these creatures form an essential part of the food chain for other larger species within our marine environment."* Harbourmaster
	"…mussels and oysters may help to improve water quality in the harbour…" Estuaries Officer
Appearance	*"Certainly, the appearance is enhanced: we don't want a blank "polished" structure."* Conservation Manager
	"…growth can interfere with pontoons and can cause scum and surface debris problems as it decays, often overwhelming efforts to keep the surface clear for aesthetic reasons." Environmental Officer

Responses varied concerning the impact of marine growth on the appearance of structures, with 46% and 31% of respondents holding positive and negative perceptions, respectively. This disagreement among respondents is indicated by an AI value close to 0 for Question 10.5 (Fig. 4.1). Those with positive views commented on the "attractive" aesthetics of colonising wildlife, and ability of marine growth to hide modern repairs and blend structures into the surrounding landscape. In contrast, a minority of respondents perceived marine growth as "unsightly" or detrimental to the long-term appearance of structures due to bio-deteriorative processes that enhances material decay.

4.3.4 Reasons and methods for removing marine growth

Over half of the questionnaire respondents (51%) indicated they did not actively remove marine growth from the structures they are responsible for. Possible motivations for this were discussed by several interview participants and included the perception that removing marine growth was costly, unnecessary in most circumstances, and could cause unintended consequences including the colonisation of cleared areas by invasive species or their spread via inappropriate waste management (i.e. disposing of cleared organic material, including invasives, into the sea). Legislative restrictions on the disturbance and removal of marine wildlife imposed by the Marine Management Organisation were also cited as a reason for not actively clearing marine growth, along with the

perception that removal should be avoided as colonisation was "natural" and should be encouraged instead (Table 4.8).

Respondents who indicated that they actively removed marine growth suggested that the main reasons for doing so related to concerns about health and safety or non-native and invasive species, or as a necessary requirement to conduct structural inspections (Fig. 4.4a). The removal of "unsightly" or smelly algae was also mentioned as a reason. Reasons for removing marine growth varied among different occupational groups. Engineers, for example, indicated that they predominantly removed surface-colonising wildlife to allow inspections and maintenance work. Harbourmasters, on the other hand, were more likely to remove marine growth due to safety concerns, while environmental officers and heritage managers were the groups most likely to remove wildlife as a response to non-native invasive species. Pressure washing was the most popular method for removing marine growth, although cleaning agents, scrubbers, and hand-tools are also used (Fig. 4.4b).

Table 4.8. Quotes illustrating why respondents do not remove marine growth from structures.

Theme	Quotes
Non-disturbance	*"…we are not going to start to remove [algae], because (a.) the cost would be phenomenal to clean it and, (b.) we should be looking to allow these colonisations that are natural."* Coastal Asset Manager *"If we removed all of it, it would probably look quite odd and would probably cost us loads of money for very little benefit if anything or negative benefit."* Environmental Officer *"It's all going to be cost driven. And the other thing with ports…you've got the marine management organisation and marine licensing. There are certain exemptions for what you can and can't do with removing growth from structures."* Environmental Officer *"I do not know any facility manager that cleans marine wildlife off their structures on a frolic. It is a tedious, costly, and dirty job that is only undertaken when absolutely necessary."* Marine Manager *"…we do not recommend any removal of biofouling from any structures in the harbour area, this is to minimise the spread of non-native species and to minimise the available surface area for non-native species to colonise."* Biodiversity Officer *"If you start cleaning and removing material…it triggers waste consideration… and then you've got the invasive species element of it, and in removing it, are you causing an invasive species issue…"* Environmental Officer

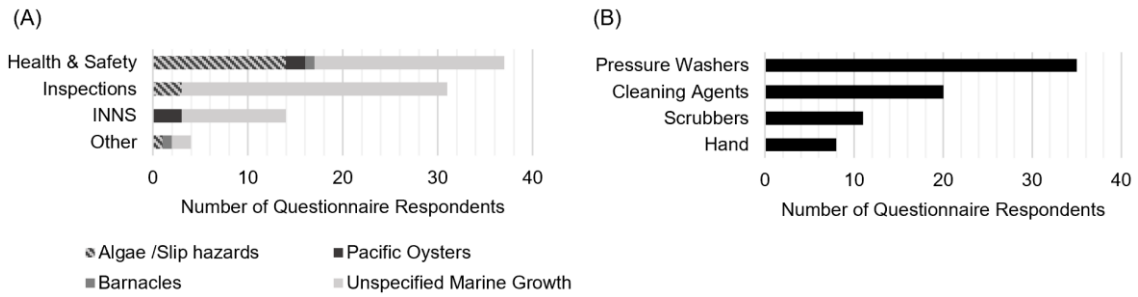


Fig. 4.4. (a) Reasons for respondents actively removing marine wildlife from the structures they manage differentiated by species type/hazard, and (b) methods used by respondents to remove marine wildlife.

4.3.5 Biodiversity conservation

The majority of respondents (61%) indicated they were involved in the conservation of marine wildlife, yet degrees of engagement varied among individuals. Respondents suggested they used both passive and active conservation methods to enhance biodiversity. Passive conservation methods mentioned by respondents include the conscious, non-disturbance of marine growth and habitats during inspections and maintenance work (Table 4.9). This includes leaving weathering features that act as unique habitats for marine wildlife, such as crevices that develop over many years of exposure, unrepaired unless necessary to maintain the safety of the structure. Active conservation methods mentioned by respondents include using eco-friendly cleaning products, conducting wildlife surveys, scheduling maintenance work to avoid important phenological events (e.g. breading seasons), tackling invasive species (e.g. culling), and retrofitting structures with ecological enhancements, such as using textured form-liners and artificial rockpools.

Table 4.9. Quotes illustrating conservation measures adopted by respondents and the reasons for not adopting conservation measures.

Theme	Quotes
Conservation measures	*"I don't tend to go out of my way to attract species growth. But we don't discourage it either. It's best just to let nature take its course. I tend to find when you intervene, things don't go as you plan."* Harbourmaster
	"We have developing crevices in some of our quay walls that we just leave as natural drains for our quays, lobster hidey holes." Harbourmaster
	"We consider it important to live alongside marine wildlife where we can, ensuring that the structure is protected ensures a home for wildlife." Harbourmaster
Reasons for not conserving wildlife	*"We do not have sufficient time, staff or finances to provide conservancy for marine organisms on our estate."* Harbourmaster
	"Maritime structures that are still in use should not be considered as areas for the conservation of marine wildlife and new structures should not be built with this as a consideration." Harbourmaster
	"Our heritage structures are Scheduled Monuments, we cannot change them to create habitat." Operations Manager

In contrast, 16% of respondents indicated they were not involved in any wildlife conservation. Reasons included the cost of implementation, prioritising safety, heritage designations that prohibit significant physical modifications to structures aimed at promoting biodiversity (e.g. the installation of eco-enhancements, such as artificial rockpools), and a general perception that wildlife conservation should not be their responsibility. Among some respondents, there was a belief that the conservation of protected structures (i.e. a listed building or Scheduled Monument) always took precedent over the enhancement of marine biodiversity. For example, one respondent commented that "heritage trumps everything" and there "couldn't be compromise" between heritage and marine wildlife conservation. In contrast, others were less sure, stating that they did not know what was more important or what they would prioritise. A Spearman's rank correlation test showed there was a weak but significant correlation between the degree to which respondents considered marine growth beneficial to a structure's condition (Q2.4) and their involvement in marine wildlife conservation (Q7.1) ($\rho(125) = 0.301$, $p < 0.001$).

4.3.6 Structures as habitats

Historic maritime structures were viewed as "havens" for marine wildlife by several interviewees, including a harbourmaster and an environmental officer (Table 4.10). Harbours in particular were highlighted for providing habitats for a variety of sessile organisms and mobile species, such as fish, marine mammals (e.g. seals), and crustaceans (e.g. prawns, shrimps, and crabs). Several interviewees commented on how structures provided habitat to species with conservation status, including Honeycomb worms (*Sabellaria alveolata*), endangered mussel species, and "priority species of algae". Interviewees also emphasised how historic structures provide nests and feeding grounds for birds, including species of conservation concern such as the ringed plover (*Charadrius hiaticula*), the purple sandpiper (*Calidris maritima*), and the kingfisher (*Alcedo atthis*). In comparison to "modern", "highly polished", "flat concrete" structures, historic structures were described as having "surface texture" and "cavities" or "crevices", which were perceived to encourage the

growth and colonisation of marine wildlife. Although generally this was seen as a positive, some commented on the possibility of historic structures providing habitats to "invasive nasties" or pests such as pigeons and mink. One interviewee expressed concern about historic structures supporting protected species, suggesting that this could cause tensions to arise between stakeholders invested in the conservation of wildlife and others invested in the maintenance and conservation of heritage assets.

Table 4.10. Quotes illustrating the perception that historic structures provide habitats for marine wildlife.

Theme	Quotes
Structures as habitat	*"…we have some of those historical features or gaps within the construction…which have been colonised as nesting sites by black guillemots."* Environmental Officer *"…in a place like the Channel Islands, you have two definitions of structures. Some are free draining…By that I mean, [they] don't have any pointing and external sealing up on the joints between the stones. And therein lies your manna from heaven for your habitats."* Engineer *"I am sure there are crabs and other crustaceans in the crevices. And lots of...different types of seaweed and algae…"* Conservation Manager *"…in terms of providing havens for creatures and things like that, yep, it definitely does. Even slightly higher up, sometimes you get birds nesting in the wall."* Harbourmaster *"…harbours and walls, they're just a haven for marine wildlife. And we do have lots of different priorities species..."* Biodiversity Officer *"[historic maritime structures] are often such a great colonisation possibility for lots of different species some of which are invasive and some of which are natural to the area, so it can be a good thing, but it can be a bad thing..."* Environmental Officer

4.3.7 Research and guidance

Nearly half of respondents (44%) indicated that they believed there was insufficient guidance concerning the management of marine growth on historic maritime structures. Several areas were identified where additional guidance and information supported by research would be welcome. These include (i) the impacts, both positive and negative, of different species on various materials used in the construction and repair of historic maritime structures, (ii) the tangible and intangible values people associate with marine growth beyond any perceived impact on the condition of a structure, including how it influences the structure's aesthetics, (iii) ways to encourage and/or discourage different types of biological growth according to material and structure type, (iv) clarity on how best to combat the spread of invasive species whilst also promoting biodiversity (i.e. clearing marine growth vs. leaving it undisturbed), (v) advice on effective ecological enhancement techniques, with a particular focus on methods used at historic sites to provide mutual benefits for

heritage and marine wildlife, and (vi) information on whether heritage assets provide unique habitats for marine wildlife (i.e. sessile species but also mobile organisms) compared to modern structures (Table 4.11).

Within these broad themes, respondents provided specific details of the information and guidance they would find useful. For example, one respondent was interested in understanding whether patterns of colonisation could be selectively encouraged to create a safe harbour environment; this respondent wanted to know whether structures could be designed or retrofitted to discourage slippery algae and encourage marine growth with a "grippier finish". Another respondent indicated that more information should be available on whether design and management decisions primarily aimed at preserving the heritage value of historic structures impacted upon colonising wildlife. This includes, for example, efforts to maintain the appearance of historic stonework during restoration projects by replacing missing blockwork with pre-weathered stones instead of concrete.

Respondents most frequently identified practical experience and formal information provided by government agencies (e.g. Marine Management Organisation) and non-departmental public bodies (e.g. the Environment Agency and Natural England) as sources of guidance for managing marine growth. However, only a small number of respondents (9%) indicated that current guidance was sufficient in relation to the management of wildlife that grows on maritime built heritage (Fig. 4.1, Q9.1).

Table 4.11. Illustrative quotes concerning guidance and research that would be welcomed by respondents.

Theme	Quotes
Guidance and Future Research	*"I would really like to know if...designated sites and harbours create a better habitat for wildlife…for me, it would be something I was able to use as a tool for protecting them [heritage assets] …"* Biodiversity Officer
	"…it would be really interesting to see…whether, by mimicking those historic structures, whether we actually get more of an ecological benefit…" Engineer
	"Any guidance in terms of what is best practice to make it [structures] both safe, but also have as much of the wildlife as possible would be really good." Conservation Manager
	"…we are on the one hand being pushed to encourage wildlife, but equally, invasive species cause us a problem commercially as a port…there is this lack of understanding…" Environmental Officer
	"I'd like insight into the types of things that grow on maritime structures, whether they are good or bad for the structures? Do they act as some sort of protection from wave action? Do they help in any way? Conservation Manager
	"What takes precedent? What is more important? I suppose the people who want to protect the monument, the heritage side of it, they're really keen to protect that, whereas folks like myself…are more about the wildlife and the priority species…it's a strange one." Biodiversity Officer

4.3.8 Overall benefits of marine growth

Over 40% of the respondents indicated they believed the benefits of marine growth on historic maritime structures outweighed the negatives. This compares to 21% of respondents who believed the opposite (Fig. 4.1, Q12.1). Nearly half (46%) of the respondents suggested that marine growth should be encouraged on structures, with only 14% indicating it should be actively discouraged. The remaining 40% of the respondents indicated that biological growth should neither be encouraged or discouraged (Fig. 4.1, Q13.1). A general perception among respondents that marine growth is beneficial and should be encouraged is highlighted by AI values between 0 and 1 for Questions 12.1 and 13.1. A weak but significant correlation was found between the degree to which respondents considered marine growth beneficial overall (Q12.1) and attitudes on whether growth should be encouraged or discouraged (Q13.1) ($\rho(129) = 0.432$, $p < 0.001$). In general, environmental officers were more likely to believe that the benefits of marine growth outweigh the negatives, and, consequently, encourage rather than discourage marine growth on structures compared to harbourmasters, engineers, and heritage managers (Fig. 4.2e, f).

Of the options provided in the questionnaire, evidence of marine growth providing protection to historic maritime structures was most frequently selected by respondents as a reason why they would be more likely to encourage surface-colonising organisms. This was followed by evidence of marine growth improving water quality and of historic structures acting as unique habitats for marine wildlife (Appendix B2).

4.4 Discussion

Practitioner attitudes towards wildlife growing on historic maritime structures were mostly positive and were generally in agreement. Environmental officers often held stronger opinions than engineers, harbourmasters, and heritage managers; however, overall, variability between groups was either small or negligible. Perceptions of marine growth were relatively consistent among

respondents irrespective of their occupation or the historic maritime structures they were responsible for managing. For instance, the overall directionality of opinions (i.e. positive vs. negative) was consistent among respondents differentiated by occupation for all but one of the questions assessing attitudes towards marine growth (i.e. Q2.1). The variability of opinions between different groups was particularity low for questions relating to the impacts of marine growth on maintenance regimes, health and safety, mortar deterioration, and the overall condition of structures. Such similarities in attitudes may indicate that certain factors, such as occupation and the type of structure managed, do not significantly influence how marine growth is perceived. Furthermore, it may indicate shared interests in finding a balance between wildlife and heritage conservation across a diverse range of marine management practitioners.

The consistent perception among respondents that marine growth negatively impacts upon maintenance work, the condition of mortar, and health and safety, as indicated by AI scores equal or close to -1, supports the notion that these impacts are experienced by practitioners from across the UK. Agreement among respondents and the strength of these perceptions may, in part, be due to the consequences associated with the mismanagement of these factors. For example, anything that is perceived to reduce safety is likely to evoke a strong response from managers given that the consequences of negligence include injury, loss, and/or serious legal repercussions. The perception that marine wildlife negatively impacts maintenance regimes, mortar condition, and safety may represent a potential barrier to the implementation of measures aimed at enhancing marine growth on coastal infrastructure, including historic maritime structures (Evans et al., 2017). As such, these concerns warrant further attention if opportunities for the integrated conservation of built heritage and marine biodiversity are to be realised. Future research aimed at tackling these concerns could, for example, examine the effects of different types of marine growth on the deterioration rates of mortar through exposure trials, or conduct assessments that determine the species that are typically most hazardous to safety.

Positive opinions of marine growth with respect to biodiversity, water quality, education and recreation, and commercial activities indicate that colonising wildlife is perceived to provide a variety of beneficial ecosystem services and social values in addition to any 'disservices' relating to its impact on safety and maintenance work (Beaumont et al., 2007; Cole et al., 2015; Potts et al., 2014). Specifically, respondents highlighted the ability of marine growth to provide provisioning services (e.g. food), regulating services (e.g. climate regulation, water regulation, erosion and weathering regulation), supporting services (e.g. provision of habitat and formation of physical barriers), and cultural services (e.g. aesthetic values, formation of seascapes, educational values, and recreation; Millennium Ecosystem Assessment, 2005; Turner et al., 2014). Interestingly, however, several services that have previously been associated with marine biodiversity were not mentioned, notably the provision of raw materials, CO_2 sequestration, cultural heritage and identify, physical and mental health benefits, and nutrient cycling (e.g. Beaumont et al., 2007; Burden et al., 2017). This may indicate that these services are less evident, less well understood, and/or less valued by practitioners than other services. As respondents were more likely to have an overall positive opinion of marine growth, the benefits associated with colonising wildlife (e.g. the provision of ecosystem services) may, on balance, be considered more important than any negative impacts. Identifying and enhancing the benefits and services provided by different aspects of marine growth may concurrently increase the value of historic maritime structures as culturally significant assets, further enhancing arguments for their continued protection and maintenance, while also incentivising managers to implement eco-friendly management practices that promote biodiversity.

The perception among respondents that historic structures can provide habitat and shelter to a variety of marine organisms indicates that the benefits associated with wildlife/ built heritage interactions within marine environments are not unidirectional; historic maritime structures may provide services to ecosystems at the same time as marine growth provides ecosystem services (Comberti et al., 2015). Typically, artificial structures in marine environments are considered ecologically poor as they generally support younger, less diverse assemblages of marine organisms

than natural shores and attract non-native and invasive species (Airoldi et al., 2015; Moschella et al., 2005; Vaselli et al., 2008). However, compared to rock revetments and modern artificial structures (e.g. Aguilera et al., 2014; Moschella et al., 2005; Pinn et al., 2005a), few studies have examined the ecological communities that are supported by historic maritime structures (López, 2019). Responses from this study highlight the potential for historic masonry structures to provide unintentional ecological benefits due to their age, traditional design, and decay mechanisms. As mentioned by several interviewees, compared to modern coastal infrastructure that is typically constructed of concrete, historic masonry structures may provide a greater density and diversity of microhabitat features (e.g. crevices, cavities, textured surfaces, etc.) that are known to favour the development of diverse ecological communities (Coombes et al., 2015; Firth et al., 2013; Hall et al., 2018; MacArthur et al., 2019; Sherrard et al., 2016). As has previously been done for built heritage in terrestrial environments (e.g. Caneva et al., 2018; Cicinelli et al., 2017; Ferraby, 2007), future research is now needed to examine the potential biodiversity value of maritime built heritage. This includes the ecological communities that grow directly on the surfaces of historic structures (e.g. sessile organisms) but also non-sessile organisms such as fish, marine mammals, and swimming invertebrates that may similarly benefit from built heritage (Lengkeek et al., 2013; Wessex Archaeology, 2008). A greater understanding of the biodiversity value of maritime built heritage could present win–win opportunities for the joint conservation of marine biodiversity and cultural heritage, such as the establishment of conservation areas around heritage sites that protect both the historic structure and the ecosystems it supports.

Although perceptions of marine growth were relatively consistent among respondents, individuals disagreed about the aesthetic impact of marine growth and the potential of different species to enhance and/or retard deteriorative weathering and erosional processes. Whether marine growth enhances or diminishes the appearance of a structure is inherently subjective, with attitudes depending on personal preferences and the type of structure and marine organisms being considered. Previous research suggests that species diversity and composition can influence the

aesthetic value people assign to marine and coastal ecosystems, including coral reefs and intertidal rock pools (Fairchild et al., 2018; Tribot et al., 2019). However, there is limited understanding of how different dimensions of biodiversity contribute to people's perceptions of wildlife growing on maritime structures. Responses in this study suggest a range of preferences, with some individuals favouring pristine, clean structures, and others indicating a preference for surfaces colonised by diverse assemblages of marine wildlife. In the latter group, responses indicate that aesthetic value is associated with the appearance of the marine growth but also its ability to hide unsympathetic repairs. The role of wildlife as a "concealer" is often viewed negatively, especially in terrestrial environments in instances where it obscures valued architectural detail (e.g. 'Bio-obscuration' by ivy; Viles et al., 2011b). However, the results of this study suggest a more nuanced understanding of the contribution of wildlife to the aesthetics of anthropogenic structures is needed, especially in dynamic marine environments where frequent maintenance work may be required. A greater understanding of how marine growth influences the aesthetics of maritime structures may help create opportunities to enhance existing structures, so they provide additional benefits/services (e.g. biodiversity and aesthetics) beyond their primary function or any associated historic/cultural value (Morris et al., 2016; Evans et al., 2017).

Contrasting viewpoints regarding the impact of marine growth on the degradation of natural stone and engineered materials expressed by respondents resonate with research that has shown that marine organisms can act as both bioprotective and bioerosive agents, concurrently, within the same environment. For example, macro-algae holdfast attachment is generally considered a superficial process (e.g. Coombes, 2014), yet holdfast growth has been observed to cause the mechanical disintegration of concrete and natural rock to a depth of up to 10 mm (Hughes et al., 2013a, b; Morrison et al., 2009). At the same time, macro-algae canopies are known to reduce the efficacy of mechanical weathering processes by regulating microclimatic conditions through increased moisture retention and shading at the rock surface (Coombes et al., 2013b; Gowell et al., 2015; Scrosati and Ellrich, 2018). Similar buffering effects have been observed for mussels (Baxter

et al., 2022; Gonzalez et al., 2021) and barnacles (Coombes et al., 2017b), with the latter also known to protect surfaces by sealing microcracks (Chlayon et al., 2018). However, research has also suggested that barnacles can enhance the corrosion of sandstone surfaces via dissolution (Pappalardo et al., 2018). As shown in our study, practical experience and formal guidance provided by government agencies and non-departmental government bodies shapes the opinions of practitioners to a greater degree than other sources of information, including academic research. However, disagreement among respondents suggests a greater understanding of the magnitude and directionality of biogeomorphic processes operating on historic maritime structures is needed if practitioners are to make informed decisions about how best to manage marine wildlife found growing on built heritage. This is further supported by a call from respondents for more guidance on the impacts (both protective and destructive) of different marine species on materials used in the construction and repair of historic maritime structures.

Unlike general perceptions of marine growth, which were relatively consistent among respondents, conservation and management practices varied among individuals and practitioner groups. For instance, engineers, environmental officers, and heritage managers were more likely to be actively involved in the conservation of marine wildlife than harbourmasters. These differences suggest that management regimes are only partly influenced by attitudes towards marine growth. Indeed, the responsibilities of different practitioners alongside associated concerns relating to safety, cost, and the preservation of features protected through heritage designations, may be equally if not more important than personal perceptions for determining how biodiversity is managed and/or enhanced at a site. Therefore, any attempts to establish more sustainable ways of managing marine wildlife, including those aimed at encouraging the joint conservation of biodiversity and built heritage, should consider attitudes towards marine growth as one of many factors requiring consideration.

Here we provide an initial assessment of the attitudes of marine managers towards the growth of marine wildlife on historic maritime structures. The focused nature of this study has allowed for an

in-depth analysis of the views and perceptions of a particular target group, namely UK harbourmasters and asset managers responsible for maintaining maritime built heritage constructed of masonry. Going forward, future research should look to build on the findings presented here by conducting perception studies that consider a greater diversity of stakeholders involved in the management of marine growth on built heritage assets and other artificial structures located in marine environments. This could include, for example, members of the public and heritage professionals who are responsible for and/or use historic maritime structures as well as practitioners involved in the conservation of marine wildlife, all of whom were represented by a relatively small number of respondents in this study. An assessment of attitudes held by members of the public would be particularly beneficial for understanding the specific services and disservices provided by sessile marine growth and other species that are supported by heritage structures. This type of assessment would enable a more nuanced understanding of the types of marine wildlife that benefits society, including sessile organisms alongside fish and marine mammals that are typically considered of high social value (e.g. for snorkelers, divers, and fishers). At the same time, a more detailed survey of individuals involved in understanding and conserving marine ecosystems (e.g. environmental/biodiversity officers, marine ecologists, etc.) could help determine the positive and negative impacts of heritage structures on marine ecosystems. Further insight is needed, for example, into whether heritage structures are thought to provide shelter for marine organisms and/or negatively impact local biodiversity by facilitating the growth and spread of invasive species. Although location was not found to significantly influence the perceptions of the respondents, future research should look to determine whether attitudes towards biological growth, and marine wildlife in general, differ across larger spatial scales (e.g. between countries). As has previously been shown for people's perceptions of harbour health and ecological engineering (e.g. Kienker et al., 2018; Strain et al., 2019), attitudes towards the growth of marine wildlife may vary in response to differences in people's connectedness to harbour environments or their vicinity to the coast. Additional factors that may influence the attitudes of stakeholders in different locations include

differences in (i) the types of ecological communities found growing on heritage structures, (ii) legislation designed to protect heritage structures and marine wildlife, and (iii) traditional management practices, all of which warrant further research attention. Finally, as we focused exclusively on determining attitudes towards marine growth on historic masonry structures, opportunities exist for expanding the scope of this research to include the perceptions of managers and users of maritime heritage constructed of other materials, including wood, metal, and plastic. Due to differences in the composition of these materials and the wildlife they typically support, management needs and practices will also likely differ.

4.5 Conclusions

The results presented here suggest that the managers of historic maritime structures generally consider surface-colonising marine wildlife as beneficial. The positive influences of marine growth on the local environment and biodiversity as well as benefits relating to the provision of ecosystem services also mean that practitioners are more likely to encourage than discourage marine growth. Negative attitudes mainly centre on potential detrimental impacts on maintenance works, safety, and the condition of structures. These concerns, alongside issues relating to the costs of implementing conservation measures and a perceived lack of guidance on how best to manage marine growth, represent potential barriers to the integrated conservation of marine biodiversity and built heritage. Future research is now required to address these concerns and other areas of uncertainty identified by practitioners so they can make more informed decisions about the sustainable management of the built and natural marine environment. Crucially, despite some differences of opinion, our results indicate that there is common ground between a diverse range of marine managers for establishing win–win solutions for maritime heritage and biodiversity, especially if some of the main concerns we have highlighted can be addressed.

4.6. Chapter 4: Summary and implications

Results from the perception study showed that:

i. Attitudes towards marine growth are generally in agreement among practitioners irrespective of their occupation or the historic maritime structures they are responsible for managing.
ii. Perceptions of marine growth are mostly positive, but concerns exist regarding its impacts on maintenance regimes, the condition of mortar, and health and safety.
iii. Several gaps in research, evidence, and guidance relating to the management of wildlife-heritage interactions exist, and these include: (i) the impact of marine growth on built heritage conservation, (ii) the values associated with marine growth on heritage assets, (iii) effective ways of encouraging marine growth through ecological enhancement techniques and/or discouraging the colonisation of invasive species, and (iv) the ecological benefits associated with heritage assets (e.g. habitat provision).

In order to address the concerns of practitioners, field-based research is needed to explore the interactions and feedbacks between maritime built heritage and marine wildlife. This includes field experiments specifically designed to assess the impact of marine growth, such as seaweed, on the condition of mortar used to construct and repair heritage assets as well as fieldwork that evaluates the ecological value of heritage assets in comparison to other forms of maritime infrastructure.

Section 3.

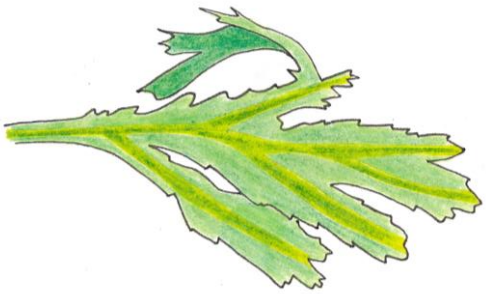
Wildlife-Heritage Interactions in the Field

Section 3 addresses

- Objective 2: to evaluate the impact of marine wildlife on the rates of deterioration of a material regularly used in the construction and repair of maritime built heritage; and,
- Objective 3: to determine whether communities of marine wildlife supported by historic maritime structures differ to those found on natural rocky cliffs and modern concrete infrastructure.

In Chapter 5 (Paper 2), a field-block exposure trial is used to assess the impact of seaweed cover on the breakdown of natural cement-based mortar after 6 months exposure to intertidal conditions at Portland Port, Dorset. In Chapter 6 (Paper 3), ecology surveys and physical habitat assessments are used to compare the biodiversity and physical habitat provision of historic (pre-1900s) masonry walls, concrete walls, and natural rocky cliffs at seven locations across the UK.

Given the interdisciplinary nature of this research, the papers presented in these chapters have been targeted at differing—but overlapping—audiences. Paper 2 is targeted at geomorphologists who are interested in biogeomorphological processes, while Paper 3 is targeted at marine ecologists interested in the impact of maritime structures on marine ecosystems.



Serrated wrack (F. serratus)
Drawn by Hope Calloway

Chapter 5.

No evidence that seaweed cover enhances the deterioration of natural cement-based mortar in intertidal environments.

Published as: Baxter, T., Coombes, M., Viles, H., 2022. No evidence that seaweed cover enhances the deterioration of natural cement-based mortar in intertidal environments. Earth Surface Processes and Landforms. 47(15), 3453–3464.*

Abstract

The breakdown of rocks and engineering materials in marine environments is both enhanced and retarded by surface-colonising marine organisms (seaweed, barnacles, etc.). However, the impact of marine growth on the deterioration of materials used to construct and repair maritime heritage assets, such as natural cement, is poorly understood.

This study assesses whether seaweed cover (*Fucus vesiculosus* and *F. serratus*) influences the breakdown of mortar prepared using natural cement through an exposure trial at Portland Port, Dorset, UK. Using microclimate monitoring and three different indicators of weathering and material breakdown (surface hardness, surface roughness and ultrasonic pulse velocity), samples of mortar with and without a cover of seaweed were compared after 6 months of exposure to intertidal conditions. Our results show that temperature variations were significantly dampened under seaweed canopies compared to uncovered substrate both in summer and winter. As mechanical rock weathering processes are influenced by surface temperature regimes, we infer that

* Minor changes have been made to this manuscript to aid the readability and continuity within the thesis. For instance, figure and table numbers have been changed. Some supplementary material is also now included in the main body of text. The published journal article is available from: https://doi.org/10.1002/esp.5467

these stabilising effects may translate to a reduction in the efficacy of particular rock breakdown processes. Seaweed cover was not found to have significant effects on the surface hardness of the samples. Conversely, significant differences in surface roughness and pulse velocity were observed, indicating that the seaweed-covered samples experienced less surface and subsurface breakdown.

Overall, we found no evidence that seaweed significantly enhances the deterioration of natural cement-based mortar during the first few months of exposure. Instead, we present the first empirical evidence of the bioprotective potential of seaweed covering materials commonly used in maritime built heritage restoration. Future work is now needed to examine the geomorphic roles of seaweed and other marine organisms on different types of materials used in maritime heritage conservation, and the extent to which their impacts on different deteriorative/protective processes vary in time and space, particularly under future climatic scenarios.

5.1 Introduction

Canopy-forming seaweeds grow prolifically on rocky shores and on the surfaces of artificial structures in marine environments (A. Lee et al., 2009; Tsiamis et al., 2020; Watanuki and Yamamoto, 1990). This includes built heritage assets, such as historic harbours and breakwaters that are valued for their historical importance and cultural significance (Fulford et al., 1997; Fig. 5.1). As well as providing functional habitats for understory species (Bertness et al., 1999; Burnaford, 2004; Umanzor et al., 2017; Watt and Scrosati, 2013), seaweed acts as an important biogeomorphological agent via a range of processes (Fig. 5.2), both enhancing and retarding rock weathering and erosional processes, and mediating the transport of sediment in coastal and marine environments (Carling, 2014; Frey and Dashtgard, 2012; Garden and Smith, 2015; Smith and Bayliss-Smith, 1998). As with other marine organisms that form dense biotic covers and encrustations, such as barnacles and mussels (Baxter et al. 2022; Coombes et al., 2017b; Gonzalez et al., 2021), seaweed canopies are thought to reduce the efficacy of mechanical weathering processes by regulating microclimatic conditions through increased moisture retention and shading at the rock's surface (Coombes et al., 2013b; Gowell et al., 2015; Scrosati and Ellrich, 2018). At the same time, holdfast growth has been observed to cause the mechanical disintegration of rock and concrete to a depth of up to 10 mm (Hughes et al., 2013a, b; Morrison et al., 2009).

Research examining the biogeomorphological roles of marine organisms has typically focused on understanding the effects of marine growth on the breakdown of rock (e.g. Andrews and Williams, 2000; Baxter et al., 2022; Gonzalez et al., 2021; Pappalardo et al., 2018; Trudgill, 1987) or engineering materials used to construct modern infrastructure, such as concrete (e.g. Chlayon et al., 2018; Coombes et al., 2011, 2017a; Lv et al., 2015b). This includes studies that have specifically analysed the role of seaweed as a biogeomorphic agent in marine environments (Table 5.1). In contrast, relatively little is known of the impacts of marine organisms on the breakdown of materials used in the maintenance, repair, and restoration of built heritage assets.

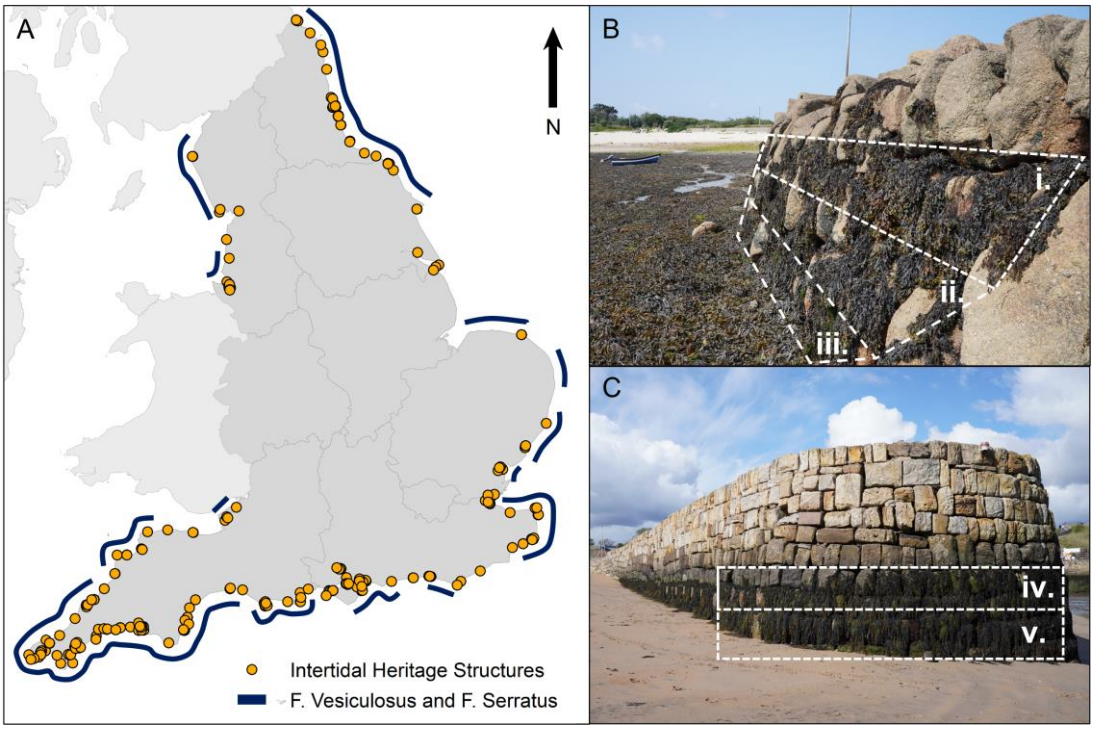
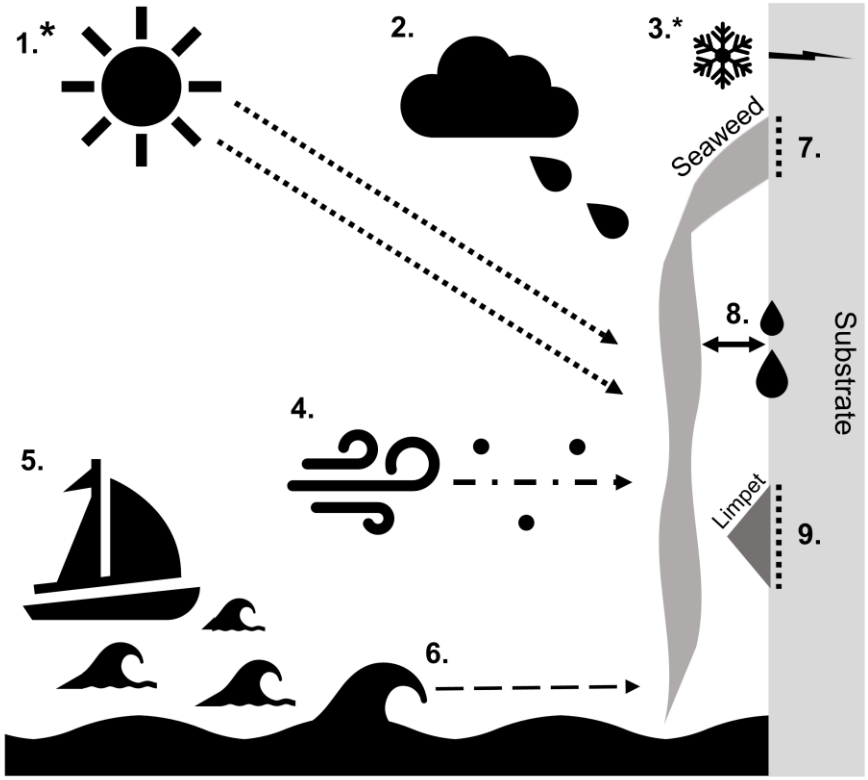


Fig. 5.1. (a) Distribution of *F. vesiculosus* and *F. serratus* in England (blue line, National Biodiversity Network Atlas occurrence data, download from nbnatlas.org [accessed 10 May 2022]) along with listed buildings and Scheduled Monuments built of stone that are located within the intertidal zone (orange circles, Historic England GIS data obtained from historicengland.org.uk [accessed 10 May 2022]. © Historic England 2022. Contains Ordnance Survey data. © Crown copyright and database right 2022). Seaweed, including (i) *F. spiralis*, (ii) *F. vesiculosus*, and (iii) *F. serratus* colonising the walls of (b) Old Town Quay, a Scheduled Monument on the Isles of Scilly. An eighteenth-century breakwater colonised by (iv) *F. spiralis* and *F. vesiculosus* and (v) *A. nodosum* at (c) St Andrew's Harbour, a Category A listed building in Fife, Scotland.

Unlike modern infrastructure, designations aimed at protecting the historic fabric of built heritage assets (e.g. listed buildings and Scheduled Monuments) often restrict the types of materials that can be used for conservation work (Historic England, 2016b, c). Generally, only original material or materials with compatible technical and aesthetic properties are considered appropriate for repair works. As such, materials used for built heritage conservation often differ from those used to construct modern infrastructure in marine environments. For example, natural cement (e.g. Vicat Prompt™ and other brands) is regularly used as a binder in mortars used to repair historic masonry structures (Gosselin et al., 2008), including harbours and coastal fortifications (e.g. Historic Environment Scotland, 2016), due to its compatibility with materials used to construct maritime structures before the twentieth century. This compares to artificial cements (e.g. 'Modern Portland' cements), which are frequently used to produce concrete for modern coastal defences and maritime infrastructure (Dupray et al., 2010; Thomas, 2016).



1. Insolation. The canopy absorbs solar radiation protecting the surface of the substrate from temperature variations thereby reducing the efficiency of mechanical weathering processes controlled by surface and subsurface thermal regimes (e.g. thermal fatigue, thermal stress, wetting–drying, salt crystallisation).
2. Rainfall and atmospheric deposition. The seaweed canopy acts like a barrier protecting the underlying substrate from freshwater runoff and airborne pollutants during low tide.
3. Freeze–thaw. Unlike surfaces with no seaweed cover, the canopy insulates the substrate, reducing the frequency, duration, rate, and magnitude of damaging freeze–thaw events during cold periods.
4. Wind. The seaweed canopy protects the substrate from the erosive effects of wind (e.g. abrasion from suspended sand).
5. Impacts. The canopy acts like a barrier protecting against impacts from boats and other floating objects/debris.
6. Wave action. The canopy dampens the impacts of waves and protects against abrasion and scour.
7. Holdfast attachment. Holdfast growth causes mechanical disintegration of the substrate. On vertical surfaces, growth increases mechanical strain. Seaweed fronds increase drag on the surfaces they are attached to, increasing the susceptibility of materials to storm damage.
8. Moisture retention. The seaweed canopy increases moisture retention at the surface reducing the frequency and intensity of wet–dry cycles and the likelihood of salt crystallisation during drying phases. Moisture retention may also affect chemical reactions.
9. Understory organisms. The canopy supports understory organisms that may also act as biogeomorphological agents.

Fig. 5.2. A conceptual model of the role of seaweed as a biogeomorphological agent on intertidal substrates. This study focuses on part 1. Note, in the published version of this manuscript, this figure does not appear in the main article, but instead in the Supporting Information as Fig. A1.

An improved understanding of the biogeomorphological effects of seaweed and other canopy-forming marine organisms on materials used to repair historic maritime structures will allow practitioners to make more informed decisions about the conservation of built heritage as well as marine biodiversity. Traditionally, the growth of seaweed on artificial structures has been viewed negatively (e.g. Fletcher, 1988), and a recent survey of harbourmasters and other marine managers from around the UK found that seaweed growth was generally perceived to negatively impact the conservation of maritime built heritage (i.e. Chapter 4, Paper 1). In particular, seaweed was thought to have a detrimental impact on the condition of mortar. As yet, however, the effects of seaweed on materials used in built heritage conservation, including natural cement, have not been quantitatively assessed.

To address this research gap, an exposure trial was developed to examine the effect of seaweed on the physical properties of natural cement-based mortar exposed to intertidal conditions. Similar to canopy-forming seaweeds (Coombes et al., 2013b; Gowell et al., 2015) and encrusting organisms that grow on natural shores and concrete surfaces (Baxter et al., 2022; Coombes et al., 2017b), we hypothesised that seaweed canopies moderate the breakdown of material by decreasing the efficiency of mechanical weathering processes by dampening temperature variability during air-exposed low-tide periods. Seaweed may also influence salt crystallisation (Gowell et al., 2015) and wetting–drying cycles by moderating moisture retention (Coombes et al., 2013b) and act as a physical barrier against erosional processes (e.g. wave abrasion), although these effects were not examined directly in this study. By using surface roughness, surface hardness, and ultrasonic pulse velocity (UPV) as proxies for weathering state, we reveal differences in the physical properties of samples of mortar with and without a cover of seaweed. Overall, our results show that rates of deterioration of mortar prepared using natural cement were not enhanced by seaweed cover during the first 6 months of exposure. Instead, the net effects of seaweed cover may be broadly bioprotective due to its influence on near-surface microclimatic regimes.

Table 5.1. Some examples of studies examining the geomorphic roles of seaweed growing on a range of natural and artificial substrates.

Location	Biological cover	Substratum type	Landform/ Structure	Scope of Study	Reference
Nova Scotia, Canada	*A. nodosum*	Unknown	Rocky shore	Influence of seaweed on near-surface microclimates during temperate winter conditions.	Scrosati and Ellrich (2018)
Cornwall and Dorset, UK	*F. vesiculosus,* *F. serratus,* *F. spiralis,* *A. nodosum,*	Concrete, Limestone	Harbour wall, Support pylons, Rock armour revetment	Influence of seaweed on (i) near-surface microclimates during temperate summer conditions and (ii) conditions for mechanical rock decay.	Coombes et al. (2013b)
Algarve, Portugal	Various marine species	Carbonate Siltstone	Rocky shore	Influence of biological covers on shore platform downwearing rates.	Moura et al. (2012)
Galway Bay, Ireland	*A. nodosum,* *F. vesiculosus,* *Lithothamnion* sp.	Granite, Limestone	Rocky shore	Biomechanical and biochemical deterioration of rocky shore substrate.	Morrison et al. (2009)
Lancashire, UK	*A. nodosum,* *F. vesiculosus,* *F. spiralis,* *Porphyra umbilicalis,* *Halidrys siliquosa,* *Ulva* sp.	Concrete	Rock armour revetment	Biomechanical biodeterioration of marine concrete.	Hughes et al. (2013a)
Puducherry, Tamil Nadu, India	*Chaetomorpha antennina*	Concrete	Exposure trial of concrete cubes	Biochemical deterioration of marine concrete.	Jayakumar et al. (2010)
Laboratory study	Artificial seaweed (chemically inert foam)	Mudstone	Laboratory simulation	Influence of (artificial) seaweed on salt weathering and mechanical rock breakdown.	Gowell et al. (2015)

5.2 Methodology and methods

5.2.1 Field block exposure trial

Sample blocks of mortar were prepared using a prompt natural cement (Vicat Prompt™) following the advice of several professionals in maritime built heritage conservation. Prompt natural cement is a quick-setting natural hydraulic binder that rapidly hardens with the addition of water. It is produced by firing standard-composition limestone high in clay content between 500 and 1200°C, followed by very fine grinding. Vicat produce the only prompt natural cement that is manufactured industrially, and this is made using argillaceous limestone excavated from homogeneous rock strata in the Chartreuse mountains near Grenoble, France. Due to its durability and long-term strength gain, resistance to seawater, fast hardening and setting time (2 min at 20°C), and 'natural' colour and aesthetic, Vicat Prompt™ natural cement has been used to construct and repair historic maritime structures throughout Europe since the middle of the nineteenth century. This includes St Andrew's Harbour (Fife, Scotland), Cove Harbour (Berwickshire, Scotland; Historic Environment Scotland, 2016), Portreath Harbour (Cornwall, England), and the Château d'If fortress (France), which have all been repaired within the last 20 years.

The aggregate used for the mortar mix was a sharp quartz sand (Bramshill) with a well-graded grain size distribution (0.75 µm to 10 mm). The binder:aggregate:water ratio was 5:5:2 by volume following standard procedures (Vicat, 2003). Small amounts of citric acid were added to the mixture (binder:citric acid ratio = 1000:7) to delay the setting time by ~10 min and increase workability. A mortar of this mixture is expected to develop strength rapidly (i.e. within the first few hours) due to the hydration of aluminates within Vicat Prompt™, and then more gradually over several days, months, and years due to the slow hydration of belite (C2S). Compared to its compressive strength after 2 years (~60 MPa), this mortar mix is expected to gain ~22.5% of its strength in the first day (~13.5 MPa), 50% over 28 days (~31 MPa), and 80% over 6 months (~48 MPa; inferred from data in Vicat, 2003). After mixing, the mortar was equally distributed into 22 identical silicone moulds

(55 × 80 × 25 mm). The samples were de-moulded after 5 days of curing under laboratory conditions. Two samples were kept as controls, both of which were stored in a small plastic container in dry conditions within a low-temperature laboratory refrigerator for 6 months.

Twenty sample blocks were attached to semi-horizontal surfaces of limestone rock armour 200 m south of Balaclava Bay, Portland Port (Dorset), UK (50°33'49"N, 02°25'31"W) at mean tide level (Fig. 5.3). The study site was chosen based on the rock armour having an existing cover of algae, and ease of obtaining access and permissions. Portland Port experiences a double-low tide (i.e. ~4 h of low water consisting of two minima separated by a small rise) and is microtidal (<2 m mean spring tidal range). According to the MarLIN wave exposure categories[7] the study site is on a 'moderately exposed' coastline; the open coast faces away from the prevailing westerlies in a northeastern direction and has a short fetch (<20 km). Although the coastline can experience strong winds, it is partially sheltered to the south by the Isle of Portland and to the north by the Grade II listed Inner Breakwater of Portland Port. At mean tide level, the rock armour is dominated by canopies of *F. vesiculosus* and *F. serratus* that are 5–10 cm thick.

To investigate the effects of macro-algal cover on the physical properties of mortar, we examined and compared sample blocks attached to areas with 95–100% seaweed cover to those attached to uncolonised areas (0% cover). Hereafter, these areas are referred to as 'covered' plots and 'uncovered' plots, respectively. Individual, purpose-built frames made using PVC-coated stainless steel cable ties and plastic cable mounts were used to house the sample blocks. The frames, which were securely attached to the substrate using marine epoxy (Plastic Padding® Marine Epoxy; Fig. 5.3c), were designed to ensure the sample blocks were not damaged during their attachment or removal. Initially, the 20 sample blocks were evenly distributed between the covered and uncovered plots (i.e. 10 samples were covered with seaweed and 10 samples were left uncovered). In the covered plots, the frames housing the sample blocks were secured directly to substrate under the

[7] www.marlin.ac.uk/glossarydefinition/waveexposure

algal canopies; in some instances, a small area of colonising macro-biology was cleared so that the frames could be attached securely. Care was taken to ensure that the sample blocks in the covered plots were directly covered with seaweed (i.e. without air voids between the samples and the seaweed canopy) and that the algal canopies were of similar densities and thicknesses (i.e. ~5 cm). The uncovered plots were already clear of macro-algae and other macro-organisms. All sample blocks were positioned at the same tidal height (i.e. mean tide level), irrespective of whether they were in covered or uncovered plots. The sample blocks were left exposed to intertidal conditions for 6 months, between 30 June 2021 and 7 January 2022. Unfortunately, five of the uncovered samples and three of the seaweed-covered samples became detached during the trial and were lost. This left 12 samples available for post-exposure analysis—five attached to uncovered plots and seven attached to covered plots.

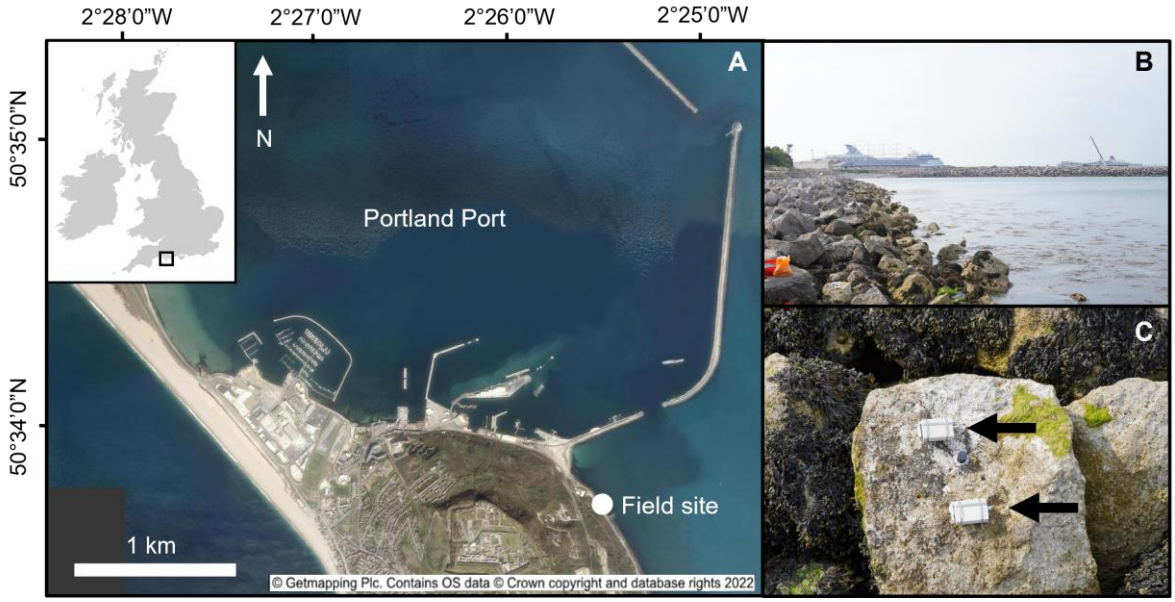


Fig. 5.3. (a) Location of the study site at Balaclava Bay, Portland Port, Dorset and (b) an on-site view of the limestone rock revetment showing the Grade II listed inner breakwater in the background. (c) Examples of 'uncovered' samples of mortar secured to the rock revetment within purpose-built frames. An iButton Thermochron (Maxim® DS1921G) is attached in a waterproof plastic casing between the samples.

Differences in pre- and post-exposure surface roughness, surface hardness, and UPV were compared between the covered and uncovered samples as well as the control samples stored in the laboratory during the exposure period. As the surfaces of the sample blocks in both the covered and uncovered plots were not directly colonised with seaweed or other macro-biology during the exposure period, any differences in surface roughness, surface hardness, and UPV detected between the samples post-exposure were attributed to differences in seaweed cover (i.e. the overhanging canopy) rather than the effects of colonising organisms (i.e. the effects of seaweed holdfast attachment). Hardness data has been used as an indicator of the efficiency of weathering processes in a number of terrestrial and coastal studies (e.g. Aoki and Matsukura, 2007; Coombes et al., 2013a; Feal-Pérez and Blanco-Chao, 2012; Gowell et al., 2015; Mol and Viles, 2010; Pappalardo et al., 2016, 2018), including assessments of the effects of biotic covers on the deterioration of historic masonry structures (Coombes et al., 2018; Cutler et al., 2013). Surface roughness has also been used to determine the extent of material breakdown (McCarroll and Nesje, 1996; Moses et al., 2014), both in coastal environments (e.g. Micallef and Williams, 2009) and for stone used in terrestrial built heritage assets (e.g. Coombes et al., 2018). UPV has been used as a non-destructive technique to detect the development of subsurface flaws and cracks within engineering materials used in historic masonry structures (e.g. Benavente et al., 2006; Svahn, 2006; Vasconcelos et al., 2007), including natural hydraulic mortars (e.g. Fusade and Viles, 2019). Typically, substrates that have experienced a greater degree of weathering are expected to be rougher, less hard, and have lower UPV values than unweathered substrates (Moses et al., 2014). The application of each technique is outlined in the following sections.

In addition to measuring the physical and surface characteristics of the sample blocks, near-surface temperature data were collected in the covered and uncovered plots. The effects of canopy-forming marine organisms on near-surface temperatures have been used as an indicator of variable weathering regimes in a number of previous studies (e.g. Coombes et al., 2013b; Gonzalez et al., 2021; Gowell et al., 2015).

5.2.2 Surface hardness

An Equotip Piccolo 2 (D-type) was used to collect surface hardness data for the sample blocks before and after they were exposed to intertidal conditions. Both pre- and post-exposure hardness measurements were recorded under laboratory conditions; the Equotip was applied perpendicular to the upper (horizontal) surface of the sample blocks which were placed on a solid limestone base atop a purpose-built, reinforced worksurface to prevent interference from vibration (Wilhelm et al., 2016). The Equotip Piccolo expresses hardness as a 'Leeb' value (HL) and has a resolution of 1 HL and an accuracy of ±4 HL (Viles et al., 2011a). On the upper surface of each sample block, 30 equally spaced measurements were recorded using the single impact method (i.e., SIM; Wilhelm et al., 2016) before and after the field exposure trial (i.e. before attachment and after removal). To avoid measurements collected post-exposure being taken from the same spot as those recorded pre-exposure, the upper surface of each block was divided into two halves; pre-exposure measurements were recorded in one half and post-exposure measurements in the other. Readings were not taken on the outer 0.5 mm of the samples to avoid potential edge effects (Gowell et al., 2015). As moisture can also affect the reliability of Equotip readings (Desarnaud et al., 2019), measurements were made when the blocks were dry and had reached a constant weight. For each sample block, the 30 measurements recorded both before and after the exposure period were averaged and then subtracted from one another as an overall measure of surface hardness change. Surface hardness measurements for the control samples were collected in a similar way, before and after being stored in the laboratory for the duration of the exposure period.

5.2.3 Surface roughness

As a non-destructive assessment of surface roughness, the topography of five randomly selected 5 × 5 mm (25 mm^2) areas on the upper surface of each sample block was quantified using an optical profilometer (INNOWEP TRACEiT®) both before and after exposure (Sanmartin et al., 2020). A TRACEiT® optical profilometer analyses the length and angle of shadows produced on the surface of

samples by three white light-emitting diodes (LEDs) to create topography measurements with a horizontal (XY-axis) resolution of <3 µm and a vertical (Z-axis) resolution of <1.5 µm (INNOWEP, 2022). For each measurement, the arithmetic average roughness (Ra) was determined from the average of 1563 transects in both the X- and Y-axis directions (Gadelmawlaa et al., 2002). A mean Ra value was then determined for each sample by averaging across the five measurement areas. Differences between pre- and post-exposure mean Ra values were then determined for each sample. An overall measure of surface roughness change was also determined for the control blocks using the same method.

Additional surface roughness measurements were made using a Keyence VHX 5000 3D microscope to verify the data obtained from the optical profilometer. As access to the 3D microscope was not possible before the exposure trial, measurements using this device were only recorded after the exposure period, for both the field-exposed samples and the control samples. Under 100× magnification, the topography of 10 randomly selected areas (3548 × 2660 µm) on the upper surface of each sample block was imaged. Ra values were then determined for each area by averaging 1597 transects in the X-axis direction and 1197 transects in the Y-axis direction. Post-exposure mean Ra values for each sample were then determined by averaging across the 10 measurement areas. When using both the TRACEiT and 3D microscope, care was taken to ensure that surface roughness measurements did not overlap with the impact features created by the Equotip.

5.2.4 Ultrasonic pulse velocity

UPV measurements were carried out on each sample block before and after field exposure with a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT Lab, Proceq, UK) with 150 kHz frequency transducers. Direct transmission was used, with transducers placed at each end of the samples on the longest axis (Fusade and Viles, 2019). The propagation velocity (vp) (m/s) was measured and results reported as the mean of three repeat measurements. Differences in mean

UPV collected pre- and post-exposure were then compared between the covered and uncovered samples and the controls, which were measured the same way.

5.2.5 Near-surface temperature

Six temperature loggers (Maxim® DS1921G iButton Thermochron) housed in protective plastic waterproof capsules (Maxim® DS9107+) were attached to the substrate using marine epoxy (Plastic Padding® Marine Epoxy). Three temperature loggers were attached in covered plots and three were attached in uncovered plots adjacent to the sample blocks. The temperature loggers in the covered plots were secured directly beneath the existing algae canopy (Coombes et al., 2013b). During air-exposed low-tide periods, the loggers recorded air temperature near the surface of the substrate, between the rock and seaweed canopy. During high-tide periods when the loggers were submerged, seawater temperature near the surface of the substrate was recorded. All loggers were positioned at mean tide level for comparability (Coombes et al., 2013b). The loggers have an operating range of −30 to 70°C, a resolution of 0.5°C, and an accuracy of ±0.5°C. The same devices have previously been used to examine the roles of marine organisms as ecosystem engineers (e.g. Jurgens and Gaylord, 2016; McAfee et al., 2022) and in weathering research to evaluate the influence of organisms on rock-surface thermal regimes in marine environments (e.g. Baxter et al., 2022; Coombes and Naylor, 2012; Gowell et al., 2015) and on terrestrial built heritage assets (e.g. André et al., 2012, 2014; Coombes et al., 2018; Sternberg et al., 2011; Viles et al., 2011b). The loggers were pre-programmed to measure the near-surface rock temperature at 30-min intervals over two 31-day periods—a 'summer' period (30 June to 30 July 2021) and a 'winter' period (6 December 2021 to 7 January 2022).

For both the summer and winter study periods, and in the covered and uncovered plots, the mean daily temperature maxima (T_{max}), mean daily temperature minima (T_{min}), mean daily temperature range (T_{range}), and mean daily highest rate of change in temperature over consecutive 30-min periods ($T_{\Delta 30}$) were calculated for each measurement day (Baxter et al., 2022; Coombes et al., 2013b). These

metrics were calculated as measures of thermal variability, which we compared between the covered and uncovered plots.

5.2.6 Statistical analysis

Two sample t-tests were performed to compare differences in Equotip surface hardness (mean HL), UPV (mean propagation velocity), and TRACEiT surface roughness (mean Ra) before and after the exposure period between the covered and uncovered samples. In all instances, assumptions for parametric tests (i.e. normality and equal variance) were checked beforehand. As the surface roughness data collected using the 3D microscope failed to meet the assumption of equal variance (Shapiro Wilks, $p < 0.01$), a non-parametric Mann–Whitney U test was used to compare post-exposure differences between the covered and uncovered samples.

5.3 Results

5.3.1 Surface hardness

The mean surface hardness of both the seaweed-covered and uncovered samples was higher after the exposure period (Fig. 5.4a); the mean surface hardness of the seaweed-covered samples increased from 236 HL pre-exposure to 357 HL post-exposure, while the mean surface hardness of the uncovered samples increased from 239 HL to 395 HL. The surface hardness of the control samples also increased, although to a lesser extent (i.e. from 226 HL to 288 HL). The mean percentage change in surface hardness between the seaweed-covered and uncovered samples was not significantly different ($t[10] = 0.946$, $p > 0.05$).

5.3.2 Ultrasonic pulse velocity

The mean UPV of both the seaweed-covered and uncovered samples was higher after the exposure period (Fig. 5.4b); the mean UPV of the seaweed-covered samples increased from 2840 m/s to 3002 m/s, while the mean UPV of the uncovered samples increased from 2840 m/s to 2900 m/s. The mean percentage change in UPV was, however, significantly greater for the seaweed-covered

samples compared to the uncovered samples (t[10] = 3.18, p < 0.01). The UPV of the control samples did not change significantly (i.e. 2810 m/s to 2816 m/s after 6 months in storage).

5.3.3 Surface roughness

Mean surface roughness (Ra) measured using the optical profilometer (TRACEiT) was higher for both the seaweed-covered and uncovered samples after field exposure (Fig. 5.4c); the mean surface roughness of the seaweed-covered samples increased from 0.547 µm pre-exposure to 1.786 µm post-exposure, while the mean surface roughness of the covered samples increased from 0.543 µm to 2.615 µm. The mean surface roughness (TRACEiT) of the control samples also increased, although to a lesser extent. The mean percentage change in surface roughness (TRACEiT) was significantly greater for the uncovered samples compared to the seaweed-covered samples (t[10] = 2.70, p = 0.024). Average (median) surface roughness measured after exposure using 3D microscopy was also higher for the uncovered samples compared to the seaweed-covered samples (i.e. 4.896 µm compared to 4.210 µm; Fig. 5.4d), although this difference was not statistically significant (U = 24, n1 = 5, n2 = 7, p > 0.05).

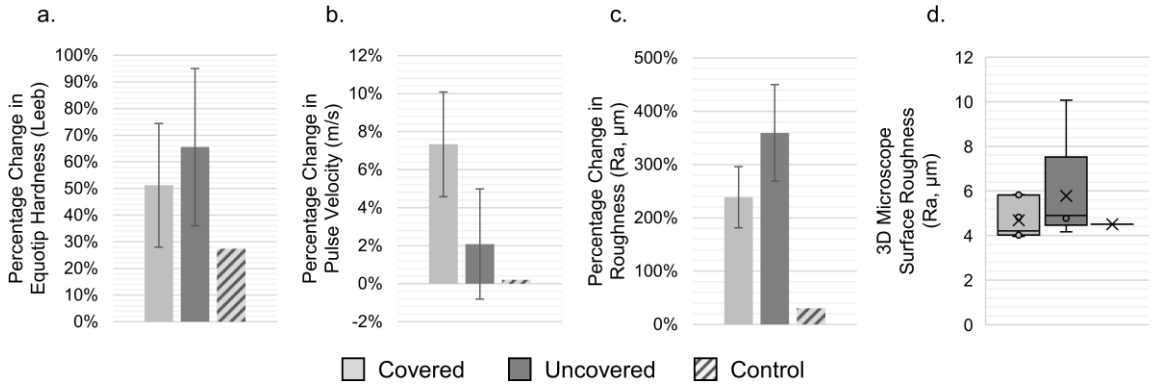


Fig. 5.4. Differences in the percentage change of (a) surface hardness, (b) ultrasonic pulse velocity, and (c) surface roughness measured using an optical profilometer (TRACEiT) between seaweed-covered samples (light grey), uncovered samples (dark grey), and controls (hashed) (mean ± standard deviation [SD]). Differences in (d) surface roughness between covered and uncovered samples measured using the 3D microscope after exposure to intertidal conditions are also shown.

5.3.4 Near-surface temperature

Time-series data of near-surface temperature collected in the seaweed-covered and uncovered plots during both the summer and winter study periods are shown in Fig. 5.5. This includes near-surface air temperature data recorded during air-exposed low-tide periods and seawater temperature data recorded during high-tide periods (i.e. when the loggers were submerged).

5.3.4.1 Summer study period

During the summer study period, the mean daily maximum temperature (T_{max}) was consistently higher in the uncovered plots compared to the seaweed-covered plots. On average, T_{max} was 7.97°C (31.1%) higher in the uncovered plots compared to the covered plots. The mean daily minimum temperature (T_{min}) was also consistently lower in the uncovered plots compared to the covered plots; T_{min} was on average 0.81°C (5.6%) lower in the uncovered plots compared to the covered plots. Consequently, the mean daily temperature range (T_{range}) was consistently higher in the uncovered plots, with values averaging 8.78°C, which was 92.3% higher than in the seaweed-covered plots.

On four occasions, the mean near-surface temperature of the uncovered plots was >15°C higher than the covered plots, with a maximum difference of 20.70°C recorded on 19 July 2021. This coincided with peak ambient air temperatures of ∼25°C and a neap tide with the low occurring during the hottest part of the day. The mean greatest daily change in temperature over a 30-min period ($T_{\Delta 30}$) was nearly always higher in the uncovered plots than the covered plots, with the opposite trend occurring on only six occasions during the 31-day study period. On average, $T_{\Delta 30}$ values were 2.51°C (i.e. 5.02°C/h) higher in the uncovered plots compared to the seaweed-covered plots, with maximum $T_{\Delta 30}$ values of 13.0°C (i.e. 26°C/h, 24 July) and 9.8°C (i.e. 19.6°C/h, 19 July), respectively.

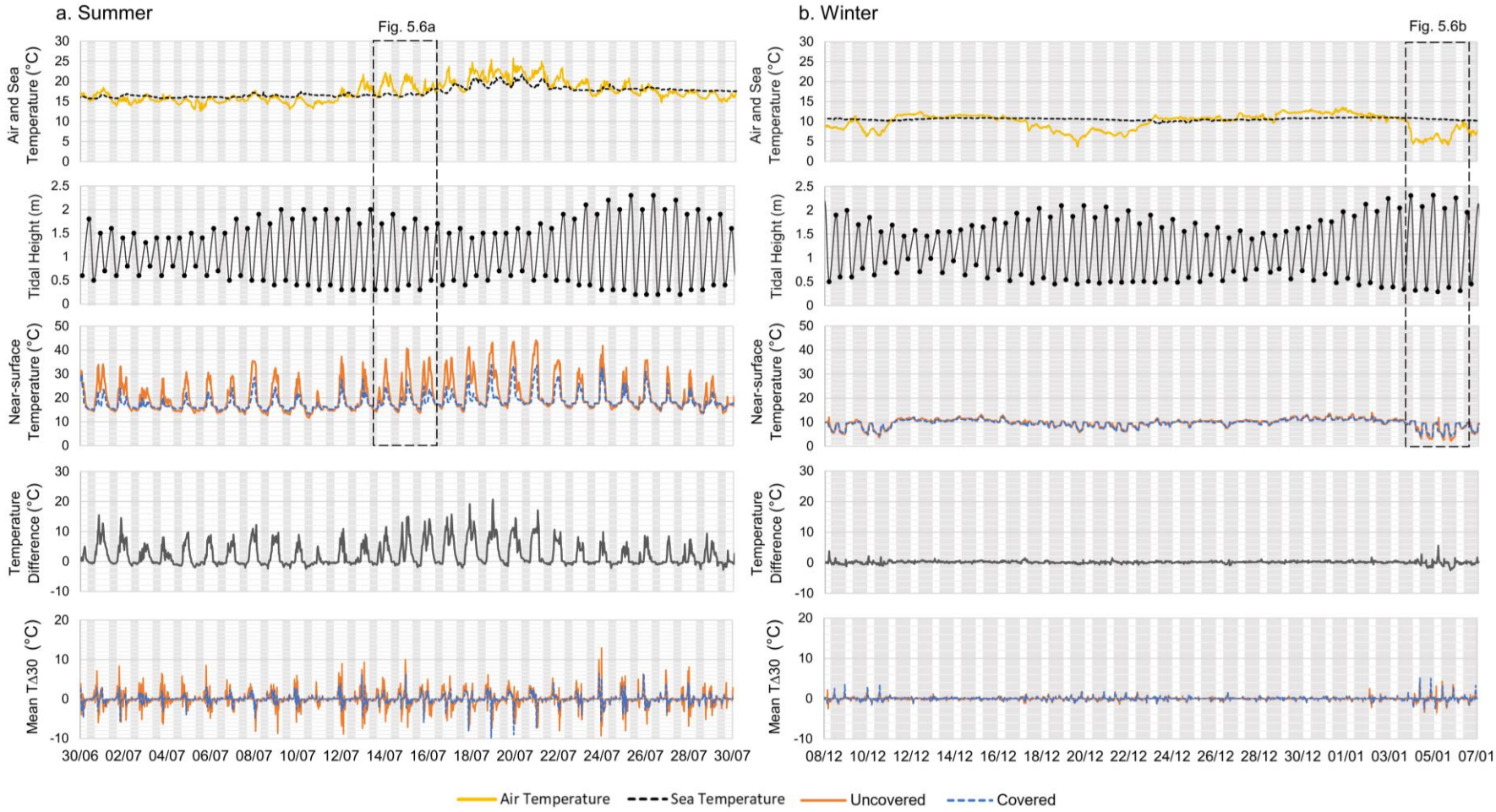


Fig 5.5. First row: Air temperature recorded at 10-min intervals (yellow solid) and sea temperature recorded at 30-min intervals (black dotted) by a directional wave measurement buoy in Weymouth Bay (50°37'22"N, 02°24'51"W) as part of the Southeast Regional Coastal Monitoring Programme (obtained from coastalmonitoring.org). Second row: Tidal regime at Portland Port during the summer (a) and winter (b) study periods. Third row: Mean near-surface temperature (°C) of seaweed-covered plots (blue dashed, n = 3) and uncovered plots (orange solid, n = 3) recorded at 30-min intervals over two 31-day study periods between 30 June and 30 July 2021, and between 8 December 2021 and 7 January 2022. Fourth row: Difference in mean near-surface temperature (°C) between the covered and uncovered plots. Fifth row: Mean $T_{\Delta 30}$ (°C) in the covered and uncovered plots across the time series. Periods of daylight (05:00 to 21:00 BST in summer; 08:00 to 16:00 GMT in winter) and darkness (21:00 to 05:00 BST in summer; 08:00 to 16:00 GMT in winter) are shown as white and grey bands, respectively. Portions of data shown in greater detail in Fig. 5.6 are indicated.

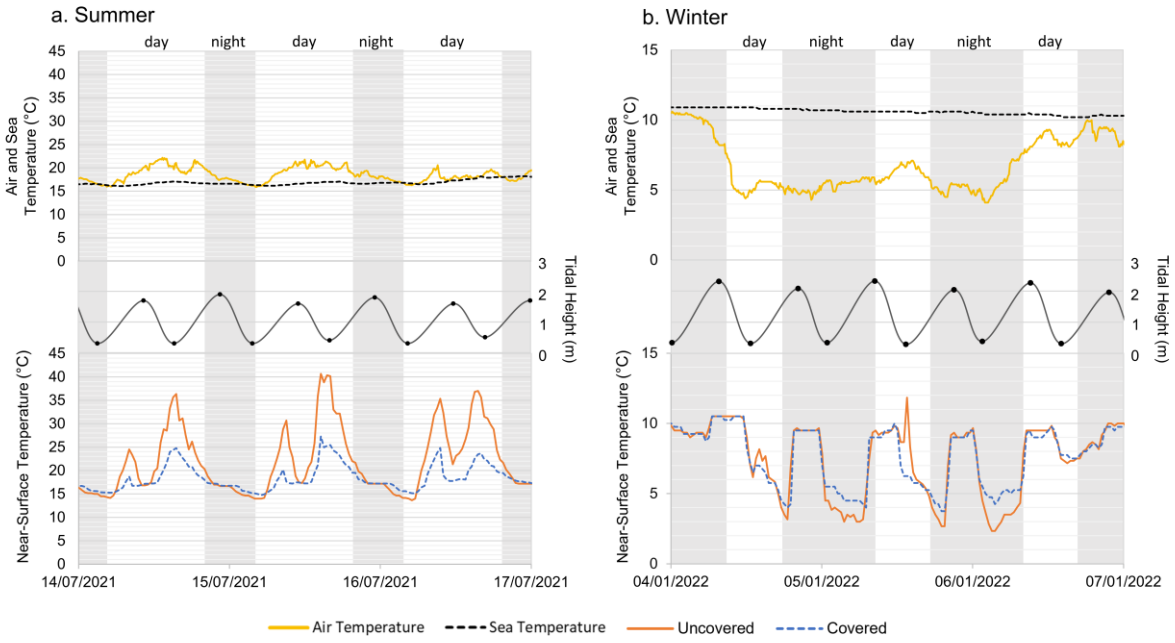


Fig. 5.6. Top: Air temperature recorded at 10-min intervals (yellow solid) and sea temperature recorded at 30-min intervals (black dotted) by a directional wave measurement buoy in Weymouth Bay (data obtained from coastalmonitoring.org). Bottom: Tidal regime at Portland Port during a warm spell (a) between 14 and 17 July 2021 and a cold spell (b) between 4 and 7 January 2022. The mean near-surface temperatures (°C) of the seaweed-covered plots (blue dashed, n = 3) and the uncovered plots (orange solid, n = 3) recorded at 30-min intervals are also shown. Note the different scales in parts (a) and (b).

5.3.4.2 Winter study period

The near-surface temperature regimes in the covered and uncovered plots were less variable during the winter study period compared to the summer study period. Air temperature recorded every 10 min by a directional wave measurement buoy in Weymouth Bay (50°37’22”N, 02°24’51”W) ~5 km from the field site also fluctuated to a lesser degree, remaining relatively stable between the day and night, and never dropping below freezing (Fig. 5.6b). The differences in near-surface temperatures between the covered and uncovered plots were also small during the winter. For instance, when ambient air temperature was above 10°C, the mean near-surface temperature in the uncovered plots was typically in the order of 1°C higher than in the covered plots. The greatest differences between the covered and uncovered plots occurred during low-tide periods when air temperatures were low (i.e. 7°C or below) at the beginning and end of the study period (10 December 2021 and 4–7 January 2022). During these periods, the mean near-surface temperature

in the uncovered plots was typically 1–2°C lower than in the covered plots (e.g. Fig. 5.6b). However, it is worth noting that a similar trend was not observed during a cold spell between 19 and 22 December 2021, when temperature differences between the plots remained small.

5.4 Discussion

5.4.1 Seaweed cover influences on indicators of substrate deterioration

After 6 months' exposure to intertidal conditions, seaweed cover was not found to significantly affect the surface hardness of mortar prepared using natural cement. The hardness of both seaweed-covered and uncovered samples increased over time, indicating that during the early phases of exposure, when curing may be continuing and cement mortars are at their most vulnerable, seaweed did not detrimentally impact the condition of the mortar. Instead, differences in surface roughness and UPV between seaweed-covered and uncovered samples suggest that seaweed may provide some protective benefit. Specifically, the increase in UPV was significantly greater for the seaweed-covered samples, indicating a greater degree of internal cohesion than the uncovered samples at the end of the study period (Fusade and Viles, 2019; Svahn, 2006). The seaweed-covered samples also had significantly lower surface roughnesses than the uncovered samples at the end of the study, indicating that they had experienced less surface change and material loss (Fornós et al., 2011; Gómez-Pujol et al., 2006; McCarroll and Nesje, 1996). When considered together, these results suggest that the impact of seaweed on the breakdown of natural cement-based mortar was, at worst, negligible. Rather, seaweed cover appeared to enhance the curing process and/or protect the mortar samples from deterioration during the first few months after initial mixing and exposure to intertidal conditions.

Differences in near-surface temperatures between areas with and without seaweed cover have been used as an indicator of differences in the intensity of thermal weathering regimes on natural rock and engineered structures (e.g. Coombes et al., 2013b). In our study, near-surface temperature extremes and fluctuations over both diurnal and minute–hour timescales were damped under

seaweed canopies, with the greatest dampening effects observed during the summer study period (Fig. 5.5 and 5.6). This dampening effect implies a bioprotective mechanism, whereby the frequency and magnitude of thermal variations associated with both 'shock' and 'fatigue' modes of thermal decay (e.g. Hall and Thorn, 2014) are reduced under a cover of seaweed. In comparison to other studies on the bioprotective properties of seaweed (e.g. Coombes et al., 2013b; Gowell et al., 2015) and other intertidal organisms, such as barnacles and mussels (e.g. Baxter et al., 2022; Coombes et al., 2017b; Gonzalez et al., 2021; Jurgens and Gaylord, 2016), the magnitude of thermal dampening by *F. vesiculosus* and *F. serratus* canopies was relatively high at our study site, which may be related to differences in aspect and, in particular, canopy thickness (Coombes et al., 2013b).

As has been previously suggested, lower temperatures under seaweed canopies during warm weather and periods of intense insolation (i.e. during low-tide periods) are likely associated with shading effects and enhanced moisture retention and evaporative cooling (Baxter et al., 2022; Coombes, 2014; Coombes et al., 2013b). Such thermal-moderating effects, also demonstrated in our data, have implications for the deterioration of natural cement mortars as fluctuations, extremes, and rates of change in temperature are closely linked to the efficiency of mechanical weathering processes acting on historic masonry (e.g. André et al., 2012, 2014; Jang and Viles, 2021; McIlroy de la Rosa et al., 2013; Sternberg et al., 2011; Viles et al., 2011b) and natural rock in marine environments (e.g. Baxter et al., 2022a; Coombes et al., 2013b; Gonzalez et al., 2021; Gowell et al., 2015; Mottershead et al., 2003; Moura et al., 2012). Although we did not directly collect data on substrate moisture, seaweed is known to retain moisture during low-tide periods (Coombes et al., 2013b; Umanzor et al., 2019), which has further implications for the wetting–drying and salt crystallisation processes that influence rock and engineering materials when exposed in the intertidal zone (Kanyaya and Trenhaile, 2005; Santhanam and Otieno, 2016; Trenhaile, 2006). For example, increased moisture retention caused by seaweed canopies has been linked to reductions in the frequency and intensity of wetting–drying cycles as well as the likelihood of salt crystallisation during drying phases on rocky shore platforms (e.g. Stephenson and Kirk, 2000). The retention of

substrate moisture may also be important for chemical weathering processes (Coombes, 2014), although compared to mechanical processes, the influence of seaweed and other intertidal species on chemical modes of breakdown remains relatively understudied.

Although sub-zero temperatures did not occur during our study, we did find evidence of thermal insulation by seaweed during the colder winter period (e.g. Fig. 5.6b), with near-surface temperatures typically being higher under the seaweed canopies when the air temperature was 7°C or below. This complements observations made under more extreme cold conditions, showing that seaweed canopies likely reduce the frequency, severity, rate, and duration of damaging freezing events in temperate environments (e.g. Scrosati and Ellrich, 2018). While such bioprotective mechanisms against extreme cold have been demonstrated in terrestrial heritage settings (e.g. Coombes et al., 2018), this has not yet been identified for heritage materials and structures exposed in the intertidal zone. This is despite the fact that freezing events can cause significant physical damage to coastal rocks when coinciding with low tide (e.g. Robinson and Jerwood, 1987). As such, the potential protective roles of algal canopies growing on maritime heritage in winter as well as summer warrant further attention.

5.4.2 Wider implications and future research opportunities

Our finding that seaweed cover did not significantly impact the deterioration of natural cement-based mortar during the first 6 months of intertidal exposure has potential implications for the conservation of maritime built heritage and marine biodiversity. Specifically, these results help address some of the concerns raised by maritime practitioners in a recent survey regarding the effects of seaweed growth on built heritage assets (e.g. Chapter 4, Paper 1). Furthermore, our findings imply that opportunities exist for the application of nature-based solutions for the management and protection of historic structures in marine environments, alongside habitat provision and biodiversity conservation. For instance, our study supports arguments for not removing seaweed from historic masonry as part of maintenance regimes unless this is necessary

for health and safety reasons, or to allow structural inspections. As with soil and turf used in the soft capping of some terrestrial heritage sites (Hanssen and Viles, 2014; Z. Lee et al., 2009; Morton et al., 2011; Wood et al., 2018) and ivy canopies growing on historic walls (Coombes et al., 2017a; English Heritage, 2010; Viles et al., 2011b), managers of coastal infrastructure may look to retain or even actively encourage biological growth, including seaweed, that has the potential to provide protective engineering functions alongside other associated benefits. This includes maintaining and/or increasing the biodiversity value of coastal engineering structures given that seaweed canopies provide cooler and wetter conditions for diverse understory communities (Scrosati and Ellrich, 2018; Watt and Scrosati, 2013). Management strategies aimed at discouraging the removal of existing seaweed or encouraging its growth may, therefore, present win–win opportunities for the conservation of built cultural heritage and biodiversity in marine environments.

Focusing on thermal effects, we examined the impact of two species of seaweed (*F. vesiculosus* and *F. serratus*) on the deterioration of natural cement mortar over a 6-month period using multiple weathering indicators (surface hardness, roughness, and ultrasonic pulse velocity). In doing so, we found no evidence of accelerated deterioration associated with seaweed cover, along with some evidence of potential protective effects. Future research is now needed to determine the full suite of biodeteriorative and/or bioprotective effects of different biological covers on built heritage assets (i.e. covers varying in constituent species, morphology, thickness, organism density, etc.), and whether processes of deterioration moderated by surface-colonising organisms vary with location, environmental conditions, and the type of material being colonised (stonework, plastic, wood, metal, etc.). The effects of marine growth on conservation materials, including natural cement, also need to be examined over longer periods of time and under changing climatic conditions. Indeed, whilst mortar is generally most vulnerable to deterioration in the initial days and weeks after it has been mixed (i.e. during the curing phase), any biodeteriorative or bioprotective effects will likely become more pronounced once exposed over longer periods of time. Understanding how marine growth influences the long-term decay of materials used to build and repair heritage assets is

particularly important for future conservation, especially in the case of older structures that have experienced longer periods of environmental exposure and, consequently, may be more vulnerable to decay. In the context of global climate change, any changes in the biogeomorphological functions of seaweed (and other types of marine growth) also warrant further attention. This includes the likely modulation of thermal buffering effects due to increases in extreme weather events, such as heatwaves, and changes in the structure of the biological communities that develop on maritime built heritage in response to changing environmental conditions (e.g. rising sea levels, ocean acidification, and changing temperatures).

5.5 Conclusions

After 6 months of exposure to intertidal conditions, we found no evidence of enhanced deterioration of mortar prepared using natural cement when covered with seaweed. Instead, our results suggest that seaweed cover may enhance the curing process and structural integrity of mortar, and limit surface breakdown associated with thermal variability under both warm (summer) and cold (winter) conditions. The thermal dampening and water-retaining effects of seaweed may also limit the decay of natural cement-based mortars caused by other physical decay mechanisms (e.g. wetting–drying and salt crystallisation), but this requires further study. Importantly, the biogeomorphological functions of seaweed should be considered in management decisions alongside the other costs, benefits, and values associated with its growth to ensure the continued conservation of maritime built heritage and marine biodiversity. Finally, future work should focus on determining the net effects of seaweed and other intertidal species on materials used in the construction and repair of built heritage exposed to intertidal conditions over varying timescales and under changing environmental conditions.

5.6. Chapter 5: Summary and implications

Results from the field block exposure trial showed that:

i. Seaweed cover does not significantly enhance the deterioration of natural cement-based mortar during the first few months of exposure.
ii. Seaweed cover dampens temperature variations on underlying substrate during both warm (summer) and cold (winter) conditions in temperate environments. The influence of seaweed cover on near-surface microclimate regimes means it may provide protective functions on materials used in maritime built heritage restoration.

As demonstrated in previous studies (e.g. Coombes et al., 2013b), the net biogeomorphological effect of biotic covers depends on a variety of factors, including the characteristics of colonising biotic (e.g. covers varying in constituent species, morphology, thickness, organism density, etc.). Consequently, an improved understanding of the composition and dynamics of ecological communities that form on historic masonry structures will help inform future research aimed at investigating the biogeomorphological impacts of marine organisms on heritage assets. In particular, more research is required to determine whether marine communities on heritage assets differ to those found on other forms of coastal infrastructure (e.g. modern coastal defences) and natural rocky substrate as, so far, this has received little research attention.

Chapter 6.

Intertidal biodiversity and physical habitat complexity on historic masonry walls: A comparison with modern concrete infrastructure and natural rocky cliffs

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Abstract

Maritime built heritage (e.g. historic seawalls) represents an important component of coastal infrastructure around the world. Despite this, the ecological communities supported by these structures are poorly understood. At seven locations across the UK, we compared the biodiversity and physical habitat characteristics of (i) historic (pre-1900s) masonry walls, (ii) concrete walls, and (iii) natural rocky cliffs.

Historic masonry walls were found to support significantly more species than concrete walls, and in some locations, more diverse communities than nearby rocky cliffs. Nevertheless, community composition remained distinct between the three habitat types at each location. We also found that historic masonry walls provided substantially more cryptic space (i.e. crevices) than both concrete walls and rocky cliffs, and this is positively associated with the ecological value of these structures. Overall, our results suggest that the unique physical properties of historic masonry walls make them an important component of habitat diversity along developed coastlines.

* Minor changes have been made to this manuscript to aid the readability and continuity within the thesis. For instance, British English is used instead of American English, and figure and table numbers have been changed. The published journal article is available from: https://doi.org/10.1016/j.marpolbul.2023.114617

6.1 Introduction

Compared to natural rocky shores, artificial structures are generally considered to be ecologically poor (Aguilera et al., 2014; Chapman and Bulleri, 2003; Moschella et al., 2005; Pister, 2009). With a few exceptions (e.g. Hill et al., 2021; Holmes et al., 2020; López, 2019; Pattrick et al., 2022), research examining the effects of artificial structures on marine wildlife has almost exclusively focused on determining the ecological impacts of modern infrastructure built from concrete and other engineering materials (e.g. metal and natural rock armour) since the beginning of the twentieth century (e.g. Airoldi et al., 2015; Bacchiocchi and Airoldi, 2003; Firth et al., 2015a; Momota and Hosokawa, 2021; Vaselli et al., 2008). As such, there is relatively limited understanding of the ecological communities that are supported by older structures (i.e. those built pre 1900s), including those with traditional block-masonry designs, despite constituting a significant proportion of coastal infrastructure around the world (Chadwick and Catchpole, 2010; Luo et al., 2019). In Cornwall, UK, for example, historic masonry structures, including stonewalled piers, seawalls, and breakwaters, constitute >50 km of the intertidal shoreline (Fig. 6.1) including heavily urbanised sections of coast (e.g. Falmouth and Plymouth) and those within areas of marine conservation (e.g. Whitsand and Looe Bay Marine Conservation Zone). Notably, research examining how biodiversity develops on rock armour over decadal timescales suggests that older structures might support more diverse ecological communities than newer structures (e.g. Pinn et al., 2005a) and communities may become more similar to those found on nearby natural rocky shores with age (e.g. Burt et al., 2011; but also see Aguilera et al., 2022). It is surprising, therefore, that the ecological functions of historic maritime infrastructure have not been considered in greater detail, especially given their relative age, potentially unique construction features, and additional heritage value.

As first discussed in Chapter 2, historic maritime structures may possess a number of characteristics relating to their traditional design (i.e. masonry configuration), material, age and decay mechanisms, maintenance regimes, and protected status that makes them favourable for marine

wildlife colonisation (Fig. 6.2). This often contrasts with more recently built structures that have been shown to alter ecological connectivity (Bishop et al., 2017), attract and promote the spread of non-native and invasive species (Airoldi et al., 2015; Bulleri and Airoldi, 2005; Glasby et al., 2007; Mineur et al., 2012; Vaselli et al., 2008), and support younger, less diverse assemblages of marine organisms than natural shores (Connell and Glasby, 1999; Moschella et al., 2005). Notably, historic structures are typically constructed of the same or similar materials to the local geology, such as locally quarried stone, which contrasts with the abundance of concrete and imported stone used in modern engineering (Bijen, 1996; Kampa and Laaser, 2009). Furthermore, textured surfaces and fine-scale topographic features typical of natural rock and quarried stone are generally considered beneficial for marine colonisation, unlike the smooth surfaces characteristic of metal and cast concrete (Coombes et al., 2011; Dodds et al., 2022; Firth et al., 2023; MacArthur et al., 2019; Sempere-Valverde et al., 2018).

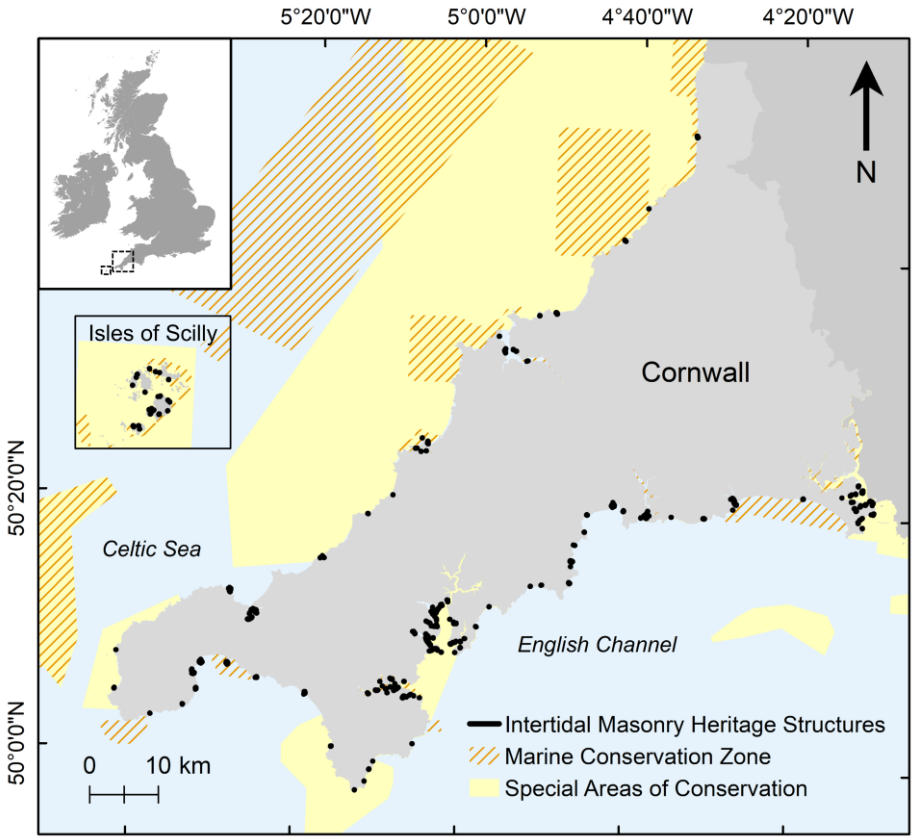


Fig. 6.1. Built heritage constructed of masonry within the intertidal zone of Cornwall, UK. This includes approximately 260 structures recorded in either the NHLE or the Cornwall and Isles of Scilly Historic Environment Record (CSHER). Marine Conservation Zones (MCZs) and Special Areas of Conservation (SACs) are also shown.

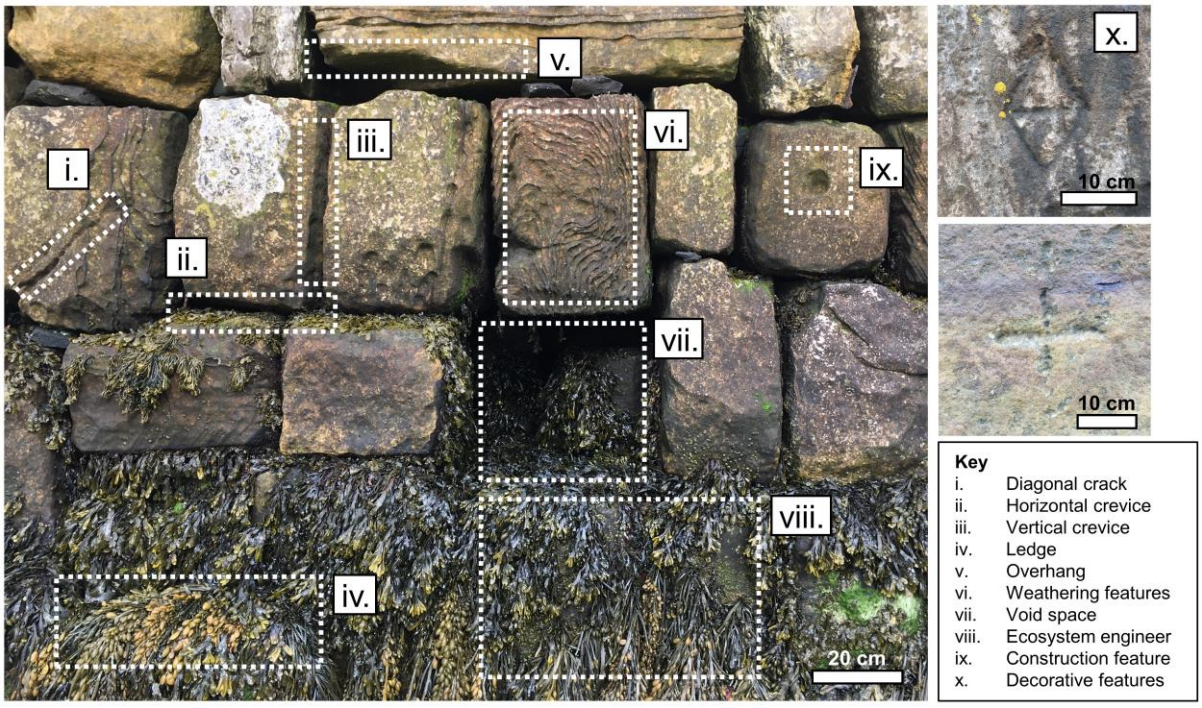


Fig. 6.2. Eighteenth-century sandstone breakwater at St Andrews harbour, Scotland, with examples of microhabitat features typically found on historic masonry walls including (i) surface cracks, (ii) horizontal and (iii) vertical crevices in the stonework or between the joints, (iv) ledges and (v) overhangs, (vi) mm-scale topographic features caused by years of weathering processes (e.g. salt weathering), (vii) void space created by missing stonework, (viii) biotic covers formed by 'ecosystem engineer' species (e.g. seaweeds), (ix) features from historic construction, such as indented grips and holes used to manoeuvre stone into place, and (x) legacy features from the prior use of materials (in this case, parts of St Andrews harbour were rebuilt with stone from the nearby ruined castle dating to 1656).

Due to years of progressive degradation by weathering and erosion, the availability of fine- (<1 cm) and meso-scale (>1 cm) surface features is expected to be higher on historic masonry structures (Fig. 6.2). For example, surface pitting from salt weathering and the development of fine cracks via the enlargement of discontinuities in natural stone may provide functional habitat space for benthic organisms (e.g. Chapman and Underwood, 2011; Moreira et al., 2007). In the particular case of old waterfront walls built from dimension stone (i.e. quarried stone selected and/or shaped for use in construction), horizontal and vertical crevices of varying sizes and shapes occur between adjacent stones both in mortared and traditional drystone configurations (i.e. free-draining structures without mortared joints), which may provide cryptic habitat space and refugia (in association with porous designs and internal void space; see Sherrard et al., 2016) for a range of sessile and mobile species (e.g. Chapman and Blockley, 2009; Dugan et al., 2011; Johnson et al., 1998; Moreira et al.,

2007). Many historic structures also provide larger-scale physical habitat features that make them more similar to natural rocky shores than simpler, modern structures, including overhangs and ledges that resemble ecologically important water-retaining features like rockpools (Firth et al., 2013; MacArthur et al., 2020; Fig. 6.2). The progressive loss of core materials and the dislodgement of individual stones may also create novel habitat space in older walls (Chapman and Blockley, 2009; Sherrard et al., 2016). Fine- and meso-scale topographic features are known to mitigate thermal stress on both natural rock shores and artificial structures (Aguilera et al., 2019; Cox and Smith, 2011; Williams and Morritt, 1995; Garrity, 1984), especially during summer and heatwave conditions. As such, the presence of these features on historic structures (whether by design or not) might facilitate more diverse assemblages compared to modern infrastructure typically lacking in topographic complexity. As of yet, however, few studies have quantified differences in the provision and biodiversity of microhabitat features between built heritage, modern infrastructure, and natural rock surfaces.

Due to their age, unique architectural features, and/or historical and cultural significance, the protected status of many historic structures (e.g. listed buildings and Scheduled Monuments) means that original materials or those with compatible technical and aesthetic properties are considered most suitable for maintenance and repair works (Historic England, 2016a, b). As such, pre-weathered stone or original materials are favoured for minor repairs to historic masonry walls (Historic England, 2016c), particularly when stonework can be salvaged from nearby (e.g. DeSilvey, 2017). This adds to the complex history of traditional construction, maintenance, repair, and replacement of old maritime walls that often gives rise to a unique mosaic of topographic features (Fig. 6.2). The age of historic masonry walls also means that, over time, ecological succession and interactions among colonising organisms (e.g. predation, competition, symbiosis, etc.), might give rise to more complex and diverse communities relative to those built more recently (Burt et al., 2011; Butler and Connolly, 1999; Perkol-Finkel et al., 2005; Pinn et al., 2005a). For instance, while key ecosystem engineers, such as canopy-forming macroalgae known to facilitate a range of

understory species (Bertness et al., 1999; Burnaford, 2004; Umanzor et al., 2017, 2019; Watt and Scrosati, 2013), are typically absent from new and flat concrete walls, historic walls often support a greater range and abundance of these species (Fig. 6.2), although this remains largely untested.

In this study, we sought to provide a detailed assessment of the ecological communities (surface and cryptic) found on historic masonry walls at several locations across the UK in comparison to nearby concrete walls and natural rocky cliffs. By specifically comparing vertical surfaces, we build on a growing number of comparisons between rock armour, vertical/steeply sloping structures, and semi-horizontal rocky shores (e.g. Aguilera et al., 2014, 2019, 2022; Bulleri, 2006; Cacabelos et al., 2018; Holloway and Field, 2020; Lam et al., 2009; Pister, 2009). We compared the (i) diversity and composition of surface ecological communities, (ii) fine-scale surface topographic complexity, and (iii) the provision and species richness of cryptic microhabitats (i.e. internal void space) between the three studied habitat types. We show that historic masonry walls support more diverse communities than modern concrete walls, but that these communities differ to those found on nearby natural rocky cliffs. Importantly, for the first time, we highlight the ecological importance of the provision of cryptic microhabitats on traditional masonry walls. Based on these findings, we argue that historic masonry walls should be considered important multifunctional assets valued not only for their functional uses and historical significance, but also the unique habitats they provide and the diverse ecological communities they can support.

6.2 Methods

6.2.1 Field sites

Field surveys were conducted at seven locations across the UK during the summer of 2021 (Fig. 6.3). At each location, three types of habitat were surveyed: (i) a historic masonry wall listed as a heritage asset that was >180 years old and had either a mortared or drystone configuration; (ii) a concrete wall constructed or significantly repaired within the last 100 years; and (iii) a rocky cliff habitat consisting of an area of vertical natural rock substrate (Table 6.1). At all but one location (Cockenzie), the historic masonry wall and the rocky cliff habitat consisted of a similar rock type. The locations for the field surveys were selected because the three habitats at each site were <200 m apart and broadly comparable in terms of gradient (steep/vertical, 60–90°), aspect, position within the tidal zone (mid-to-high intertidal), MarLIN wave exposure category, and surrounding habitat (i.e. rocky, sandy, or mixed).

To gain a holistic understanding of the biodiversity and physical complexity of the three habitat types, data were collected from two distinct environments on each wall/cliff: (i) the outer, seaward-facing surface, and (ii) within cryptic microhabitat features (i.e. internal void space connected to the surface, such as crevices and holes). As discussed in the following sections, due to fundamental differences in the morphology (flat surfaces vs. crevices) and accessibility of the two environments, different sampling techniques were used to collect biodiversity and habitat complexity data from each. As such, the data from these two environments were analysed separately, although overall biodiversity was also compared qualitatively. Near-surface temperature data were also collected at one location (Aberdour) using an infra-red camera to provide preliminary evidence of differences in the thermal behaviours of surface and cryptic microhabitats (Appendix Fig. C1).

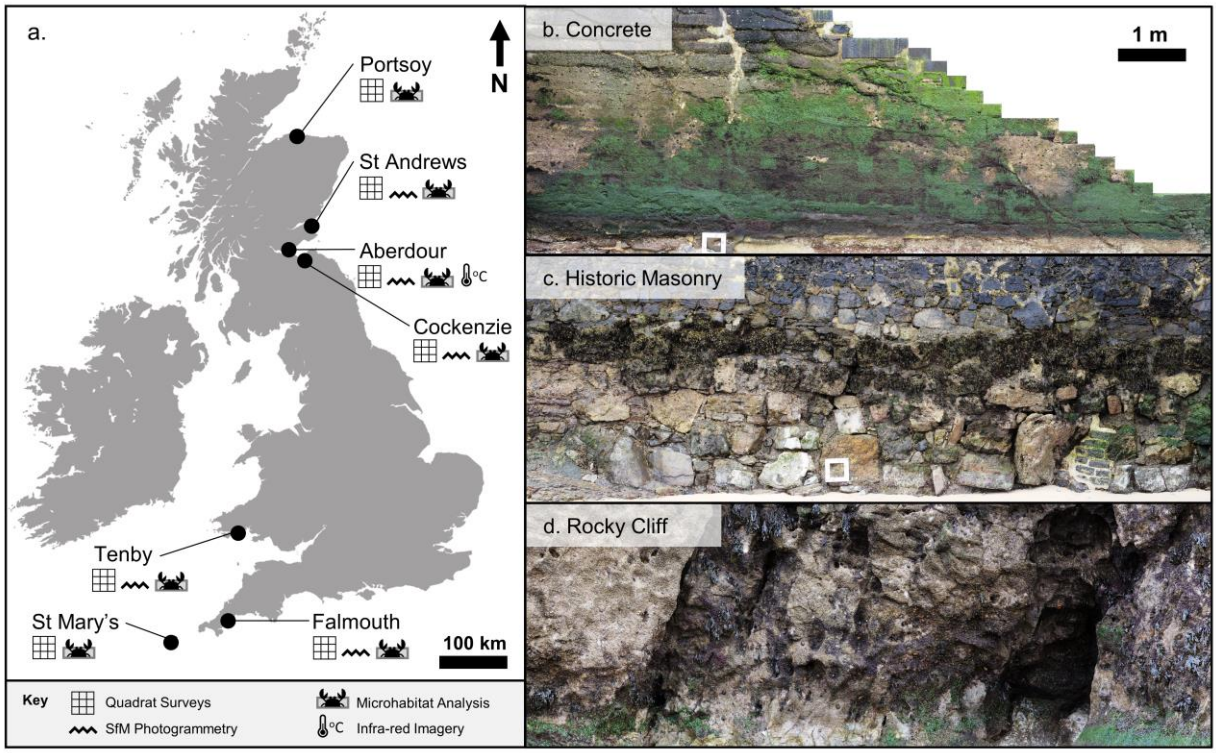


Fig. 6.3. (a) Locations of field surveys around the UK and the methods used at each site. Examples, from Tenby, Wales, of the different types of habitats surveyed at each location are shown, including (b) a concrete seawall, (c) a historic masonry breakwater, and (d) a near-vertical natural cliff.

Table 6.1. Locations of ecology surveys conducted on three types of coastal structure (masonry walls, concrete walls, and rocky cliffs) at seven sites across the UK (also see Fig. 6.3).

Location	Structure	Coordinates	Age	Material	Orientation	Listed Status†
Portsoy	Drystone Breakwater	57.685, -2.691	1692	Igneous rubble	North-East	Category A
(Scotland)	Concrete Breakwater	57.686, -2.688	1883	Concrete	North	-
	Rocky cliff	57.686, -2.691	-	Olivine-gabbro	North-East	-
St Andrews	Drystone Breakwater	56.339, -2.783	1700-27*	Sandstone	South-East	Category A
(Scotland)	Concrete Breakwater	56.339, -2.782	1910-1920*	Concrete	South	-
	Rocky cliff	56.340, -2.784	-	Sandstone	South-East	-
Aberdour	Drystone Breakwater	56.052, -3.295	1703	Sandstone	South	Category B
(Scotland)	Concrete Slipway	56.052, -3.295	Post-1850s	Concrete	South	-
	Rocky cliff	56.051, -3.297	-	Sandstone	South	-
Cockenzie	Masonry Breakwater	55.970, -2.967	1835	Sandstone	North	Category B
(Scotland)	Concrete Seawall	55.970, -2.969	~1967*	Concrete	North-West	-
	Rocky cliff	55.970, -2.968	-	Quartz-dolerite	North	-
Tenby	Masonry Breakwater	51.673, -4.697	1328, 1842	Limestone	North-East	Grade II
(Wales)	Concrete Seawall	51.673, -4.697	Pre-1890	Concrete	North-East	-
	Rocky cliff	51.673, -4.696	-	Limestone	North	-
Falmouth	Masonry Pier	50.162, -5.060	1700-1839*	Shale	West	Grade II
(S. England)	Concrete Seawall	50.154, -5.067	1960-1970*	Concrete	North-West	-
	Rocky cliff	50.162, -5.062	-	Slate, Siltstone	North-West	-
St Mary's	Drystone Breakwater	49.916, -6.317	1751	Granite	South	Grade II
(Isles of Scilly)	Concrete Outflow	49.916, -6.317	1900-89*	Concrete	South	-
	Rocky cliff	49.917, -6.312	-	Granite	South	-

* Estimated age of construction based on historic maps and/or heritage records.

† Listed status as reported by Historic England in the NHLE (Grade II = buildings of special interest) or by Historic Environment Scotland (Category A = buildings of national or international importance; Category B = buildings or regional or more than local importance).

6.2.2 External surface surveys

6.2.2.1 Surface biodiversity

The biological communities on the outer, seaward-facing surfaces of each habitat type were sampled at the seven locations using ten 20 × 20 cm quadrats placed at least 1 m apart at mid-tide level, as determined using local tide tables. The percent cover of sessile organisms (e.g. barnacles and algae) and counts of mobile fauna were recorded within the quadrats (Evans et al., 2021). Individual count records were subsequently converted to percent cover depending on organism size (i.e. 0–20 mm = 1 %, 20–40 mm = 2 %, >40 mm = 4 %) to aid further analysis and comparison between each habitat type. Mobile organisms observed within quadrats that were too small to count by eye (i.e. <2 mm, e.g. *Anurida maritima*) were given a nominal cover value of 1 %. Taxa were recorded to species level or, where this was not possible, by genus or family. A record was also made of whether the taxa were native or non-native according to the GB Non-native Species Secretariat (NNSS)[8] and National Biodiversity Network (NBN)[9] websites.

6.2.2.2 Surface topography

To identify potential associations between surface topographic complexity and ecological communities present on each of the habitat types, at five of the study sites (Falmouth, Tenby, Cockenzie, Aberdour, and St Andrews), we used SfM photogrammetry to record the surface topography of the substrates beneath the ecological communities surveyed using the 20 × 20 cm quadrats (Evans et al., 2021; Grasselli and Airoldi, 2021). Surface topography was not recorded at Portsoy and St Mary's due to practical constraints. At the other five sites, a wire brush was used to remove all colonising organisms from within the quadrat areas; care was taken to ensure the underlying substrate was not damaged during this procedure. A 23 × 23 cm frame with six control points was then placed centrally on each cleared area. A Sony Alpha a6600 APS-C Mirrorless Camera

[8] Accessed at: https://www.nonnativespecies.org/
[9] Accessed at: https://nbnatlas.org/

with an E 20 mm F2.8 lens was then used to take 19 photographs of the substrate surface: four photographs were taken from each corner angled 45° towards the centre, and then three sets of five overlapping perpendicular photographs (i.e. 15 in total) were taken below, above, and in line with the centre of each quadrat. Using Darktable v4.0, the raw images were checked to ensure they were well exposed, and no photometric correction was required before conversion to tiff format (Verma and Bourke, 2019). Accurately scaled (1 mm) digital elevation models (DEMs) with Cartesian co-ordinates were then generated using Agisoft Metashape Professional v1.6.5 and CloudCompre v2.11.3. For each model, the central 20 × 20 cm area was clipped so that the final topographic model represented the substrate directly beneath the surveyed biological community (Evans et al., 2021). The slope (i.e. the maximum rate of change in height from one 1-mm^2 cell to its neighbouring cells) in each topographic model (n = 40,000 cells per model) was then calculated using the Benthic Terrain Modeler (BTM) v3.0 add-on in ArcMap v10.8 (Walbridge et al., 2018). Mean slope values (S, deg.) were then determined for each area surveyed, with higher values indicating greater variability in mm-scale surface topography and lower values indicating flatter surfaces. Slope (mm-scale) has previously been identified as an important topographic variable that influences the biodiversity of substrates in marine environments (e.g. Evans et al., 2021).

6.2.3 Cryptic microhabitat provision and biodiversity surveys

To determine whether the provision and biodiversity of cryptic microhabitats (i.e. internal void space) varied between habitat type, the presence/absence of taxa within microhabitat features in a 15-cm area around each surveyed quadrat (i.e. 0.21 m^2 survey area) was recorded along with the dimensions (length, width, and approximate depth) of each feature. The approximate (internal) 3D surface area of each microhabitat feature was then calculated as follows:

$$\text{Surface area} = (\text{width} \times \text{depth} \times 2) + (\text{length} \times \text{depth} \times 2) + (\text{width} \times \text{length})$$

where length represents the longest distance between two points at the (surface) opening of a microhabitat feature, width represents the dimension perpendicular to length at the opening of a

microhabitat feature, and depth represents the internal dimension of a microhabitat feature (i.e. how far the void associated with a feature penetrates into a wall/cliff). The cryptic microhabitats were then grouped into one of six categories (crack, crevice, chasm, pit, hole, and hollow) based on size and shape using a classification system that corresponds to previous attempts to categorise topographic features on natural and artificial substrate in marine and coastal environments (e.g. MacArthur et al., 2020; Strain et al., 2018; Table 6.2). The frequency, total surface area, and total species richness (R_C) of the cryptic microhabitats per 2.1 m^2 of surveyed area (i.e. 0.21 m^2 × 10 areas) were then compared between each habitat type (masonry wall, concrete wall, and natural cliff) at each location.

Table 6.2. Categories of cryptic microhabitat features recorded on walls and cliffs at seven sites across the UK. The dimension ratios are based on those used in a classification system developed by Strain et al. (2018).

Type	Definition	Dimensions	Length*	Width†	Depth††
Crack	Narrow space of any length between two surfaces	Length: Width ratio > 3:1	Any	h ≤ 1 cm	≥ 0.5 cm
Crevice	Small, linear gap of any length between two surfaces	Length: Width ratio > 3:1	Any	5 cm ≥ h > 1 cm	≥ 1 cm
Chasm	Large, linear gap of any length between two surfaces	Length: Width ratio > 3:1	Any	h > 5 cm	≥ 5 cm
Pit	Small, round hole	Length: Width ratio ≤ 3:1	L ≤ 3 cm	h ≤ 3 cm	≥ 0.5 cm
Hole	Medium, round hole	Length: Width ratio ≤ 3:1	15 cm ≤ L < 3 cm	15 cm ≤ h < 3 cm	≥ 1 cm
Hollow	Large, round hole	Length: Width ratio ≤ 3:1	L > 15 cm	h > 5 cm	≥ 5 cm

* Longest distance between two points at the opening of a microhabitat feature.
† Dimension perpendicular to length at the opening of a microhabitat feature.
†† Internal dimension.

6.2.4 Statistical analysis

To compare the surface communities across the three habitat types, species richness was first calculated for each quadrat (R_Q) using the DIVERSE function in PRIMER-e v.7 (Anderson et al., 2008; Clarke, 1993; Clarke et al., 2014; Clarke and Gorley, 2015). To model R_Q as a function of habitat type, a Poisson Generalised Linear Mixed Effects Model (GLMM) with a log link function was used (Zuur and Leno, 2016; Zuur et al., 2009). The log link function ensures positive fitted values, and the Poisson distribution is typically used for count data. 'Habitat type' was treated as a fixed factor

(categorical with three levels: Concrete, Masonry, and Rocky cliff). To incorporate the dependency among observations of the same location, 'location' was used as a random intercept.

Differences in the composition of the ecological communities on the surfaces of each habitat type were also compared using PRIMER-E v.7 and PERMANOVA+ statistical software (Anderson et al., 2008; Clarke, 1993; Clarke et al., 2014). After examining shade plots, percentage abundance data were square-root-transformed to reduce the dominance of abundant species on similarity computations (Clarke and Gorley, 2015). A Bray–Curtis similarity matrix (Bray and Curtis, 1957) was then created for the statistical tests. Non-metric multidimensional scaling (nMDS) plots were created to visualise patterns using rank similarities and hierarchical clustering in the multivariate output (Clarke, 1993; Clarke et al., 2014). Permutational multivariate analysis of variance (PERMANOVA, McArdle and Anderson, 2001; Anderson, 2005) was also performed to test for differences in the assemblages, based on 9999 unrestricted random permutations of residuals (Anderson et al., 2008). Factors used in the analysis were 'habitat' (fixed, three levels: concrete, masonry, and rocky cliff) and 'location' (random, seven levels: see Table 6.1 and Fig. 6.3). Pairwise comparisons were used to test differences in overall community structure between the three habitat types at each location. An analysis of similarity percentages (SIMPER) was then used to identify the percentage contributions of individual species to the dissimilarities between the habitat levels (Anderson et al., 2008; Clarke, 1993; Clarke et al., 2014; Sherrard et al., 2016).

To evaluate the surface topography data obtained from the SfM models, slope was modelled as a function of habitat type using a Linear Mixed Effects Model (LMM). To allow assumptions of normality and equal variance, the mean slope data (S) were square-root transformed. As with the GLMM, 'Habitat type' was treated as a fixed factor (categorical with three levels: Concrete, Masonry, and Rocky cliff), while 'location' was used as a random intercept. Both the GLMM and LMM were run using R v4.0.3 (R Core Team, 2021) and the package "lme4" version 1.1-30. Model assumptions

were verified by plotting residuals against the fitted values and covariates in each model (Zuur and Leno, 2016).

6.3 Results

6.3.1 External surfaces

6.3.1.1 Surface species richness

Across all seven locations, a total of 56 taxa were recorded on the outer, seaward-facing surfaces of the three habitats surveyed (i.e. concrete walls, historic masonry walls, and rocky cliffs). Of these, 31 were recorded on concrete walls, 40 on historic masonry walls, and 48 on rocky cliffs (Appendix Table C1). Three taxa were uniquely observed on the concrete walls, one on the historic masonry walls, and nine on the rocky cliff faces. Across all locations, only native species were observed on the outer surfaces of these habitats.

Significant differences in the number of surface-colonising species (R_Q) were found between the habitat types (Table 6.3). Compared to historic masonry walls, R_Q was significantly lower on concrete walls ($\beta = -0.46476$, $z = -6.429$, $p < 0.001$), and significantly higher on rocky cliff habitats ($\beta = 0.12516$, $z = 2.032$, $p < 0.05$). Concrete walls were found to have the lowest average R_Q at each of the study locations, apart from Portsoy (Fig. 6.4). In contrast, rocky cliff habitats had the highest average R_Q at four locations (Falmouth, St Andrews, St Mary's, and Tenby), while masonry walls had the highest values at three locations (Aberdour, Cockenzie, and Portsoy). When averaged across all seven locations, mean R_Q values for concrete, historic masonry, and rocky cliff habitats were 4.44, 7.07, and 8.01, respectively.

Table 6.3. Estimated regression parameters, standard errors, *z*-values and *p*-values for the Poisson GLMM used to model the number of surface-colonising species (R_Q) as a function of habitat type (*$p < 0.05$, ***$p < 0.001$).

Fixed Effects	**Estimate**	**Std. Error**	***z* value**	***p*-value**
Intercept	1.93964	0.08244	23.527	< 2e-16 ***
Habitat Type Concrete (Relative to Masonry)	-0.46478	0.07229	-6.429	1.28e-10 ***
Habitat Type Rocky Cliff (Relative to Masonry)	0.12516	0.06161	2.032	0.0422 *
Random Effects	**Variance**	**Std. Dev.**		
Location	0.03328	0.1824		

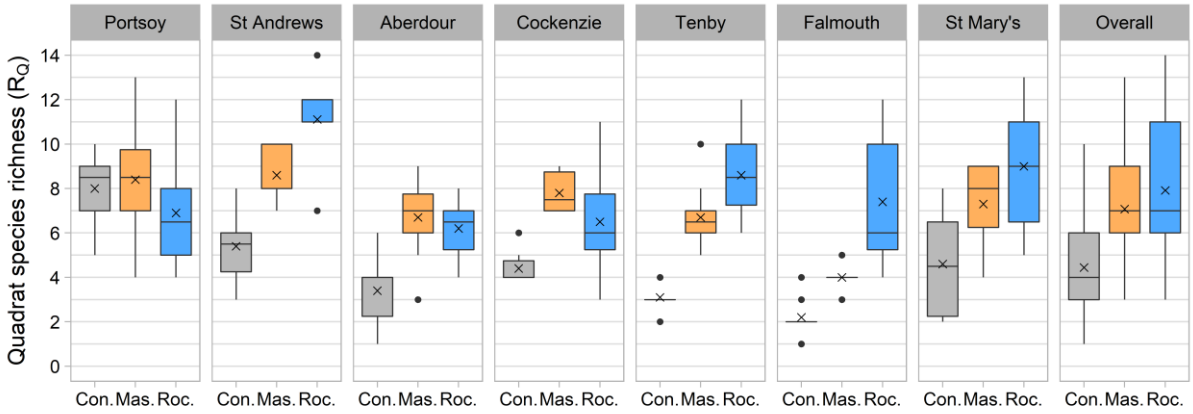


Fig. 6.4. Numbers of species observed within 20 × 20 cm quadrats (R_Q, n = 10) on the external, seaward-facing surfaces of concrete (grey, 'Con.'), historic masonry (orange, 'Mas.'), and rocky cliff habitats (blue, 'Roc.') at seven locations in the UK (see Fig. 6.3a). Pooled R_Q data across all locations (n = 70, 'overall') are also shown. Interquartile range (IQR) = boxes; median = horizontal line within boxes; mean = '×'; whiskers = "minimum" (Q1 − 1.5 ∗ IQR) and "maximum" (Q3 + 1.5 ∗ IQR); outliers = dots.

6.3.1.2 Surface community composition

There was significant interaction between habitat type and location in the community analysis (*Pseudo-F* = 17.412, $p \leq 0.0001$; Table 6.4), with the post-hoc pair-wise comparisons revealing significant differences between the three habitat types at each location ($p \leq 0.01$). These differences are evident in the nMDS ordination plots (Fig. 6.5). The SIMPER analysis revealed that dissimilarities between the habitat types at each location were driven by different species. For example, although barnacles (e.g. *Semibalanus balanodies*) were typically most abundant on the concrete walls at St Andrews, Portsoy, Falmouth, and Cockenzie, they were least abundant on the concrete walls and most abundant on the rocky cliffs at Tenby, St Mary's, and Aberdour. In general, historic masonry walls and rocky cliff habitats supported greater abundances of canopy-forming ecosystem engineers (e.g. seaweeds and mussels) and associated understory species, while concrete walls were typically dominated by a few, opportunistic species (e.g. *S. balanoides*, *Ulva* spp., etc.).

Table 6.4. Comparison of community composition (PERMANOVA) among concrete walls, historic masonry walls, and rocky cliff habitats. Analyses were based on Bray–Curtis similarities. All tests used 9999 permutations under a reduced model (***$p < 0.001$).

Source	**df**	**MS**	***Pseudo-F***	***p*-value**
Location	6	41,657	57.218	0.0001***
Habitat	2	14,289	1.1272	0.3591
Location × Habitat	12	12,676	17.412	0.0001***
Residual	189	728.03		

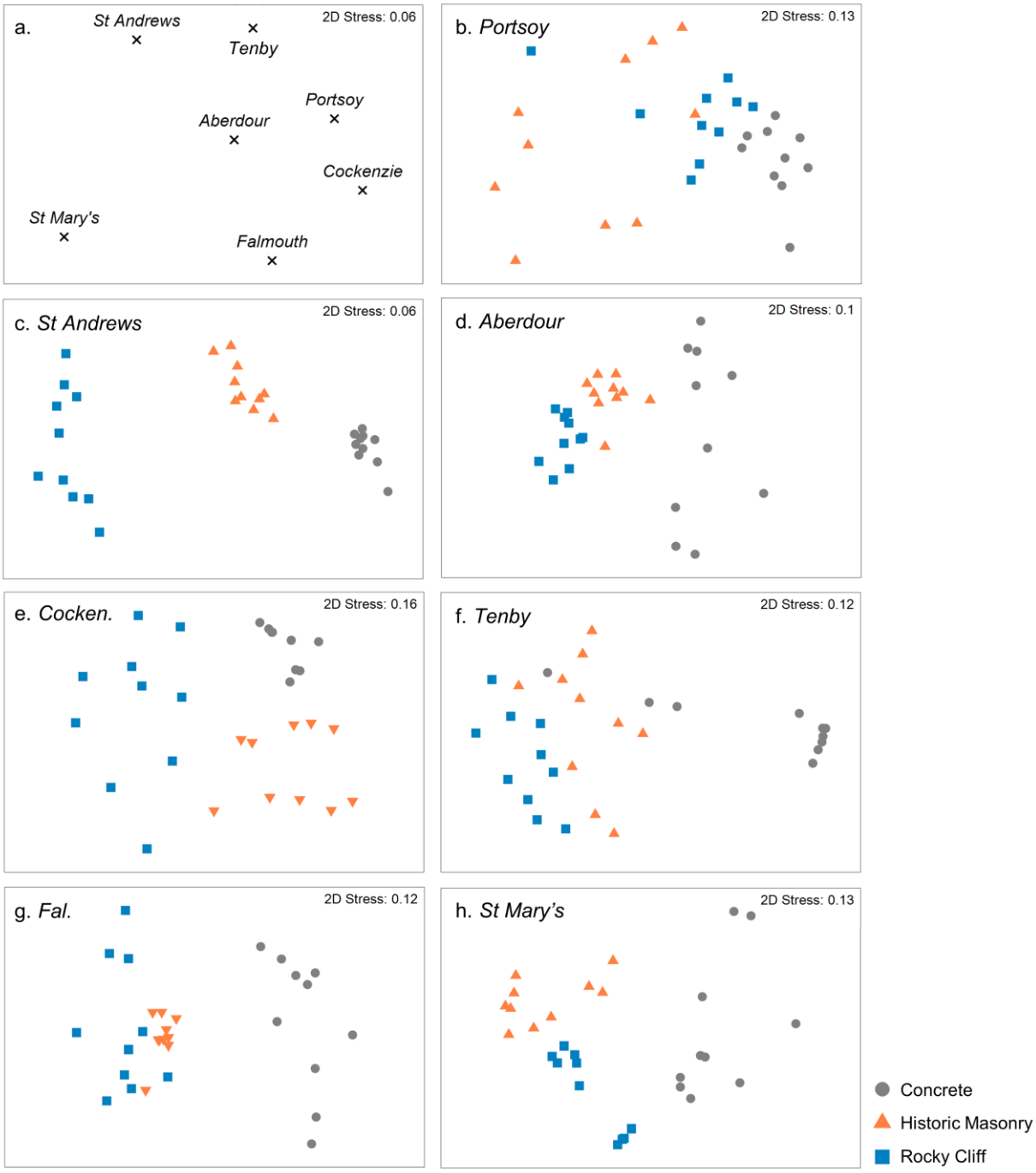


Fig. 6.5. Non-metric multidimensional scaling (nMDS) ordination of intertidal assemblage composition recorded at (a) the seven study locations (black crosses), and on the outer, seaward-facing surfaces of concrete walls (grey circles), historic masonry walls (orange triangles), and rocky cliff habitats (blue squares) at (b) Portsoy, Scotland, (c) St Andrews, Scotland, (d) Aberdour, Scotland, (e) Cockenzie, Scotland, (f) Tenby, Wales, (g) Falmouth, South England, and (h) St Mary's, Isles of Scilly. In part a, each point represents the average of 30 quadrats (i.e. 10 × concrete, 10 × historic masonry, and 10 × rocky cliff), whereas in parts b–h, each point represents one replicate quadrat.

6.3.1.3 Surface topographic complexity

As a measure of topographic complexity, significant differences in square-root transformed mean slope (S_{sqrt}) were found between the three habitat types (Table 6.5). Compared to the historic masonry walls, S_{sqrt} was significantly lower on the concrete walls ($\beta = -1.157568$, $t = -8.126218$, $p < 0.001$) while the rocky cliff surfaces were no different ($\beta = 0.126654$, $t = 0.910160$, $p < 0.3643$). At all seven locations, concrete walls had the lowest average S_{sqrt} (Fig. 6.6); when averaged across all seven locations, mean S_{sqrt} values for concrete, historic masonry, and rocky cliff habitats were 2.96°, 4.01°, and 4.23°, respectively.

Table 6.5. Estimated regression parameters, standard errors, *t*-values, and *p*-values for the LMM used to model square-root-transformed mean slope (S_{sqrt}) as a measure of surface topographic complexity, as a function of habitat type (***$p < 0.001$).

Fixed Effects	**Estimate**	**Std. Error**	***t* value**	***p*-value**
Intercept	4.099988	0.148576	27.595123	< 0.001 ***
Habitat Type Concrete (Relative to Masonry)	-1.157568	0.1424486	-8.126218	< 0.001 ***
Habitat Type Rocky Cliff (Relative to Masonry)	0.126654	0.1391560	0.910160	0.3643

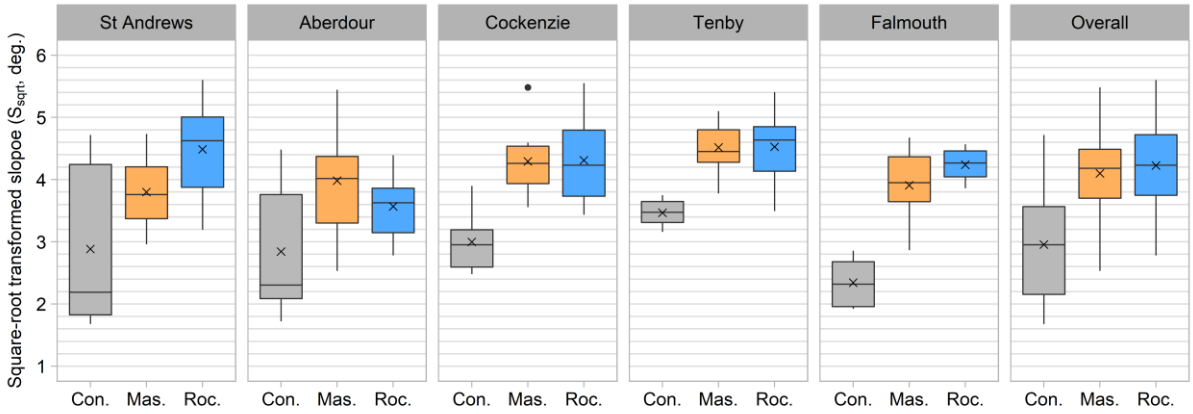


Fig. 6.6. Square-root-transformed mean slope (S_{sqrt}, deg.) on the external, seaward-facing surfaces of concrete (grey, 'Con.'), historic masonry (orange, 'Mas.'), and rocky cliff habitats (blue, 'Roc.') at seven locations in the UK. Pooled S_{sqrt} data across all locations (i.e. n = 50) is also shown. Interquartile range (IQR) = boxes; median = horizontal line within boxes; mean = '×'; whiskers = "minimum" (Q1 − 1.5 ∗ IQR) and "maximum" (Q3 + 1.5 ∗ IQR); outliers = dots.

6.3.2 Cryptic microhabitats

6.3.2.1 Microhabitat frequency and surface area

At all locations, the historic masonry walls had the greatest number of microhabitat features (i.e. internal void space connected to the surface), while concrete walls had the least (Fig. 6.7). On average, the number of microhabitat features recorded on concrete, historic masonry, and rocky cliff habitats per m^2 area of wall/cliff surveyed was 0.75, 11.56, 4.49, respectively. Microhabitat features were particularly prevalent on free-draining masonry walls (i.e. without mortared joints), such as those at Aberdour, Portsoy, St Andrews, and St Mary's. In contrast, no microhabitat features were found on three of the seven concrete walls surveyed (Cockenzie, Falmouth, and St Mary's). Crevices were the most common cryptic feature type on masonry and concrete walls, while holes were most common on the rocky cliff habitats. However, microhabitat features of every type (Table 6.2) were on average most frequently observed on the historic masonry walls (Fig. 6.7).

Corresponding to the frequency data, with the exception of Tenby, the combined surface area of microhabitat features was typically greatest on the historic masonry walls and lowest on the concrete walls (Fig. 6.7). When averaged across all locations, the mean total (internal) 3D surface area of cryptic microhabitats on the concrete wall, historic masonry wall, and rocky cliff habitats per m^2 of surveyed area was 0.02, 1.63, and 0.35 m^2, respectively.

6.3.2.2 Cryptic microhabitat species richness

The total number of species observed within the cryptic microhabitat features at each location (R_C) was typically greatest for the masonry walls and lowest for the concrete walls (Fig. 6.7). With the exception of Tenby, the masonry walls also supported the greatest number of species found uniquely within the cryptic microhabitats. At Tenby, most cryptic species were found on the rocky cliff, which also supported the greatest proportion of species unique to these microhabitats. When averaged across all locations, R_C for the concrete, historic masonry, and rocky cliff habitats was 2.9,

21.3, and 15.0, respectively, of which 25 %, 48 %, and 34 % were only found in these microhabitat features and not on the surfaces of the walls/cliffs. In general, species richness increased in association with the number and total surface area of microhabitat features, both of which were generally highest on the historic masonry walls (Fig. 6.8). Only one non-native and invasive species (*Watersipora subatra*) was identified while surveying the cryptic microhabitats, which was found at low abundances within crevices on the historic masonry wall on St Mary's, the southernmost site surveyed.



Fig. 6.7. Top row: Total number of species found within cryptic microhabitat features (R_C) per 2.1 m^2 of surveyed area on each habitat type ('Con.', concrete wall; 'Mas.', historic masonry wall; 'Roc.', natural rocky cliff) at seven locations in the UK. The number of species observed uniquely within the cryptic microhabitat features are shown in light grey, while those also observed on the outer surfaces of the walls/cliffs are shown in dark grey. Middle Row: Frequency of different types of microhabitat features per 2.1 m^2 of surveyed area on each habitat type at each location. Bottom Row: Total surface area (m^2) of microhabitat features per 2.1 m^2 of surveyed area on each habitat type at each location. Mean values across all locations are also shown.

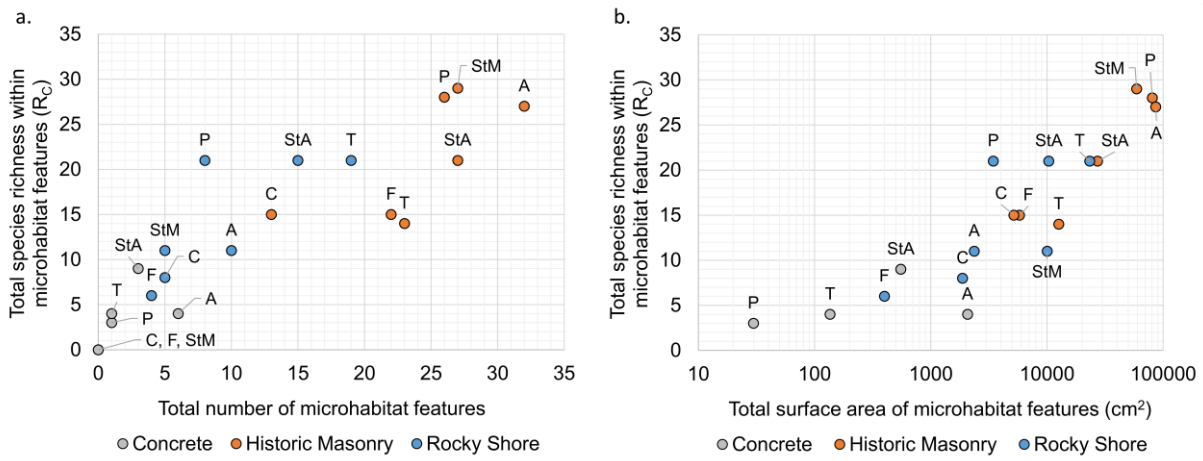


Fig. 6.8. The total number of species found within cryptic microhabitat features (R_C) against (a) the total number and (b) total surface area of microhabitat features (cm^2) found per 2.1 m^2 of surveyed area on concrete (grey), historic masonry (orange), and rocky cliff (blue) habitats at each location (A = Aberdour, C = Cockenzie, F = Falmouth, P = Portsoy, StA = St Andrews, StM = St Mary's, T = Tenby). Note that at three locations (Cockenzie, Falmouth, and St Mary's), no cryptic microhabitats were observed on the concrete walls surveyed.

3.3. Overall species richness

While recognising the limitations of jointly analysing biodiversity data collected using different sampling techniques, overall species richness (R_T) for each habitat type at each location was determined by combining the number of species observed on the surfaces of each wall/cliff with those observed uniquely within the microhabitat features (Appendix Fig. C2). At four locations (Portsoy, Aberdour, Cockenzie, and St Mary's), the historic masonry walls had the highest R_T values, while rocky cliff habitats had the highest values at three locations (St Andrews, Tenby, and Falmouth). In contrast, the concrete walls had the lowest R_T values at every location. When averaged across all locations, the most species were present on the historic masonry walls while fewest were present on the concrete walls.

6.4 Discussion

6.4.1 Surface biodiversity

We found significant differences between the biodiversity and community composition of ecological assemblages present on the external, seaward-facing surfaces of concrete walls, historic masonry

walls, and rocky cliff habitats. In general, species richness was greatest on the external surfaces of rocky cliff habitats and least on concrete walls. However, the strength and direction of this trend varied with location, indicating the potential importance of other ecological (e.g. larval recruitment regime), environmental (e.g. wave exposure, salinity, climate, light, etc.), and anthropogenic factors (e.g. trampling, harvesting, pollution, etc.) in determining community structure beyond habitat type (Amstutz et al., 2021; Bracewell et al., 2018; Bulleri, 2005b; Cacabelos et al., 2016; Crowe et al., 2000; Southward and Orton, 1954). Notably, at three of the seven locations surveyed (Aberdour, Cockenzie, and Portsoy), the historic masonry habitats were found to support the greatest diversity of surface-colonising organisms. Furthermore, across all locations, species richness was consistently higher on the surfaces of the historic masonry walls than on the concrete walls, supporting results reported elsewhere in the UK, including the Isles of Scilly (see Chapter 7, Paper 4). Together, these findings indicate that not all artificial structures should be considered ecologically poor and, in some cases, historic masonry walls can support comparable numbers of species to natural rocky cliffs. We also found no evidence that the historic masonry walls supported significantly more non-native or invasive species. However, based on composition, the communities supported by the artificial structures were distinct from the natural rocky cliff habitats, even after hundreds of years of colonisation in the case of the historic masonry walls. As with previous research examining ecological communities on rock armour defences, our results suggest that communities on artificial structures become more diverse with age (Burt et al., 2011; Pinn et al., 2005a) yet remain distinct from those found on rocky shores (Gacia et al., 2007; López, 2019).

Differences in topographic complexity may explain some of the observed patterns in species richness (Evans et al., 2021). As well as influencing the attachment strength of colonising organisms, topographic variability benefits marine species by providing predatory and environmental refuge during low-tide periods (Aguilera et al., 2014, 2019; Coombes et al., 2015; Fletcher and Callow, 1992). For instance, a lack of physical refuges on smooth seawalls has been shown to facilitate the grazing activity of limpets, in some cases, resulting in the exclusion of almost all other types of

colonising wildlife (Firth et al., 2023). In this study, topographic variability (quantified as slope) was significantly lower on the concrete walls, while there was no difference between the masonry walls and rocky cliffs at the measured scale. This supports previous research showing that concrete structures often lack surface heterogeneity compared to quarried stone and natural rock (e.g. Lawrence et al., 2021). This primarily relates to differences in construction design and engineering standards between cast concrete and masonry structures, but also possible differences in structure age, material type, and the formation of ecologically relevant surface features from progressive deterioration in the marine environment (e.g. Coombes, 2011a; Coombes et al., 2011). Furthermore, given the vulnerability of reinforced concrete to corrosion and salt ingress, concrete walls might be more regularly maintained (e.g. patch repairs) than masonry walls to avoid more serious damage (Cork and Chamberlain, 2015). In the case of older concrete structures, topographic variability may increase if use and maintenance have declined. For example, at St Andrews and Aberdour, the ~100-year-old concrete walls had the highest range and maximum S_{sqrt} values of the five concrete walls surveyed. These walls consist of relatively smooth areas of intact concrete as well as significantly deteriorated areas where spalling (i.e. surface breakdown, such as cracking or delamination) has exposed more topographically complex internal aggregates. As with natural rock, this indicates that the surface complexity of concrete structures—and especially older ones—is intrinsically linked to decay mechanisms acting upon their surfaces. Although the overall biodiversity of the concrete walls at St Andrews and Aberdour was relatively low, these deteriorated surfaces tended to support more species than adjacent areas of smooth intact concrete. While colonisation might be favoured on deteriorating assets (with greater surface complexity), this will clearly not be desirable if structures are vulnerable to further biodeterioration; on the other hand, there may be situations where colonising organisms provide some degree of protection, with research on these issues gradually gathering pace (e.g. Chapter 5, Paper 2; Bone et al., 2022b; Chlayon et al., 2018; Coombes et al., 2017b).

In addition to differences in topographic complexity, variations in ecological processes and dynamics may explain some of the observed patterns of species richness on the surfaces of the three habitat types. Previous studies have shown greater rates of dislodgement/disturbance and reduced fecundity for ecosystem engineer species, such as seaweeds (e.g. *F. vesiculosus*), on artificial structures compared to natural shores (Drakard et al., 2021). In this study, the historic masonry walls and rocky cliff habitats were found to support greater abundances of canopy-forming seaweeds and mussels than the concrete walls. In addition to contributing to overall biodiversity, these species support epiphytic organisms, such as bryozoans (e.g. *Flustrellidra hispida*, *Electra pilosa*, etc.) and hydroids (e.g. *Dynamena pumila*), and also provide habitat space and refuge for understory species (Bertness et al., 1999; Burnaford, 2004; Umanzor et al., 2019; Watt and Scrosati, 2013). By supporting more ecosystem engineer species, abiotic stresses on the colonised sections of the historic masonry walls and rocky cliffs are likely reduced compared to the, often, less colonised concrete walls (Aguilera et al., 2019). This is supported by our preliminary temperature data, which indicate that at Aberdour in Scotland, the colonised surfaces of the masonry wall and natural cliff remained relatively cool during low-tide periods compared to bare areas of the nearby concrete wall (Appendix Fig. C1). As few studies have yet compared the thermal characteristics of biotic canopies and abiotic microhabitats (e.g. crevices and other cryptic features) between vertical rocky substrate and different types of coastal engineering assets, including heritage buildings and modern infrastructure, this represents a potential avenue for future research.

6.4.2 Cryptic microhabitat provision and biodiversity

In contrast to previous studies that have analysed and compared the provision of microhabitats on natural shores and artificial structures across latitudinal gradients (e.g. Aguilera et al., 2022), no meaningful association was identified between latitude and microhabitat availability and associated biodiversity in this study. Instead, microhabitat availability varied between the three habitat types, with historic masonry walls providing substantially more cryptic space than both concrete walls and

rocky cliff habitats at every location surveyed. This finding contributes to a growing field of research comparing the physical structure of coastal infrastructure and natural shores (e.g. Aguilera et al., 2014, 2022; Grasselli and Airoldi, 2021; Lawrence et al., 2021), and in terms of vertically orientated substrate, indicates that historic masonry walls may represent some of the most physically complex habitats along many developed coastlines. Microhabitat features on historic masonry walls not only provide unique habitat conditions, but also increase the available surface area for colonisation. It is unsurprising, therefore, that microhabitats on the historic masonry walls generally supported more species than the concrete walls and rocky cliff habitats. The cryptic microhabitats provided by free-draining masonry walls, such as those at Aberdour, Portsoy, St Andrews, and St Mary's, were found to be particularly valuable for marine wildlife; of all the habitats surveyed, these structures had the highest densities of cryptic microhabitats and, concurrently, supported the greatest numbers of species. This included unique species not found on the surfaces of these walls, including sea anemones (e.g. *Actinia equina*), blennies (e.g. *Lipophrys pholis*), and sponges. As with porous rock armour, habitat space between unmortared stonework likely provides valuable refuge for a range of species (Sherrard et al., 2016). For example, temperatures within cryptic microhabitats on the historic masonry wall at Aberdour were consistently cooler (and presumably wetter) than their surfaces during low-tide periods (Appendix Fig. C1). Thus, when considered together, the surface and cryptic habitats provided by historic masonry walls (particularly free-draining/drystone constructions) can support some of the most diverse assemblages of comparable vertical habitat in the coastal environment (Appendix Fig. C2).

6.4.3 Implications

Maritime built heritage is valued for its functional uses (e.g. flood protection, access to the sea, etc.) as well as its historical and cultural significance (Fulford et al., 1997). Increasingly, wrecks and other submerged aspects of built heritage are recognised for the diverse ecological communities they support (Castelló y Tickell et al., 2019; Gravina et al., 2021; Lengkeek et al., 2013; Meyer-Kaiser and

Mires, 2022). Our results suggest that the ecological value of built heritage is not limited to underwater structures. Rather, based on seven sites across the UK, historic masonry walls within the intertidal zone support assemblages of marine wildlife that are significantly more diverse than those found on nearby concrete walls and, in some cases, adjacent vertical rocky cliffs. Crucially, for the first time, our results highlight the provision and ecological importance of cryptic habitat on seaward-facing traditional masonry walls and, as such, their multi-functional value as heritage assets and for ecosystem service provision, including supporting biodiversity. This typically contrasts with modern coastal infrastructure that can lack secondary benefits beyond its primary purpose (e.g. flood protection; Evans et al., 2017). By highlighting the ecological potential of historic masonry walls, this study contributes to a small but growing field of research examining the ecological communities supported by intertidal stone-built heritage, including centuries-old rock-walled terraces used to enhance shellfish production in North America (i.e. 'clam gardens'; Cox et al., 2019; Holmes et al., 2020), and ancient stone fish traps found along coastlines around the world (e.g. Favier Dubois et al., 2018; Pattrick et al., 2022; Kemp, 2006, Kemp et al., 2009). Fundamentally, the ecological value of maritime built heritage should contribute to arguments for its continued protection and conservation in the face of multiple threats associated with climate change, increasing coastal urbanisation, and neglect.

An improved understanding of the ecological value of maritime built heritage presents mutually beneficial opportunities for the conservation of cultural heritage and marine biodiversity. For instance, our results highlight the importance of preserving tradition structures and construction features of historical or architectural interest that provide unique habitats for marine wildlife. This includes cryptic space between the stonework of free-draining masonry walls as well as older, weathered, and more topographically complex stone. The potential for cavities within historic masonry to function as refuge for marine wildlife also strengthens arguments for using unintrusive repair methods that aim to preserve these features (e.g. Hine et al., 2015). This includes repurposing old stone to replace damaged or missing original stonework as well as using traditional maintenance

techniques to secure dislodged material that retains rather than covers over or fills in novel habitat space (e.g. wooden pegs vs. pointing). Knowledge that historic masonry structures can support diverse ecological communities may also influence how managers of these sites perceive marine growth, in addition to the frequency and methods used to control and/or encourage colonisation by marine wildlife. For instance, based on a survey of >130 practitioners, we found that asset managers are more inclined to use eco-friendly cleaning techniques in historic harbours when they are aware of the biodiversity that maritime infrastructure can support (Chapter 4, Paper 1).

Given that coastal development is predicted to increase over the next century in response to urbanisation and the threats associated with climate change (e.g. rising sea-levels, more frequent storm events), historic masonry structures may become increasingly important refuges for marine wildlife along with more recently constructed infrastructure designed or retrofitted to maximise ecological potential as well as any natural habitat left undisturbed or restored. This includes heavily urbanised coastlines dominated by vertical concrete infrastructure, where historic masonry walls might provide some of the only suitable habitat for marine organisms, particularly cryptic species (e.g. *L. pholis*).

Finally, features characteristic of historic masonry walls that we found to benefit marine wildlife may provide inspiration for the design of coastal eco-engineering solutions (Naylor et al., 2017a, b; O'Shaughnessy et al., 2019). This could include: (i) using naturally or artificially pre-weathered materials or those that are more prone to weathering (e.g. limestone and sandstone) and the formation of complex surface texture (e.g. honeycomb weathering, pits, etc.) on their seaward-exposed sides (Coombes et al., 2011); (ii) using materials that are the same or have similar physical, chemical, and aesthetic (e.g. colour) properties to the local geology (Firth et al., 2014; Naylor et al., 2012a); (iii) selecting and positioning stonework so that complex surface features (both natural and artificial artefacts of quarrying and construction) face outwards (i.e. 'passive' ecological enhancement; MacArthur et al., 2020; Naylor et al., 2017a, b); (iv) deliberately indenting

mortar joints to mimic cryptic microhabitats (e.g. Chapman and Underwood, 2011; Dugan et al., 2011; Firth et al., 2014; O'Shaughnessy et al., 2019); (v) eliminating the use of mortar completely to replicate the cavities between stonework in free-draining masonry structures, and; (vi) omitting blocks to replicate the habitat space created by missing stonework in historic masonry structures (e.g. Chapman and Blockley, 2009; Chapman and Underwood, 2011). In the case of concrete structures, similar retrofit options might be suitable to improve ecological potential (e.g. Hall et al., 2019; O'Shaughnessy et al., 2019; Paalvast et al., 2012; Strain et al., 2018), and for new-build assets, historic masonry walls can serve as inspiration for the design of physically complex surface textures produced using novel casting techniques (e.g. MacArthur et al., 2019; Bone et al., 2022c; Sheffield et al., 2022).

6.5 Conclusions

Until now, artificial coastal structures have generally been considered ecologically poor, acting as poor surrogates for natural shores due to a lack of surface heterogeneity and structural complexity. By comparing the ecological communities associated with both the surface and cryptic microhabitats of historic masonry walls, concrete walls, and vertical rocky cliff habitats at seven locations around the UK, we have shown that historic maritime walls not only support a greater range of species than nearby concrete assets but can also support communities with comparable species richness to adjacent vertical rocky habitats. In particular, our observations highlight the importance of cryptic microhabitat provision on traditional masonry walls (drystone and mortared types) relative to other types of engineering construction. Recognition of the importance of historic structures as potential hotspots of marine biodiversity along heavily urbanised coastlines supports arguments for built heritage to be conserved as valuable multi-functional assets. Going forward, the ecological value of other types of built heritage located within the marine environment, including those constructed of different materials (e.g. metal and wood) and with different functions or designs, warrants further research attention. More work is also needed to better understand species

and community dynamics on historic masonry structures (e.g. colonisation rates, disturbance regimes and patch dynamics, trophic interactions, and community resilience in response to environmental change), especially in comparison to other asset types and natural rocky habitats. Finally, with coastal urbanisation predicted to increase into the twenty-first century, future studies should explore in greater detail how construction features associated with built heritage may help guide the future design of coastal infrastructure and ecological enhancement techniques.

6.6. Chapter 6: Summary and implications

Results from the ecology surveys and physical habitat assessments showed that:

i. Historic masonry walls are able to support communities of marine wildlife that are significantly more diverse than those found on modern concrete infrastructure and, at some locations, nearby rocky cliffs.
ii. The unique physical properties of historic masonry walls make them a potentially important component of habitat diversity along developed coastlines.

Given that the ecological communities supported by historic masonry walls are shaped by historical human niche construction and long-term biological and social relationships (e.g. traditional building and management practices) they may represent important, but largely unrecognised, examples of biological cultural heritage (Eriksson, 2018).

To ensure the ecological benefits associated with stone-built heritage assets, such as historic masonry walls, are identified and sustainably managed, a practical tool for identifying historic structures with the greatest potential to support diverse ecological communities could be created. This would enable practitioners and conservation managers to prioritise areas for implementing win–win conservation strategies aimed at protecting/enhancing marine biodiversity and cultural heritage.

Section 4.

A Methodology for Regional-Scale Joint-Conservation Assessment

Section 4 addresses objective 4: to develop and apply a methodology for identifying joint priority areas for biodiversity and maritime heritage conservation at a regional scale.

In Chapter 7 (Paper 4), historical datasets (e.g. heritage records) are used alongside remote-sensing data and records of modern coastal defences to develop and test a methodology for (i) the rapid and remote mapping of maritime structures (including heritage assets) at a regional scale, (ii) predicting the ecological potential of structures based on key features including construction type and tidal position, and (iii) identifying priority structures for joint biodiversity and heritage conservation. The methodology is applied and tested on the Isles of Scilly using desk-based research that is validated through ground-truthing.

Paper 4 is written for heritage science researchers and practitioners interested in identifying areas with the greatest potential to provide win–win benefits for cultural heritage and marine biodiversity conservation.



Common limpet (Patella vulgata)
Drawn by Hope Calloway

Chapter 7.

Identifying priorities for the joint conservation of maritime built heritage and marine biodiversity: An assessment of shoreline engineering on the Isles of Scilly, UK, using historical datasets

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Abstract

Growing concern over the ecological impact of maritime structures has led to increasing attempts to quantify the extent of marine human development. However, maritime heritage assets (i.e. historic structures of cultural significance, such as decommissioned quays) are often missing in these assessments as many of these structures are not recorded in conventional datasets of maritime infrastructure, instead featuring exclusively in heritage registers. At the same time, heritage assets may provide unintentional ecological benefits to marine wildlife due to their age, traditional construction, and protected status, and as such, comprehensive assessments of marine human development cannot be achieved without the inclusion of historical data. Using the Isles of Scilly as a geographically confined case study, we present a novel methodology for quantifying the full extent

* Minor changes have been made to this manuscript to aid the readability and continuity within the thesis. For instance, British English is used instead of American English, and figure and table numbers have been changed. Some supplementary material is also now included in the main body of text. The published journal article is available from: https://doi.org/10.1016/j.ocecoaman.2022.106288

of marine engineering structures (including heritage assets) at a regional scale, and for identifying priority structures for joint biodiversity and heritage conservation.

Historical datasets were considered alongside remote-sensing data and records of modern coastal defences in a rapid desk-based assessment to create a full inventory of marine structures along the entire coastline of the Isles of Scilly. In total, 68 structures were recorded, totalling 6180 m in length. By evaluating the ecological potential and heritage value of each structure using a novel scoring system that was verified in the field, priorities for conservation and other managed interventions are identified. This includes (i) listed buildings and Scheduled Monuments that due to their construction features and shore position are most likely to support diverse marine assemblages, and (ii) modern structures where eco-enhancement adaptations may be favourable.

As demonstrated here, combined ecological-heritage evaluations allow for the identification of structures with the greatest potential for the joint conservation of built heritage and marine wildlife. Research is now needed to develop this method further and test its application in other geographical locations and at varying spatial scales.

7.1 Introduction

Maritime structures provide important functions to coastal communities around the world. For example, breakwaters and seawalls, which are primarily designed to defend coastlines, can also serve to create sheltered harbours and provide access to the sea. In the UK, maritime structures of historical importance and/or cultural significance are also valued as heritage assets, with many protected as listed buildings or Scheduled Monuments (Fulford et al., 1997). Heritage structures vary in size, form, and age, although typically only structures at least 30 years old are considered to be of special architectural or historical interest.[10] These structures range from disused quays with no formal protection to functional breakwaters several kilometres in length.

Artificial structures can have detrimental impacts upon marine environments at a variety of scales (Heery et al., 2017). For instance, studies suggest that artificial structures generally support younger, less diverse assemblages of marine organisms than natural shores (Moschella et al., 2005), attract non-native and invasive species (Airoldi et al., 2015; Vaselli et al., 2008), and affect ecological connectivity (Bishop et al., 2017). However, due to their age, traditional construction, and protected status, when compared to modern infrastructure, heritage structures may provide unintentional ecological benefits alongside any functional benefits and cultural/historical values associated with them. Broadly speaking, research which has examined how assemblages of intertidal organisms respond to maritime structures over time suggests: (i) older structures support more diverse communities than newer structures (e.g. Pinn et al., 2005a); (ii) the communities they support continue to change after decadal timescales (Burt et al., 2011; Butler and Connolly, 1999); (iii) the communities become more similar to those found on nearby natural shores with age (Burt et al., 2011), and yet; (iv) they remain ecologically distinct (Gacia et al., 2007; López, 2019).

[10] The Department for Digital, Culture, Media & Sport's principles of selection for listing buildings, available at: https://www.gov.uk/government/publications/principles-of-selection-for-listing-buildings

The reasons for these observed patterns in community development are likely to be the result of a catalogue of dynamic, interacting environmental, ecological, and physical factors (Evans, 2016). However, as has been discussed for terrestrial structures (e.g. Caneva et al., 2002; Ferraby, 2006), the traditional design (i.e. masonry configuration), materials, and decay mechanisms of historic maritime structures will likely influence the communities they support (Table 7.1). For example, historic structures are typically constructed of materials with fine-scale topographic features, such as quarried rock, that are considered beneficial to marine biodiversity (Macarthur et al., 2020; Sempere-Valverde et al., 2018). Years of degradation caused by weathering and erosional processes also increase the availability of fine- (<1 cm) and medium-scale (>1 cm) water-retaining surface features that can favour the development of diverse marine communities if left undisturbed (Firth et al., 2013). This contrasts with modern concrete structures that typically have flat, smooth surfaces, and which tend to be maintained in good state of repair (Lawrence et al., 2021). Crevices and void spaces that characteristically occur in ruined or traditional drystone constructions may also provide habitat niches and refuges for marine wildlife (Sherrard et al., 2016). Over many years, ecological succession in association with microhabitats and fine-scale topographic features may result in the establishment of canopy forming ecosystem engineers, such as macroalgae, which can provide micro-climatic niches for understory species and further increase biodiversity on older structures relative to those built more recently (Umanzor et al., 2019; Watt and Scrosati, 2013). Statutory legislation designed to conserve heritage structures may, at the same time, serve to protect marine wildlife from disruptive anthropogenic activity (e.g. trampling). Marine organisms supported by ruins and decommissioned structures may in particular experience low levels of anthropogenic disturbance as they are unlikely to be regularly maintained (Wyatt and Prizeman, 2018). This compares to some functioning assets, such as slipways and rock armour, which are more likely to receive occasional maintenance to ensure they function effectively and remain safe to use, particularly after damaging storm events (Airoldi and Bulleri, 2011; Bacchiocchi and Airoldi, 2003; Burcharth et al., 2007; Moreira et al., 2007; Moschella et al., 2005; Sherrard et al., 2016).

Table 7.1. Characteristic factors that influence the development of marine communities on the surfaces of maritime structures.

Factor	Effects on Marine Communities	Reason	Example References
Age	Older structures support more diverse communities than newer structures. With age, these communities become increasingly similar to those found on nearby natural shores/ reefs.	Over time, structures develop weathering features that favour marine colonisation. Ecological succession will increasingly lead to the development of diverse marine communities via facilitation/ community-level effects.	Burt et al. (2011) Butler and Connolly (1999) Perkol-Finkel et al. (2005) Pinn et al. (2005a)
Material and Design			
- Material	Natural rock typically supports greater abundances of marine species than artificial materials.	Natural rock typically has rougher surfaces than man-made materials which is beneficial to ecology. The weathering of calcareous materials (e.g. limestone) can create favourable water-retaining microhabitats.	Connell and Glasby (1999) Coombes et al. (2011) Dodds et al. (2022) Herbert and Hawkins (2006) Sempere-Valverde et al. (2018)
- Surface texture	Surfaces with fine-scale topographic features (<1 cm) will typically colonise faster and support more abundant and diverse communities than smooth surfaces.	Textured surfaces can provide shade, increase water retention, and aid organism settlement, recruitment and attachment.	Coombes et al. (2015) MacArthur et al. (2019) Naylor et al. (2011)
- Structural complexity	Species richness and diversity typically increase with the availability of meso-scale topographic features (>1 cm) such as rockpools and crevices.	Water-retaining features can provide refuge from physical and biotic stress.	Aguilera et al. (2014) Moreira et al. (2007) Moschella et al. (2005) Naylor et al. (2011)
- Availability of cryptic habitats	Porous structures with internal habitats typically support more diverse ecological communities than those without.	Voids within structures can provide functional habitat space for marine organisms not found elsewhere.	Sherrard et al. (2016)
Maintenance regime	Structures that are regularly maintained tend to support less diverse ecological communities than those that are not.	Maintenance practices can result in the disruption, removal or destruction of habitats and marine organisms, and create opportunities for opportunistic and invasive species to colonise.	Airoldi and Bulleri (2011) Moschella et al. (2005) Sherrard et al. (2016)

The ecological benefits associated with historic structures means they may provide win–win opportunities for the joint conservation of maritime heritage and marine biodiversity. For instance, the conservation of construction features of historical or architectural interest may have mutually beneficial impacts for wildlife. However, these opportunities are rarely identified as compared to modern artificial structures built of concrete and other artificial materials since the middle of the twentieth century, the extent and ecological impact of historic structures are relatively understudied. For instance, global and regional assessments of marine human development often fail to consider small and/or decommissioned historic structures as these typically do not feature in conventional datasets of maritime infrastructure (Bugnot et al., 2020). Instead, existing assessments have focused on analysing the extent and effects of a subset of large, functional structures such as

oil rigs, wind farms, and coastal defences that have rapidly proliferated in marine environments in the last few decades (Bugnot et al., 2020; Firth et al., 2016b; Halpern et al., 2015).

Despite these advances, given the potential ecological benefits of heritage structures, comprehensive assessments of marine human development can only be achieved with the inclusion of historical data. This includes national and regional heritage registers, such as the NHLE and Historic Environment Records (HER), that contain information about small and/or disused historic structures not recorded elsewhere. As of yet, no attempts to identify the extent and potential combined ecological/heritage value of maritime structures have been made, including historic and decommissioned assets as well as those that remain in use. In order to address this research gap, we developed a methodology for (i) the rapid and remote mapping of maritime structures at a regional scale that fully considers historic assets alongside modern structures, and (ii) predicting the ecological potential of structures based on key features including construction type and tidal position that was tested through on-site ground-truthing. Importantly, we provide the first regional scale assessment of marine human development that considers information recorded exclusively in heritage databases, alongside more conventional records of maritime infrastructure.

The main aim of this study is to develop and apply a methodology that allows the identification of joint priority areas for biodiversity and heritage conservation. We apply our methodology to the Isles of Scilly, Cornwall, UK, as a geographically contained case study with a long history of maritime development extending from the Neolithic to the present day. Using a comprehensive inventory of human development in the intertidal zone developed from remote-sensing data (LiDAR and aerial photography), HERs, and flood risk management reports, we (i) determine the total extent of all maritime structures on the Isles of Scilly and the relative contribution of heritage assets to coastal/marine development, (ii) assess the ecological potential of all the identified structures using a rapid and remote-based ranking system that was validated in the field, (iii) identify ‘conservation priority structures’ for both heritage and marine biodiversity, and (iv) provide an initial assessment

of intervention opportunities for enhancing joint heritage and biodiversity conservation. Our approach enables the rapid mapping and ecological assessment of artificial coastal structures using open data, providing valuable information that can guide subsequent field surveys and support the identification of conservation priorities.

7.2 Methodology

7.2.1 Study area

The Isles of Scilly are located 45 km off the southwestern tip of Cornwall, UK (Fig. 7.1). The archipelago consists of 145 islands, five of which are inhabited and have an area greater than 1 km^2 (i.e. St Mary's, Tresco, St Agnes, Bryher, St Martin). All the islands are composed of granite rock of Early Permian age. The islands have been inhabited for centuries, with evidence of Neolithic burial mounds and field systems visible in the landscape alongside modern infrastructure. The marine environment around the Isles of Scilly supports unique marine ecosystems which are protected by various designations as Marine Protected Areas (e.g. SAC, MCZ, Site of Special Scientific Interest i.e., SSSI).

7.2.2 Inventory of structures

An inventory of structures on the Isles of Scilly was created by assessing the location and features of the structures from different data sources and giving them ranks in each of 5 different environmental and historical score categories (Fig. 7.2). The locations of maritime structures within the intertidal zone were determined by consulting the following datasets: (i) the Environment Agency's (EA) Spatial Flood Defences Dataset,[11] a register of flood defences owned, managed or inspected by the EA; (ii) local reports detailing flood defences on the Isles of Scilly, and; (iii) registers

[11] Accessible at: https://data.gov.uk/dataset/cc76738e-fc17-49f9-a216-977c61858dda/aims-spatial-flood-defences-inc-standardised-attributes.

of protected and unlisted heritage assets of national and local importance, including the NHLE and the Cornwall and Scilly Historic Environment Record (CSHER).

For each structure identified, its location, area, and length (sea-facing) were recorded using ArcGIS Desktop V10.8. In addition, each structure was categorised as one of six broad construction types (Table 7.2). These six categories were based on fundamental characteristics known to influence bioreceptivity (Guillitte, 1995; Sanmartín et al., 2021) as identified from the literature (Table 7.1), including their age, material, shape, and construction method. Structures built over multiple phases at different times were separated, with each distinct section being recorded as a separate structural unit.

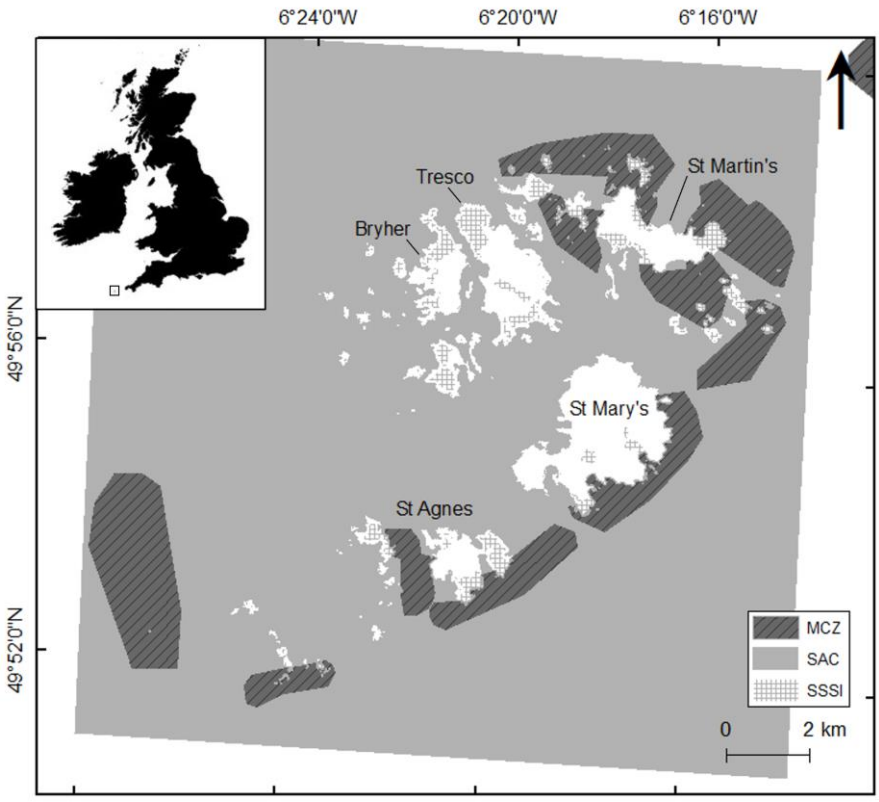


Fig. 7.1. Isles of Scilly Marine Conservation Zones (MCZ), Special Areas of Conservation (SAC), and Sites of Special Scientific Interest (SSSI).

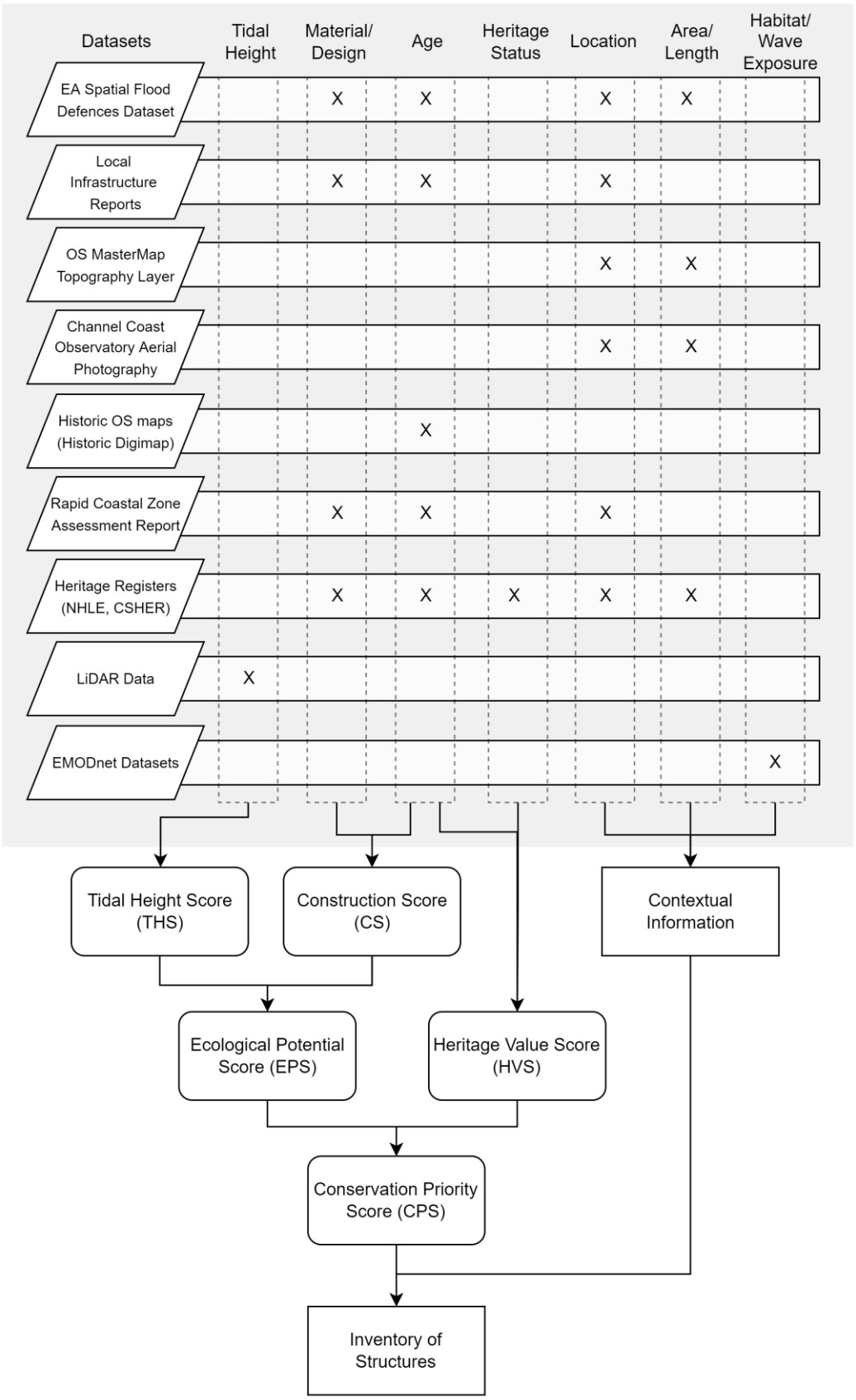


Fig. 7.2. Schematic showing how information from different datasets (parallelogram) was used in the scoring system (rounded rectangles) to create an inventory of structures on the Isles of Scilly.

Table 7.2. Construction types for the Isles of Scilly and associated Construction Scores (CS) based on theoretical assumptions of ecological potential (also see Table 7.1).

Type	Age and Description	Material	Surface Texture (<1 cm)	Structural Complexity (>1 cm)	Cryptic Habitats	Maintenance	CS Score
Ruins	Ruined/abandoned structures, typically more than 100 years old and constructed of natural stone.	Natural stone (i.e. local granite)	Very likely	Very likely	Likely	Unlikely	3 (High)
Drystone	Vertical structures constructed of natural stone without mortar. Typically, more than 100 years old.	Natural stone (i.e. local granite)	Very likely	Very likely	Likely	Likely	3 (High)
Masonry	Vertical structures constructed of natural stone and mortar. Age can vary.	Natural stone and mortar	Likely	Unlikely	Unlikely	Likely	2 (Medium)
Rock Armour	Boulders of rock used in rubble structures to defend shorelines. Typically, less than 30 years old.	Natural stone (i.e. typically granite sourced from Norway)	Likely	Likely	Likely	Likely	2 (Medium)
Blockwork	Vertical structures constructed of large blocks of dressed stone or concrete with little or no mortar. Age can vary.	Natural stone or concrete	Unlikely	Unlikely	Unlikely	Likely	1 (Low)
Concrete	Vertical structures constructed of mass concrete. Typically, less than 30 years old, although age can vary.	Concrete	Unlikely	Unlikely	Unlikely	Likely	1 (Low)

Information regarding contemporary coastal defences on the Isles of Scilly was primarily obtained from the following four documents: the Isles of Scilly Local Flood Risk Management Strategy (Council of the Isles of Scilly, 2017); the Isles of Scilly Infrastructure Plan (Three Dragons, 2014); the Isles of Scilly Water Interests Survey (ARUP, 2011); and the Cornwall and Isles of Scilly Shoreline Management Plan (CISCAG, 2011). The NHLE and the CSHER provided additional information on maritime heritage structures not included in these reports or the EA Spatial Flood Defences Dataset. This was supplemented by information within the Isles of Scilly Rapid Coastal Zone Assessment (RCZA; Johns et al., 2004) and two reports produced by the Cornwall archaeological Unit (Johns and Fleming, 2016; Thomas et al., 2016), which provide historical characterisations of two coastal regions (i.e. St Martin's Higher Town and St Mary's Harbour). Historic Ordnance Survey (OS) maps (Historic Digimap®) were also consulted to obtain the approximate age of a structure when this information was not otherwise available from the sources

already mentioned. The location and length of all the structures was confirmed by consulting the OS MasterMap Topography Layer® and Channel Coast Observatory Aerial Photography in ArcGIS.

7.2.2.1 Construction scores

Each construction type was given a 'Construction Score' (CS) between 1 (low) to 3 (high) based on the theoretical assumptions presented in Table 7.1 (i.e. whether its distinguishing features are known to have low or high ecological potential). The CS approach aimed to provide a simple, theoretically based comparative measure (rank) of whether a structure was more or less likely to support diverse marine communities due to its distinguishing physical characteristics (Table 7.2). Note that the influence of tidal position is considered separately in the next sub-section (i.e. Section 7.2.2.2). A three-point ranking was used to avoid the need for arbitrary weighting when later determining overall scores of Ecological Potential (Section 7.2.2.3). The factors considered when assigning a CS were structure (i) age, (ii) material, (iii) surface texture (cm-mm scale), (iv) structural complexity (cm-m scale), (v) provision of cryptic habitats (i.e. cooler, wetter, and wave-protected functional habitat space provided by porous structures), and (vi) level of anthropogenic disturbance based on current use (i.e. ruined, decommissioned, actively in use, etc.). For example, ruined and drystone structures were given a CS of 3 because, on Scilly, they are typically older, constructed of natural stone and, owing to their state of decay, exhibit high structural complexity including overhangs and water-retaining features. In contrast, blockwork and concrete structures were given a score of 1 because they are typically modern structures with comparatively low structural complexity and bioreceptivity (i.e. concrete). Despite an assumed high level of surface roughness and structural complexity, rock armour installations were given a score of 2 as on Scilly these are typically younger in age and constructed of natural stone different to the local geology, such as Norwegian granite. The categorisation adopted here was designed based on the specific structures identified on the Isles of Scilly. As such, a different categorisation may be more/less

suitable elsewhere. This includes, for example, coastal regions with marine infrastructure constructed predominantly of wood or metal which were not identified in this assessment.

7.2.2.2 Tidal height scores

In addition to structural, material, and disturbance characteristics, marine communities are strongly influenced by the environmental conditions they are exposed to. For intertidal species, tidal elevation is the most important control on abiotic stresses related to temperature, desiccation, and irradiance (Scrosati and Heaven, 2007). As such, natural and artificial substrates located within the supratidal/splash and high-tide zones typically support fewer individuals and less diverse communities than those within the middle and lower tide zones (Crapp, 1973; Firth et al., 2013; McCarter and Thomas, 1980; Moschella et al., 2005; Scrosati et al., 2010; Underwood, 1981, 1984, 1985). Therefore, as a simple metric of environmental stress, the extent of each of the identified structures within the intertidal zone was determined using LiDAR data obtained from the National Network of Regional Coastal Monitoring Programmes of England website.[12] The LiDAR data was collected between 2013 and 2014 as part of the South West Regional Coastal Monitoring Programme (SWRCMP). The Mean High Water Neap (MHWN) and Mean Low Water Neap (MLWN) tide levels recorded between 2008 and 2020 at St Mary's Harbour, Isles of Scilly, were also obtained from the National Tidal and Sea Level Facility.[13] These tidal heights were converted from Admiralty chart datum to ordnance datum so that they could be directly compared to the LiDAR data. We then identified three tidal zones (above MHWN, between MHWN and MLWN, and below MLWN) using the LiDAR data (Table 7.3). The length of each structure within these three tidal zones was subsequently determined within ArcGIS. Each structure was subsequently given a 'Tidal Height Score' (THS) dependent on whether it extended into a particular zone or not; structures extending

[12] Accessed at: https://coastalmonitoring.org/
[13] Accessed at: https://www.ntslf.org/

into the low-tide zone scored a maximum of 3, those extending into the mid-tide zone scored 2, and those within only the high-tide zone scored 1.

Table 7.3. Positions within the tidal profile and the corresponding Tidal Height Scores (THS) assigned to each structure.

Tidal Zone	Definition	Admiralty datum height (m)	Ordnance datum height (m)	Tidal Height Score (THS)
High tide	Region above MHWN	> 4.35	> 1.44	1
Mid tide	Region between MHWN and MLWN	2.04 to 4.35	-0.87 to 1.44	2
Low tide	Region below MLWN	< 2.04	< -0.87	3

7.2.2.3 Ecological potential ranking

The CS and THS of each structure were then used to determine an overall score of Ecological Potential (EPS) for which equal weighting was assumed for simplicity, as follows:

$$\text{Ecological Potential} = (\text{Construction Score} + \text{Tidal Height Score})/2$$

Additional contextual information regarding each structure and its surrounding environment deemed important for understanding the types of ecological communities it supports was also recorded, including (i) orientation to the shore (i.e. parallel or perpendicular), (ii) overlap with European Marine Observation and Data Network (EMODnet) seabed habitat,[14] (iii) MarLIN wave exposure category,[15] (iv) potential for scour, (v) proximity to terrestrial outflows (e.g. storm drains) (vi) surrounding population density (i.e. urban vs. rural), as a simple indicator of disturbance and pollution potential, and (vii) proximity to Marine Protected Areas. This information was not included in the EPS calculations, for which we assumed construction type (CS) and tidal position (THS) were most influential, but served to help interpret and contextualise our results.

7.2.2.4 Heritage value scores

As a simple metric of historical and cultural value, we also allocated a Heritage Value Score (HVS) to each structure based on its age and whether it was registered on the NHLE or HER as a historical

[14] Accessed at: https://emodnet.ec.europa.eu/en
[15] Accessed at: https://www.marlin.ac.uk/glossarydefinition/waveexposure

structure of national or local importance. Structures protected as listed buildings or Scheduled Monuments scored a maximum of 3, including those recorded on Historic England's Heritage at Risk (HAR) register; those recorded on the HER but with no formal protection (e.g. listing or scheduling) and those more than 50 years old were given a score of 2; and those constructed or significantly repaired within the last 50 years that did not appear on either the NHLE or HER scored a minimum of 1.

7.2.2.5 Conservation priority scores

Finally, we used the EPS and HVS scorings to derive a Conservation Priority Score (CPS) for each structure, assuming equal weighting, as follows:

$$\text{Conservation Priority Score} = (\text{Ecological Potential Score} + \text{Heritage Value Score})/2$$

Each structure was subsequently plotted in a Conservation Priority Matrix based on its corresponding CPS value, enabling the rapid, remote, and preliminary identification of joint heritage and biodiversity conservation priorities.

7.2.3 Ground-truthing surveys

To verify the EPS assigned during the desk-based assessment, ecological field surveys were conducted on 13 of the maritime structures identified on the Isles of Scilly. This included 12 structures on St Mary's across four locations (i.e. St Mary's Pool, Porth Cressa, Old Town Bay and Porth Minick, and Porth Hellick), and one structure on Tresco (Fig. 7.3). These structures, which could be safely accessed during low tide, were selected to be representative of maritime structures on Scilly and varied in age, construction type, exposure, and position within the tidal zone (Table 7.4). Importantly, the structures also represent the full range of EPS that were assigned (i.e. 1–3).

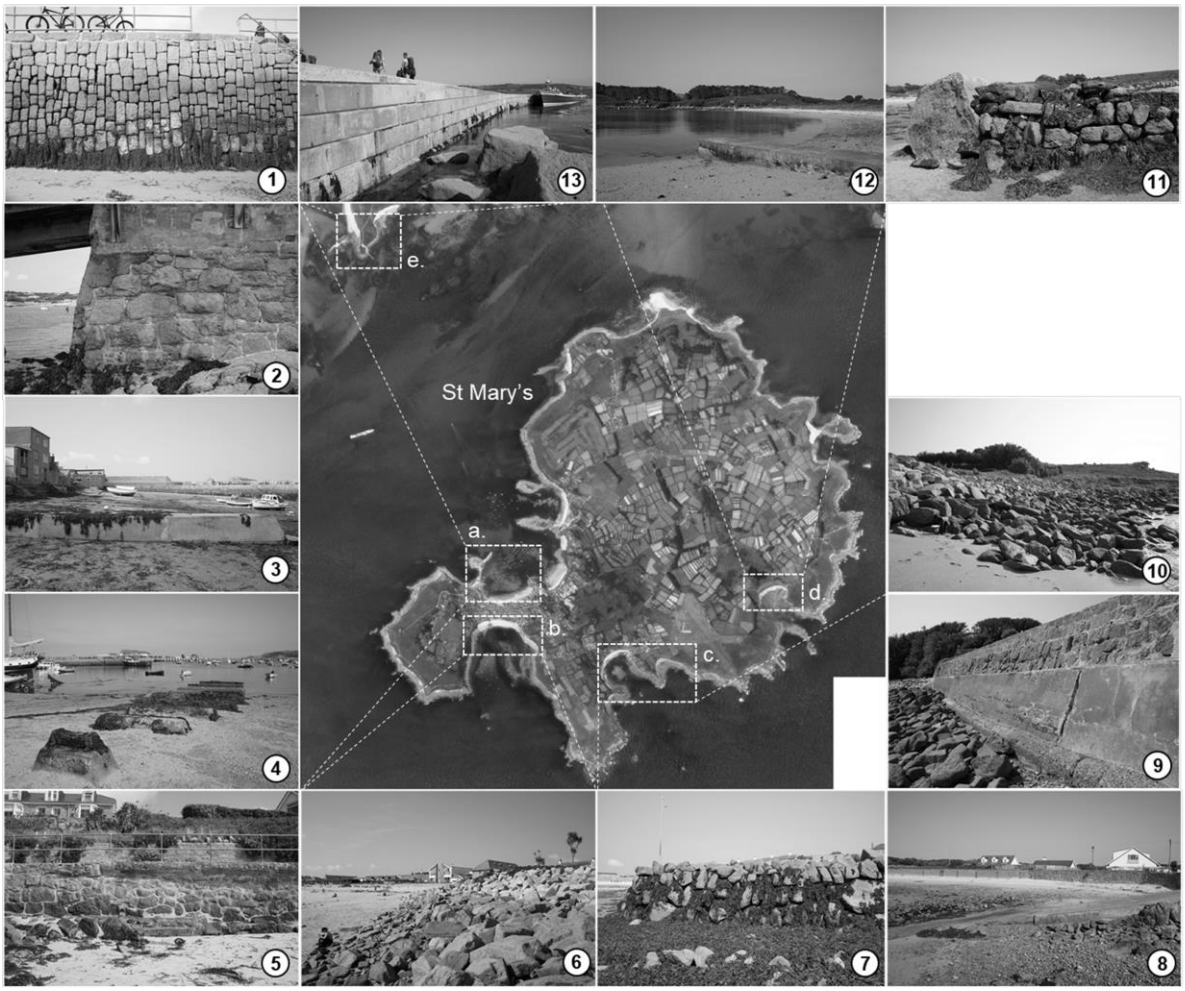


Fig. 7.3. Location of the 13 ground-truthed structures including five structures (1–5) within (a) St Mary's Pool, one structure (6) within (b) Porth Cressa, four structures (7–10) within (c) Old Town Bay and Porth Minick, two structures (11–12) within (d) Porth Hellick, and one structure (13) on (e) Tresco.

Table 7.4. Structures identified during the desk-based assessment where on-site ground-truthing ecological field surveys were conducted.

No.	Name	Abbreviation	Period	Age	Material	Construction Type	Tidal Height	EPS
1	Hugh Town Old Quay	HTQ	Post-Med	1749–51	Granite	Drystone	High to Low	3
2	Carn Thomas Lifeboat Station	CT	Post-Med	1899	Granite	Masonry	High to Low	2.5
3	Hugh Town Beach Outflow	HTBO	Modern	1900–89	Concrete	Concrete	Mid	1.5
4	Hugh Town Shipyard Remains	HTSR	Post-Med	1958–89	Concrete	Concrete	High to Mid	1.5
5	Hugh Town Beach Seawall	HTSW	Modern	>1901	Concrete	Concrete	High	1
6	Porth Cressa Rock Armour	PCRA	Modern	1995	Granite	R. Armour	High	1.5
7	Old Town Quay	OTQ	Medieval	~1554	Granite	Ruin	High to Low	3
8	Old Town Slipway	OTSL	Modern	1960–89	Concrete	Concrete	High to Mid	1.5
9	Old Town Seawall (West)	OTSW	Modern	>1901	Concrete	Concrete	High	1
10	Porth Minick Rock Armour	PMRA	Modern	2000	Granite	R. Armour	High	1.5
11	Porth Hellick Quay	PHQ	Post-Med	1960–89	Granite	Drystone	High to Mid	2.5
12	Porth Hellick Outflow	PHO	Modern	1960–89	Concrete	Concrete	High	1
13	Carn Near Quay	CNQ	Modern	2006–08	Concrete	Blockwork	High to Low	2

The biological communities found on the surfaces of each structure were sampled using 12 20 × 20 cm quadrats. The placement of these quadrats was dependent on the position of the structures within the intertidal zone as an equal number of quadrats were sampled within each zone (e.g. high-, mid-, and low-tide). For structures located across all three intertidal zones, four quadrats were sampled per zone; for structures located across two intertidal zones, six quadrats were sampled per zone; and when a structure extended within a single tidal zone, all 12 quadrats were positioned at the same height. Quadrats were placed randomly on steep or vertical (60-90°), seaward-facing surfaces along a 6-m transect in each of the sampled tidal zones, as determined using local tide tables.

The percent cover of sessile organisms (e.g. barnacles and algae) and counts of mobile fauna within the quadrats were recorded (Evans et al., 2021). Individual count records were subsequently converted to percent cover values depending on the size of the organism (i.e. 2–10 mm = 1%, 10–30 mm = 2%, >30 mm = 5%). Mobile organisms observed within quadrats that were too small or numerous to count by eye (i.e. <2 mm, e.g. *A. maritima*) were given a nominal cover value of 1%. For each structure, the presence of all taxa encountered within microhabitat features (e.g. crevices) during a 10-min search was also recorded along the same 6-m transect to assess the association of microhabitat features with species richness. For both the quadrat surveys and timed searches, taxa were recorded to species level or, where this was not possible, by genus. A record was also made of whether the taxa were native or non-native.

In addition to the ecological surveys, physical and environmental information was also recorded on-site at 52 of the maritime structures on the Isles of Scilly to verify the key assumptions of the desk-based assessment (Evans, 2016). This included all of the structures where ecological data were recorded. The assumptions verified at these sites included each structures' (i) construction type, (ii) position within the tidal zone (i.e. supra-tidal, high, mid, low, or sub-tidal), (iii) material (i.e. concrete, granite, etc.), (iv) MarLIN wave exposure category, (v) aspect, (vi) surrounding habitat (i.e.

sandy, rocky, or mixed), (vii) surface texture (i.e. smooth vs. rough), (viii) abundance and diversity of microhabitat features >1 cm as a measure of structural complexity, and (ix) provision of cryptic habitats, along with evidence of (x) repair/maintenance work and (xi) scour.

THS scorings were evaluated from direct observations of a structure's position within the tidal zone. CS scorings, on the other hand, were qualitatively evaluated from structural, material, and disturbance characteristics observed on-site.

7.2.4 Statistical analysis

Non-native species were not considered in calculations of biodiversity indices for two reasons: first, non-native species are typically viewed as threats to native biodiversity; second, only one non-native species was observed on the structures surveyed in this study, and preliminary analysis revealed its presence did not significantly influence biodiversity measures (see Section 7.3.2). For native taxa, mean species richness (R), mean abundance (N), and mean Shannon-Weiner diversity index (H') were determined using the DIVERSE function in PRIMER-e V7 (Clarke and Gorley, 2015). The total number of native species found on the surfaces of each structure (i.e. within the quadrats) and within microhabitat features during the 10-min searches was also determined. This was then used to determine the combined, total number of species supported by a structure (i.e. on the surface and within microhabitat features) hereafter referred to as overall species richness (R_T). To evaluate the desk-based EPS, the Spearman's Rank Coefficient was used to determine whether there was any correlation between the EPS and different measures of biodiversity (e.g. R, R_T, N, H').

7.3 Results

7.3.1 Inventory of structures

In total, 61 structures were recorded within the intertidal zone of the Isles of Scilly (Fig. 7.4). This represents 68 unique structural units when structures built over multiple phases at different times are considered separately (Table 7.5). The location and extent of three historic structures (i.e. Porth

Cressa Slipway, Arthur Quay, and The Porth Quay) could not be identified through satellite imagery, however approximate locations were determined using HER data. The remaining 58 structures were found to cover a combined area of 24,000 m^2. Of this area, approximately 15,900 m^2 of natural sandy or mixed substrate has been replaced by hard artificial structures. These structures have a total length of 6180 m, which represents ~4% of the total length of coastline at high tide on the Isles of Scilly.

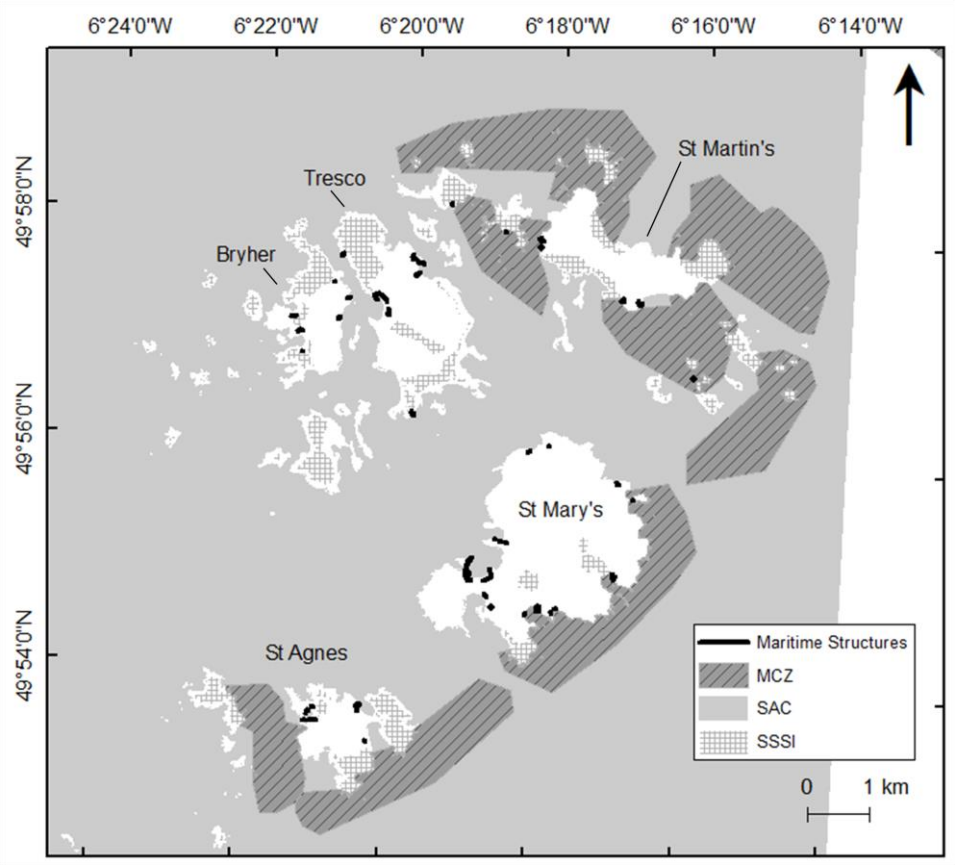
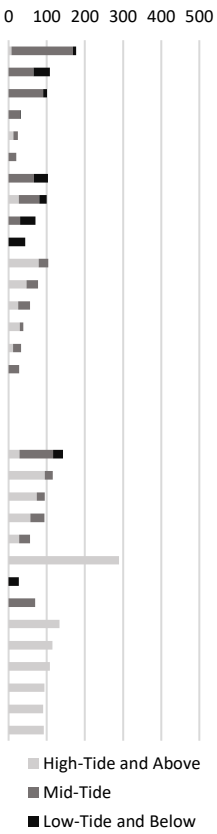


Fig. 7.4. Location of maritime structures identified on the Isles of Scilly during the desk-based assessment. Marine Protected Areas (MCZ and SAC) and Sites of Special Scientific Interest (SSSI) are also shown.

Table 7.5. Inventory of structural units identified on the Isles of Scilly during the desk-based assessment. Assigned scores for Ecological Potential (EPS), Heritage value (HVS), and Conservation Priority (CPS) are shown. Note, in the published version of this manuscript, this table does not appear in the main article, but instead in the Supporting Material as Table. A1.

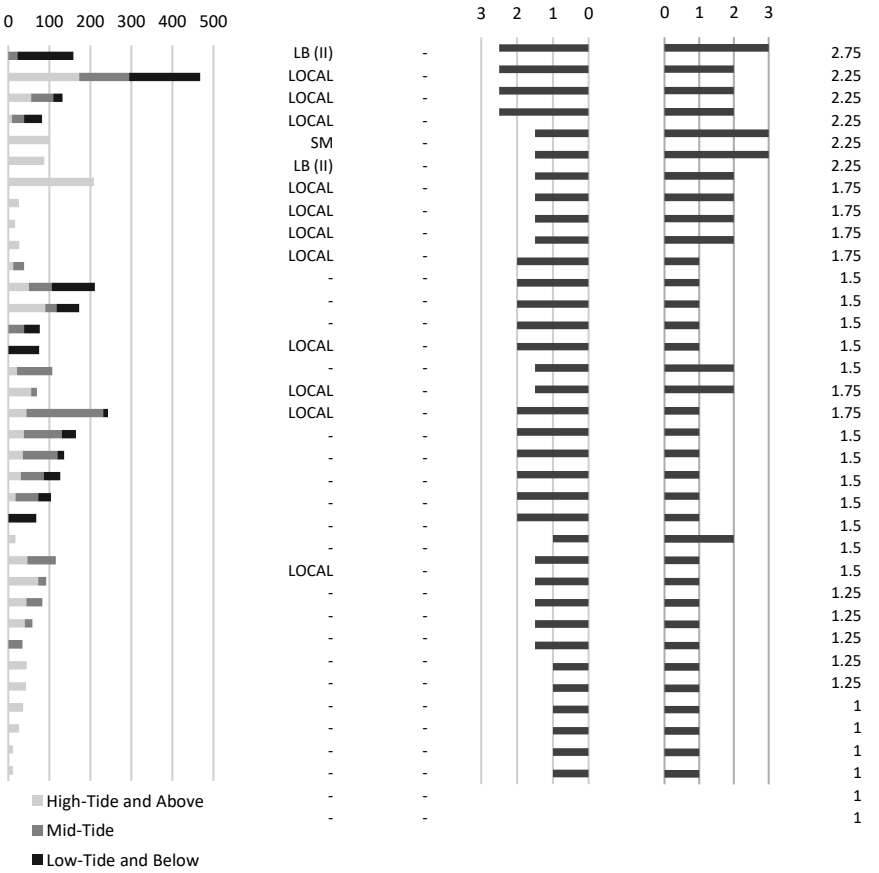
Name	Location (Island)	Latitude, Longitude (DD)	Age	Protected Areas[‡]	Ecological Potential: Construction	Ecological Potential: Extent within Tidal Zones (m)	Heritage Value: Grade[§]	Heritage Value: Heritage at Risk	Conservation Priority Scoring: EPS	Conservation Priority Scoring: HVS	Conservation Priority Scoring: CPS
						0 100 200 300 400 500			3 2 1 0	0 1 2 3	
Old Town Quay*†	St Mary's	49.958, -6.285	~1554	MCZ, SAC	Ruins		SM	Yes			3
Uncle Tom's Quay	St Agnes	49.895, -6.352	~1888	SAC	Ruins		SM	-			3
St Helen's Quay	St Helen's	49.970, -6.325	<1901	SAC	Ruins		SM	-			3
Tolls Island Quay	St Mary's	49.928, -6.280	<1901	MCZ, SAC	Ruins		SM	-			3
East Porth Quay	Tean	49.967, -6.313	<1901	MCZ, SAC	Ruins		SM	-			2.75
Great Porth Quay	Bryher	49.948, -6.358	~1794	SAC	Ruins		SM	Yes			2.75
Crow Point Slipway*	Tresco	49.939, -6.331	~1889	SAC	Ruins		LOCAL	-			2.5
Turks Head Slipway*	St Agnes	49.896, -6.340	~1890	SAC	Ruins		LOCAL	-			2.5
Newford Island Quay (East)*	St Mary's	49.921, -6.310	<1879	SAC	Ruins		LOCAL	-			2.5
Newford Island Quay (West)*	St Mary's	49.922, -6.311	<1879	SAC	Ruins		LOCAL	-			2.5
New Quay (St Mary's)*	St Mary's	49.931, -6.284	1909	SAC	Ruins		LOCAL	-			2.25
Point of Fields Quay*	St Martin's	49.966, -6.304	~1888	MCZ, SAC	Ruins		LOCAL	-			2.25
Pendrathen Quay*	St Mary's	49.935, -6.305	~1795	SAC	Ruins		LOCAL	-			2.25
Turks Head Quay*	St Agnes	49.895, -6.340	~1908	SAC	Ruins		LOCAL	-			2.25
Hole of Cove Vean Quay*	St Agnes	49.891, -6.338	<1901	SAC	Ruins		LOCAL	-			2.25
Kitchen Porth Quay	Bryher	49.958, -6.351	<1901	SAC	Ruins		LOCAL	-			2.25
Porth Cressa Slipway	St Mary's	-	<1901	SAC	Ruins		LOCAL	-			N/A
Arthur Quay	Eastern Isl.	-	<1901	MCZ, SAC, SSSI	Ruins		LOCAL	-			N/A
The Porth Quay	St Martin's	-	<1901	SAC, SSSI	Ruins		LOCAL	-			N/A
Hugh Town Old Quay*†	St Mary's	49.916, -6.317	1749–51	SAC	Drystone		LB (II)	-			3
Porth Hellick Quay*†	St Mary's	49.917, -6.284	1960–89	MCZ, SAC	Drystone		LOCAL	-			2.25
Old Grimsby Quay (Drystone)*[a]	Tresco	49.960, -6.333	~1890	SAC	Drystone		LOCAL	-			2.25
St Martin's Old Quay*	St Martin's	49.958, -6.285	1737	MCZ, SAC, SSSI	Drystone		LOCAL	-			2.25
New Grimsby Quay (Drystone)*[b]	Tresco	49.956, -6.342	~1792	SAC	Drystone		LOCAL	-			2.25
New Grimsby Seawall*	Tresco	49.957, -6.341	1890-99	SAC	Drystone		LOCAL	-			2
Turks Head Defences*	St Agnes	49.896, -6.340	2006-08	SAC	R. Armour		-	-			1.75
New Quay Defences*	St Martin's	49.958, -6.281	1980-89	SAC	R. Armour		-	-			1.5
Sea Garden Cottage Defences	Tresco	49.962, -6.333	2000	SAC	R. Armour		-	-			1.25
Great Porth Defences*	Bryher	49.951, -6.358	1990–99	SAC	R. Armour		-	-			1.25
Porth Minick Defences*†	St Mary's	49.912, -6.297	2000	SAC	R. Armour		-	-			1.25
St Agnes Defences*	St Agnes	49.895, -6.350	1996	SAC, SSSI	R. Armour		-	-			1.25
Great Popplestone Defences*	Bryher	49.953, -6.360	1990–99	SAC, SSSI	R. Armour		-	-			1.25
Porthcressa Defences*†	St Mary's	49.913, -6.313	1995	SAC	R. Armour		-	-			1.25



* Structures where physical and environmental conditions were assessed on-site.
† Structures where on-site ground-truthing ecological field surveys were conducted.
‡ Marine Protected Areas in which the structure is located: MCZ = Marine Conservation Zone; SAC = Special Area of Conservation; SSSI = Site of Special Scientific Interest.
§ SM = Scheduled Monument registered on the NHLE and HER; LB (II) = Grade 2 Listed Building registered on the NHLE and HER; LOCAL = structure registered on the HER only.
[a] Structural units for Old Grimsby Quay.
[b] Structural units for New Grimsby Quay.
[c] Structural units for Hugh Town Quay.

Fig. 7.5 (continued).

Name	Location (Island)	Latitude, Longitude (DD)	Age	Protected Areas[‡]	Ecological Potential: Construction	Ecological Potential: Extent within Tidal Zones (m)	Heritage Value: Grade[§]	Heritage Value: Heritage At Risk	Conservation Priority Scoring: EPS	Conservation Priority Scoring: HVS	CPS
Hugh Town New Pier*[c]	St Mary's	49.917, -6.317	1835–38	SAC	Masonry		LB (II)	-			2.75
Periglis Lifeboat Station*	St Agnes	49.894, -6.350	1908	SAC	Masonry		LOCAL	-			2.25
New Grimsby Quay (Masonry)*[b]	Tresco	49.956, -6.341	~1792	SAC	Masonry		LOCAL	-			2.25
Carn Thomas Lifeboat Station*†	St Mary's	49.917, -6.312	1899	SAC	Masonry		LOCAL	-			2.25
Cromwell's Castle	Tresco	49.962, -6.350	1651, 1990s	SAC	Masonry		SM	-			2.25
Hugh Town Quay Strengthening*[c]	St Mary's	49.917, -6.317	Mid-20th c	SAC	Masonry		LB (II)	-			2.25
Hugh Town Sea Wall (East)*	St Mary's	49.916, -6.312	1930s, 2011	SAC	Masonry		LOCAL	-			1.75
Hugh Town Slipway*	St Mary's	49.916, -6.317	>1901	SAC	Masonry		LOCAL	-			1.75
Mermaid Pub (Sea Wall)*	St Mary's	49.916, -6.318	>1901	SAC	Masonry		LOCAL	-			1.75
St Martin's Old Quay Slipway*	St Martin's	49.958, -6.285	1890	MCZ, SAC	Masonry		LOCAL	-			1.75
Hugh Town Quay (Widening)*[c]	St Mary's	49.917, -6.317	2014	SAC	Masonry		-	-			1.5
Carn Near Quay*†	Tresco	49.939, -6.331	2006–08	SAC	Blockwork		-	-			1.5
Porthconger Quay*	St Agnes	49.896, -6.340	2006–08	SAC	Blockwork		-	-			1.5
Hugh Town Quay (Pier Extension)*[c]	St Mary's	49.918, -6.317	1889	SAC	Blockwork		LOCAL	-			1.5
Hugh Town Quay (Sea Extension)*[c]	St Mary's	49.918, -6.316	1993–94	SAC	Blockwork		-	-			1.5
Hugh Town Shipyard Remains*†	St Mary's	49.915, -6.316	1958–89	SAC	Concrete		LOCAL	-			1.75
Abbey Farm Flying Boat Station*	Tresco	49.954, -6.339	1911–14	SAC	Concrete		LOCAL	-			1.75
Long Point*	Tresco	49.961, -6.331	>1901	SAC	Concrete		-	-			1.5
Lower Town Quay*	St Martin's	49.966, -6.305	>1980	MCZ, SAC	Concrete		-	-			1.5
Anneka's Quay*	Bryher	49.956, -6.347	2006–08	SAC	Concrete		-	-			1.5
St Martin's New Quay*	St Martin's	49.958, -6.281	1890s, 2007	SAC	Concrete		-	-			1.5
Old Grimsby Quay (Concrete)*[a]	Tresco	49.960, -6.332	>1901	SAC	Concrete		-	-			1.5
Hugh Town Quay (Wave Wall)*[c]	St Mary's	49.919, -6.316	2014	SAC	Concrete		-	-			1.5
Pendrathen Pillbox*	St Mary's	49.936, -6.300	1939–45	SAC	Concrete		LOCAL	-			1.5
Church Quay*	Bryher	49.953, -6.349	1880, 2000s	SAC	Concrete		-	-			1.25
Porthloo Slipway*	St Mary's	49.921, -6.309	1960–89	SAC	Concrete		-	-			1.25
Old Town Slipway*†	St Mary's	49.912, -6.301	1960–89	MCZ, SAC	Concrete		-	-			1.25
Pendrathen Slipway*	St Mary's	49.935, -6.304	>1901	SAC	Concrete		-	-			1.25
Hugh Town Beach Outflow*†	St Mary's	49.916, -6.317	1900–89	SAC	Concrete		-	-			1.25
Old Town Sea Wall (West)* †	St Mary's	49.911, -6.303	>1901	MCZ, SAC	Concrete		-	-			1
Hugh Town Property (Sea Wall)*	St Mary's	49.916, -6.317	>1901	SAC	Concrete		-	-			1
Atlantic Hotel (Sea Wall)*	St Mary's	49.915, -6.317	>1901	SAC	Concrete		-	-			1
Porth Hellick Outflow*†	St Mary's	49.917, -6.284	1960–89	MCZ SAC	Concrete		-	-			1
The Anchorage Pub (Sea Wall)*	St Mary's	49.916, -6.317	>1901	SAC	Concrete		-	-			1
Hugh Town Beach Sea Wall*†	St Mary's	49.915, -6.316	>1901	SAC	Concrete		-	-			1



* Structures where physical and environmental conditions were assessed on-site.
† Structures where on-site ground-truthing ecological field surveys were conducted.
‡ Marine Protected Areas in which the structure is located: MCZ = Marine Conservation Zone; SAC = Special Area of Conservation; SSSI = Site of Special Scientific Interest.
§ SM = Scheduled Monument registered on the NHLE and HER; LB (II) = Grade 2 Listed Building registered on the NHLE and HER; LOCAL = structure registered on the HER only.
[a] Structural units for Old Grimsby Quay.
[b] Structural units for New Grimsby Quay.
[c] Structural units for Hugh Town Quay.

The most frequently identified structures were quays or piers (30) followed by slipways (10) and rock armour installations (8). Of the 68 structural units identified, 39 were recorded on databases containing records of heritage assets (i.e. NHLE and HER) with 27 appearing exclusively on these registers. This includes all of the structures categorised as ruins. The periods of greatest marine construction activity on the Isles of Scilly were 1880 to 1915 and 1980 to 2015, when at least 15 structures were built within each 35-year time period (Fig. 7.5).

An additional 30 structures were identified in the supra-tidal zone, with a combined length of 2450 m. Of these, nine were recorded in registers of heritage assets. Structures categorised as rock armour were found to have the greatest combined area; however, these structures were typically located in the high-tide zone. In contrast, structures categorised as ruins extended disproportionately into the mid- and low-tide zones despite covering the smallest combined area. Concrete structures and blockwork structures similarly extend disproportionately into the mid- and low-tide zones.

7.3.2 Ground-truthing assumptions of the desk-based assessment

In total, 60 different taxa were observed colonising the 13 maritime structures surveyed on the Isles of Scilly (Appendix Table D1). This included one non-native species, *W. subatra*, which was found in low abundances on three structures located within St Mary's Pool (i.e. Hugh Town Old Quay, Carn Thomas Lifeboat Station and the Hugh Town Shipyard Remains). Preliminary analysis revealed that biodiversity indices were not significantly influenced by the inclusion of *W. subatra* as it was encountered on only a few occasions and in low abundances. As such, the decision was made to remove *W. subatra* from any further analysis and to consider native species only. This was done to ensure that non-native species, which are typically considered a threat to native biodiversity, did not contribute favourably to biodiversity measures used to determine the observed ecological value of a structure.

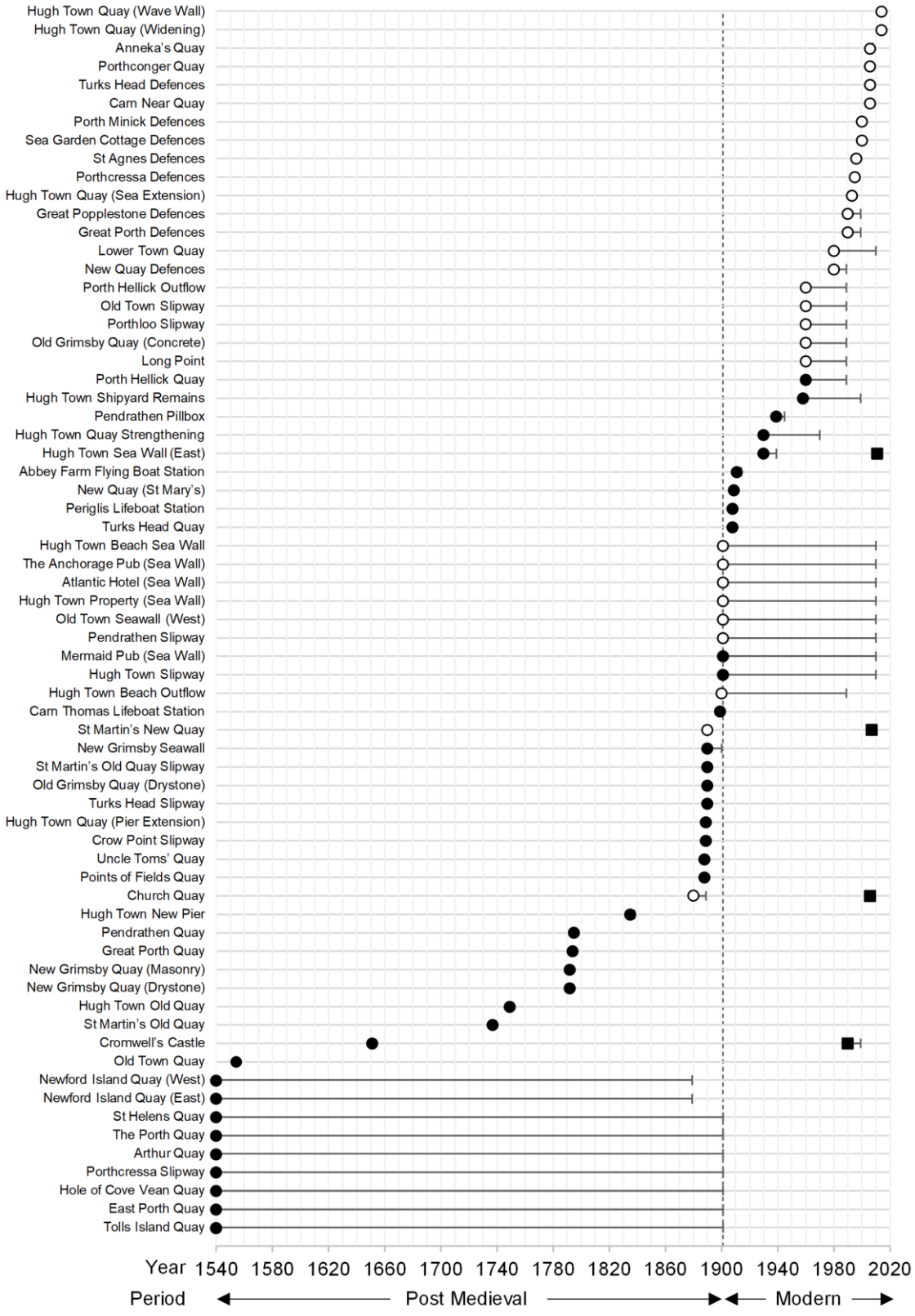


Fig. 7.5. Timeline showing the approximate construction dates of structures identified on the Isles of Scilly. Structures recorded in heritage registers (e.g. NHLE and/or HER) are shown as black circles, while those not recorded in heritage registers are shown as white circles. Error bars indicate uncertainty surrounding a structure's construction date. The dates of substantial repair work are also shown (black squares). One structure, Kitchen Porth Quay, is not included in the figure as it was constructed in the Early Medieval Period (410–1066 AD).

Structures given high EPS scores during the desk-based assessment, including drystone and masonry constructions located within the low-tide zone, typically supported more diverse ecological communities than those given low scores, such as mass concrete structures located within the high-tide zone (Fig. 7.6). For instance, the combined total number of native species observed on a structure during both the quadrat survey and the timed search (i.e. R_T) was typically greater on structures assigned EPS scores of 2.5 and above than those assigned EPS scores of 2 and below (Fig. 7.6a). Similar trends were also observed for mean species richness (Fig. 7.6b), mean abundance (Fig. 7.6c), and mean Shannon Index (Fig. 7.6d). Drystone structures such as Hugh Town Old Quay (HTQ), Old Town Quay (OTQ), and Porth Hellick Quay (PHQ) were found to support the greatest number of native species uniquely observed within microhabitat features as shown by the diagonally hashed bars in Fig. 7.6a. However, rock armour installations (i.e. Porth Minick Rock Armour, PMRA, and Porth Hellick Rock Armour, PHRA) and several concrete structures (i.e. Hugh Town Shipyard Remains, HTSR, and Hugh Town Sea Wall, HTSW) were also found to support marine species within microhabitat features not observed elsewhere on the structure.

Overall, Spearman-rank tests show there were significant positive correlations between EPS and the different measures of biodiversity (Table 7.6). The strongest correlation was found between EPS and overall species richness, R_T ($R_s = 0.8491$, $p < 0.001$).

Information regarding the physical state and environmental setting of the structures inferred during the desk-based assessment was also found to closely match conditions observed in the field at 52 structures where this was qualitatively evaluated. This includes important variables such as tidal height and construction type, which were used to determine the ecological potential of each structure.

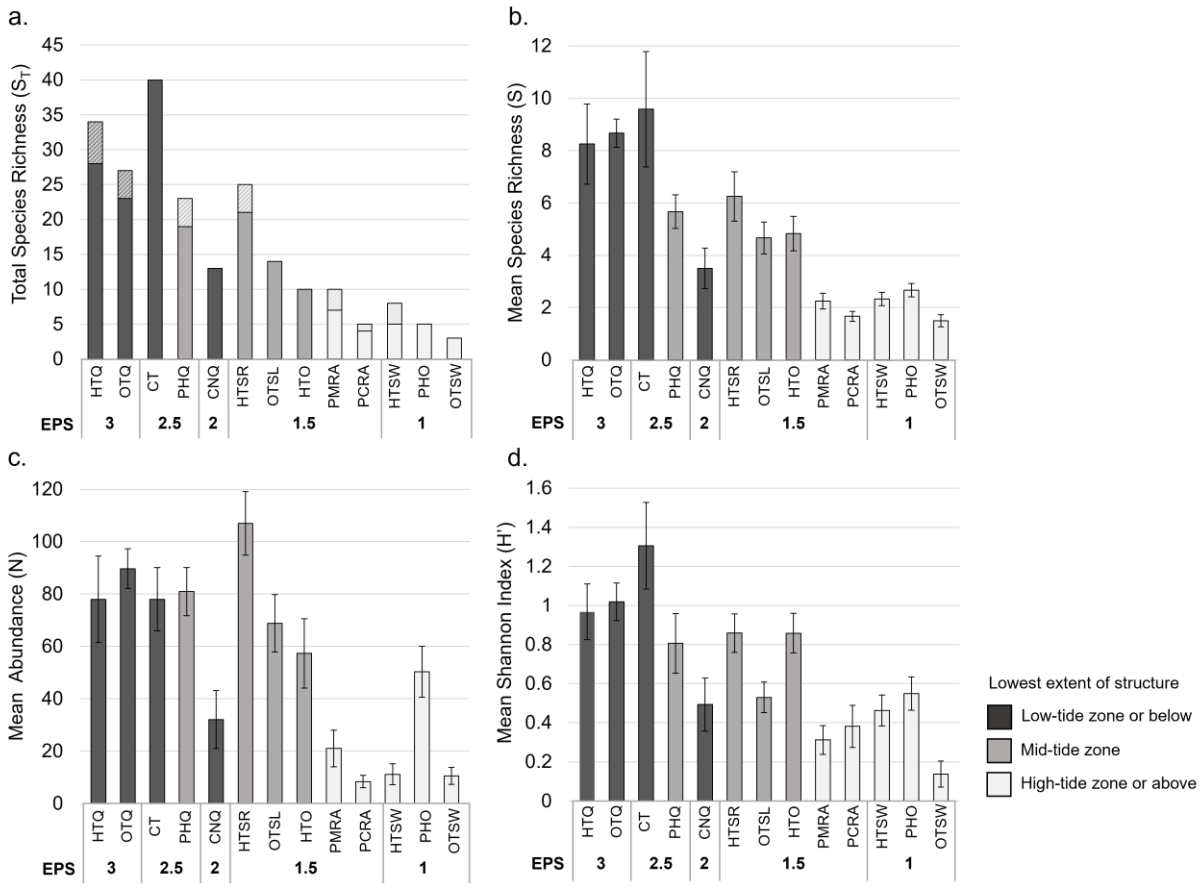


Fig. 7.6. Total number of native species (R_T), (a) observed on the surface of structures during quadrat surveys (filled) in addition to the number of native species found uniquely within microhabitat features during timed searches (hashed); and (b) mean species richness (R); (c) mean abundance (N); and (d) mean Shannon-Wiener Index (H') of quadrats surveyed on each structure. Structures are differentiated by their scores of Ecological Potential (EPS, 1–3) and by tidal height (dark grey = low-tide or below, light grey = mid-tide, white = high-tide or above).

Table 7.6. Spearman-rank correlation coefficients (R_s) and associated *p*-values between Ecological Potential Scores (EPS) and different measures of native biodiversity recorded at 13 structures on the Isles of Scilly (*p < 0.05, **p < 0.01, ***p < 0.001).

	Diversity Measure	R_s	*p*-value
EPS vs.	Mean Species Richness (R)	0.7726	0.002**
	Mean Abundance (N)	0.6395	0.019*
	Mean Shannon Wiener (H')	0.6842	0.010*
	Total Species Richness (surface only)	0.8365	<0.001***
	Total Species Richness (R_T)	0.8491	<0.001***

7.3.3 Conservation priority structures

Of the 68 structural units identified during the desk-based assessment, nine and ten structures were given the highest scores for Ecological Potential and Heritage Value, respectively (Table 7.5). When

considered in combination to produce scores of Conservation Priority (CPS), eight structures were assigned scores of 2.75 or more indicating they are valued as heritage assets and have the greatest potential to support diverse ecological communities when compared to other maritime structures in the region. This includes Old Town Quay (OTQ, CPS = 3), a medieval structure designated as a Scheduled Monument that has the potential to support diverse communities of marine wildlife due to its unmortared, water-worn granite boulder construction and position within the mid- and low-tide zones. In contrast, 17 structures were assigned conservation priority scores of 1.25 or less, suggesting they have limited heritage value and the lowest potential to support diverse ecological communities due to their construction type and position within the tidal profile. This includes the rock armour defences at Porthcressa (PCRA, CPS = 1.25) which were constructed in 1995 and are positioned in the high-tide zone.

7.4 Discussion

7.4.1 Shoreline engineering over space and time

Artificial structures within the intertidal zone of the Isles of Scilly account for approximately 4% of the coastline. When supra-tidal defence structures are also considered, almost 6% of the coastline was found to be artificially hardened. This is an order of magnitude lower than major coastal cities such as New York, Sydney, and Hong Kong where 50% or more of the shoreline has been hardened (Chapman and Bulleri, 2003; Floerl et al., 2021; Gittman et al., 2015; Lam et al., 2009). However, given that the Isles of Scilly is rural, has a low population density (~139 inhabitant/km^2), and its marine environment is protected, the extent of shoreline hardening within this archipelago cannot be considered insignificant. Importantly, in addition to larger-scale assessments (e.g. Bugnot et al., 2020; Firth et al., 2016b; Halpern et al., 2015), our findings demonstrate a need for more coherent regional-scale mapping of maritime structures if the full extent of marine human development is to be known. This includes rural and/or remote coastal locations that have so far received little attention compared to major urbanised centres around the world. The extent of maritime structures

within rural locations may be considered relatively inconsequential when viewed in isolation; however, collectively, they may represent a substantial impact on marine environments at national and/or international scales. Furthermore, in cases such as the Isles of Scilly, these locations may include historic assets that have specific heritage and ecological interest (and opportunities) for the reasons outlined in this study. As such, in addition to highly developed coastlines, we suggest that comprehensive evaluations of marine human development cannot be achieved without the inclusion of regional-scale assessments of coastlines typically considered relatively undisturbed by human activity.

Over half the structures identified within the intertidal zone of the Isles of Scilly were recorded in registers of heritage assets, with 27 identified exclusively using information recorded in these registers. This includes historic structures such as Hugh Town Old Quay, Old Town Quay, and Porth Hellick Quay, which were found to support diverse communities of marine wildlife during field surveys. The prevalence of heritage structures within the intertidal zone of the Isles of Scilly and the ecological value they may provide compared to modern maritime structures demonstrates a need to include historical data when making assessments of human development in marine environments, particularly at a regional scale. To the authors' knowledge, this study is the first to use registers of heritage assets to assess marine human development at any scale. Historical records (e.g. heritage registers and historic maps) can be used to complement conventional datasets of marine infrastructure by providing additional information about a structure, such as its age. Furthermore, by considering historical records, small, disused, and/or ruined historic structures that are not recorded elsewhere are more likely to be identified, allowing for more complete assessments of marine human development. The inclusion of historical data is particularly valuable when assessing the proliferation of artificial structures in coastal and marine environments over time. This is highlighted by Fig. 7.5, which provides a timeline of marine human development on the Isles of Scilly demonstrating a steady increase in the artificialisation of the coastline since the beginning of the twentieth century. Although certain information recorded within historical datasets

is sometimes imprecise (e.g. construction dates), the total omission of historical data from assessments of marine human development risks underestimation both in space and time. In the UK, our work demonstrates that data stored in the NHLE and local HERs can be effectively used alongside satellite imagery and records of contemporary infrastructure when attempting to determine the extent and impact of maritime structures. This approach not only allows for the rapid and remote identification of maritime structures but also the evaluation of conservation priorities. The existence of regional and national databases of built heritage assets in countries beyond the UK (e.g. the Merimée database of historic monuments in France) suggest that opportunities exist for determining the extent and conservation value of structures in other locations across Europe and around the world.

7.4.2 Identifying conservation priorities and appropriate interventions

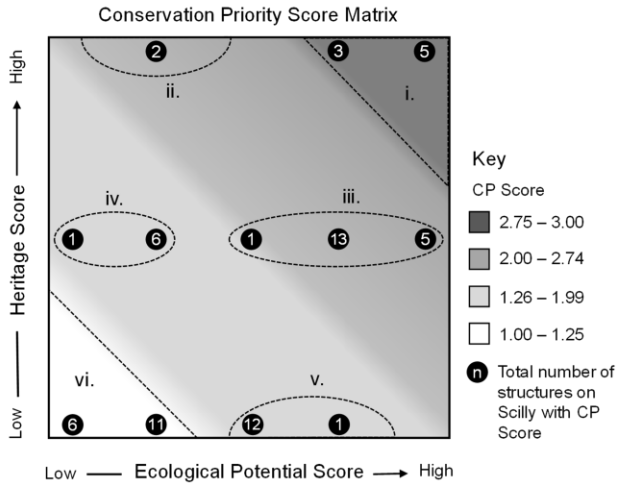
Ranked EPS determined by a structure's construction type and location within the tidal profile were significantly correlated to measures of biodiversity recorded in the field. In general, greater levels of biodiversity were observed on structures assigned high EPS scores compared to those with low EPS scores. There were, however, some exceptions to this trend; at Carn Near Quay (CNQ) biodiversity was found to be lower than expected, while at Carn Thomas Lifeboat Station (CT) and Hugh Town Shipyard Remains (HTSR) biodiversity was found to be higher than expected. This indicates that for some structures, factors beyond construction type and/or tidal height may be more important for determining the types of ecological communities they support. These include local environmental factors, such as wave exposure, insolation, salinity, pollution levels, and the particle size of the surrounding substratum (e.g. mud, sand, boulders, bedrock, etc.), biological factors and interactions, (e.g. recruitment, predation, competition, symbiosis, etc.), and the rate and extent of anthropogenic disturbances, all of which are known to influence the composition of ecological communities found on artificial marine structures (Cacabelos et al., 2016; Ferrario et al., 2016; Ivesa et al., 2010; Raffaelli and Hawkins, 1996). At Carn Near Quay, for example, ecological

communities may be significantly impacted by high wave exposure and frequent anthropogenic disturbance caused by the quay's regular use as a landing point (Connell, 1972; Raffaelli and Hawkins, 1996; Southward and Orton, 1954). In contrast, shade provided by overhanging ledges at Carn Thomas Lifeboat Station and Hugh Town Shipyard Remains may reduce the abiotic stresses experienced by marine wildlife found growing on these structures during low-tide periods (Blockley and Chapman, 2006; Firth et al., 2015b; Pardal-Souza et al., 2017; Takada, 1999; Williams, 1994). Nevertheless, the overall agreement between the EPS scores and the measures of biodiversity suggests that relatively simple information recorded in open data about a structure's age, design, disturbance characteristics, and tidal position can be used for initial, remote assessments of the ecological communities supported by maritime infrastructure. In turn, such information can be used to guide ground-truthing surveys aimed at providing a more detailed assessment of the types of marine wildlife that colonise different structures.

Non-native species did not significantly influence the biodiversity of the structures surveyed in this study as few were encountered; *W. subatra* was the only non-native species observed and this was found in low abundances on just three structures. These structures had a range of assigned EPS scores (i.e. 2.5–1.5) indicating that local factors beyond construction type and tidal height may influence the colonisation of *W. subatra* in this region. Specifically, the colonisation of *W. subatra* on structures located within St Mary's Pool is likely associated with Hugh Town harbour, a nearby major transport hub for visiting yachts and other marine vessels capable of transporting the invasive species on their hulls (Bishop et al., 2015; Reverter-Gil and Souto, 2019). Importantly, our results suggest there is no evidence that older, heritage structures support more or less non-native species than newer, modern structures. In this study, biodiversity indices were not significantly affected by the inclusion/omission of non-native species as they made up a very small proportion of all the taxa encountered. However, in areas beyond the Isles of Scilly where non-native species may be more widespread, such as major urban centres, evaluations of ecological value should consider in greater detail the potential impact of non-native species on the biodiversity of

maritime structures. Typically, artificial structures are thought to support a greater proportion of non-native and invasive species then natural rocky shores (e.g. Airoldi et al., 2015; Vaselli et al., 2008). However, there is limited understanding of whether this trend persists with a structure's age or for heritage assets constructed using materials and with surface features similar to those found on rocky shores. Going forward, further work is needed to determine the types of ecological communities that are supported by built heritage assets so that native and non-native taxa are both considered in future ecological assessments. By doing this, the methodology presented here could be more effectively applied to regions beyond the Isles of Scilly where non-native species pose a greater threat to marine biodiversity.

When considered in combination with a structure's heritage value, scores of ecological potential can be used to determine conservation priorities and appropriate interventions aimed at protecting/enhancing marine ecosystems and the historic built environment. By plotting maritime structures identified in Scilly on a 'Conservation Priority Matrix' based on their heritage value (HVS) and potential to support diverse ecological communities (EPS), we categorised the structures into six broad groups (Fig. 7.7) that could be used to guide conservation interventions. For instance, at nationally important heritage structures predicted to have the greatest potential to support diverse marine communities due to their age, traditional construction, and position in the tidal profile (e.g. Old Town Quay; Fig. 7.7i), suitable interventions may include the preservation and protection of structural features that not only have heritage value but also provide functional habitats for marine organisms. Other passive conservation strategies include the conscious non-disturbance of colonising organisms (excluding invasive and non-native species) and regular monitoring to assess the condition of a structure and the wildlife it supports (O'Shaughnessy et al., 2019). As is gaining increasing research attention, such an approach can help identify opportunities for valuing and protecting structures both as heritage assets and functional habitats, helping better integrate social and ecological conservation values in the coastal environment (Dafforn et al., 2015; Evans et al., 2017; Kienker et al., 2018; Morris et al., 2016).



CPS		Description	Example structures	Possible conservation interventions
2.75 - 3.00	i	Nationally important heritage assets which, due to their age, traditional construction, and position in the tidal zone, have the potential to support diverse marine communities compared to other structures.	Old Town Quay, Hugh Town Old Quay, Hugh Town New Pier,	Preservation of traditional construction that is both favourable to marine wildlife and of historical/ architectural interest.
2.00 – 2.74	ii	Nationally important heritage assets unlikely to support diverse marine communities. Typically, high in the tidal zone and constructed of masonry or blockwork.	Cromwell's Castle, Hugh Town Quay Strengthening,	Limited opportunities to encourage marine wildlife on structure due to position in the tidal profile. However, any modern defences (e.g., rock armour) situated lower on the shore and used to protect the heritage asset against coastal erosion may provide opportunities for ecological enhancement.
	iii	Locally important heritage assets which due to their age , traditional construction, and position in the tidal zone, have the potential support diverse ecological communities compared to other structures.	Porth Hellick Quay, New Quay (St Mary's), St Martin's Old Quay	Preservation of traditional construction that is both favourable to marine wildlife and of historical/ architectural interest.
1.26 - 1.99	iv	Locally important heritage structures unlikely to support diverse marine communities. Typically, high in the tidal zone and constructed of masonry or blockwork.	Pendrathen Pillbox, Mermaid Pub, Hugh Town Slipway	Ecological enhancements to encourage marine colonisation may be possible, however impact of adaptation to heritage value should be considered.
	v	Modern structures with limited heritage value but with the potential to support diverse ecological communities if ecological enhancements were applied. Includes rock armour in the low tidal zone.	Carn Near Quay, St Martin's New Quay, Turks Head Defences	Ecological enhancements to encourage marine colonisation in mid to low tide zones potentially favourable.
1.00 - 1.25	vi	Modern structures unlikely to support diverse ecological communities. Typically constructed of concrete and positioned in the high tide zone.	Porthcressa Defences, Porth Hellick Outflow, Church Quay,	Opportunities for ecological enhancements aimed at encouraging marine colonisation in high-tide zone may exist.

Fig. 7.7. Conservation Priority Matrix showing the number of unique structural units (black circle) with Conservation Priority scores (CPS) of 2.75–3.0 (Dark Grey), 2.00–2.74 (Grey), 1.26–1.99 (Light Grey) and 1.0–1.25 (White). These scores are based on a structures' heritage value (HVS) and ecological potential (EPS). The structures are separated into six different sectors (i to vi) based on the potential suitability of different conservation or enhancement interventions.

For modern structures with limited historical or cultural value (Fig. 7.7v), appropriate interventions may include the implementation of ecological enhancement techniques, such as the installation of artificial rockpools, that aim to increase the availability and diversity of microhabitat features favourable to marine ecology (Browne and Chapman, 2011; Firth et al., 2016a; Hall et al.,

2019; Morris et al., 2018; Naylor et al., 2011). Compared to heritage structures, opportunities for eco-enhancement may be less constrained on modern structures as they are unlikely to have designations that prohibit significant physical modifications (e.g. listings). Active eco-enhancement techniques implemented on these structures may provide some of the greatest net benefits to local marine biodiversity, as currently, many of these structures are assumed to be ecologically poor (Chapman and Bulleri, 2003; Moschella et al., 2005; Vaselli et al., 2008).

The appropriateness of specific interventions will depend on numerous factors including (i) a structure's function and heritage designation, (ii) practical considerations, such as the cost of implementing different interventions, (iii) the proximity of a structure to known sites of marine pest populations, (iv) and the types of marine organisms favoured for colonisation (O'Shaughnessy et al., 2019). Nevertheless, our study demonstrates that preliminary evaluations of structures based on their combined heritage value and ecological potential provides a useful first step to guide more detailed, targeted assessments. Furthermore, by considering the joint heritage and ecological value of maritime structures, opportunities for adopting nature-based solutions for enhancing the resilience of coastal infrastructure may be identified, which in turn could unlock co-benefits for cultural heritage and biodiversity conservation in marine environments (Coombes and Viles, 2021).

The methodology presented here has been specifically designed to help compare the historical and ecological value of artificial structures. As such, as a practical tool for prioritising areas for conservation, it may be particularly useful for defining conservation priorities along heavily urbanised coastlines where artificial structures dominate the foreshore and natural habitats with a good ecological status are often rare. In more rural locations, priorities for ecological conservation are more likely to focus on areas that have received limited anthropogenic disturbance (e.g. non-modified, natural habitats), and as such, this methodology may be less applicable. However, even within these regions, the methodology may be useful for quantifying the anthropogenic footprint of artificial structures on the marine environment and for determining where and what type of

ecological interventions may be most effective for promoting local biodiversity. Furthermore, by defining the ecological value of built heritage assets, arguments for protecting these structures may be enhanced. This may be particularly useful in rural areas where the conservation of maritime built heritage has disproportionately been neglected (Wyatt and Prizeman, 2018).

To build on this work, future studies should look to expand and develop ways of identifying the nature and extent of regional-scale human development in the marine zone to inform joint conservation priorities beyond the Isles of Scilly. This may include modifying the scoring system described here based on the particular suites of structures identified in different locations, including those with unique design characteristics (e.g. Tetrapods, floating pontoons, and fish traps) and those constructed from materials not considered here (e.g. wood, metal, and plastic). The extent and ecological function of submerged structures, such as shipwrecks, should also be considered in future assessments as these may represent sites of both high ecological and heritage value (Evans and Davidson, 2019; Lengkeek et al., 2013; Wessex Archaeology, 2008).

7.5 Conclusions

Using the Isles of Scilly as an example, this study demonstrates the potential for the regional-scale assessment of marine human development that fully considers historical datasets alongside more conventional records of maritime infrastructure. Our results suggest that the inclusion of historical datasets not only enables the more comprehensive mapping of maritime structures, but can also form a basis for identifying conservation priorities. Furthermore, we have shown that key information about a structure's age, construction, and tidal position that can be obtained remotely provides an effective basis for the rapid prediction of ecological potential. This in turn can be used to guide interventions aimed at improving the sustainable management and resilience of built heritage and marine wildlife. We encourage the further application and development of the approaches presented here, particularly in different locations, for a greater diversity of coastal and marine structures, and across larger spatial scales.

7.6. Chapter 7: Summary and implications

Results from Chapter 7 showed that:

i. Comprehensive assessments of marine human development can only be achieved with the inclusion of historical data.
ii. When considered alongside remote-sensing data and records of modern coastal defences, historical datasets can be used to develop a robust methodology for: (i) mapping maritime structures (including heritage assets) at a regional scale and (ii) identifying structures with the greatest potential for the joint conservation of maritime built heritage and marine wildlife.
iii. Evaluating the ecological potential and heritage value of maritime structures can be used to guide conservation strategies aimed at improving the sustainable management and resilience of the historic built environment.

Although the methodology presented in Chapter 7 (Paper 4) was designed to identify and evaluate maritime structures on the Isles of Scilly, with minor modifications (e.g. to the scoring system), it could be used as a practical tool for prioritising areas for conservation in other coastal regions in the UK and around the world.

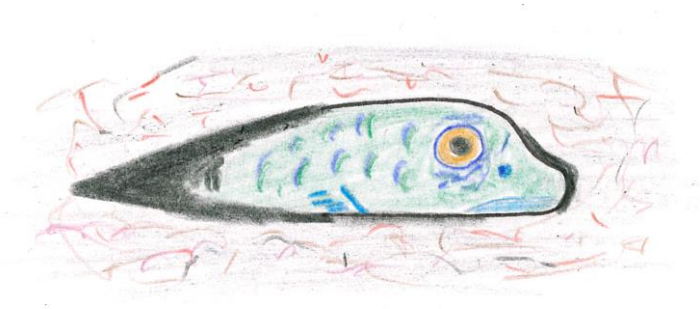
To increase the relevance of these findings for practitioners and conservation managers, a synthesis of conservation strategies with the potential to protect/enhance both marine biodiversity and cultural heritage could be usefully created to help inform and improve decision-making once priority conservation areas have been identified.

Section 5.

Implications

Section 5 summaries the main findings of the thesis and discusses how the four main objectives have been met. In addition, three opportunities for advancing research into wildlife-heritage interactions and feedbacks, and the joint conservation of cultural heritage and marine wildlife, are discussed. This is followed by a penultimate section that reflects on how wildlife-heritage interactions might transform in the future in response to coastal urbanisation and climate change, and the potential consequences this might have on the practical conservation of built heritage and marine wildlife.

Finally, the contributions of my research to wildlife/heritage conservation and the fields of geomorphology, heritage science, and marine ecology are discussed in the conclusions. Potential avenues for further research are also suggested.



A shanny (Lipophrys pholis) within a cryptic microhabitat feature
Drawn by Hope Calloway

Chapter 8

Discussion and conclusions

The overall aim of this thesis has been to improve scientific understanding of the two-way interactions and feedbacks between maritime built heritage and the marine wildlife it supports. In doing so, this research has sought to address the concerns of practitioners responsible for managing heritage sites and highlight potential opportunities for joint wildlife-heritage conservation. Four objectives were addressed throughout this thesis in order to achieve the overall aim, with each paper focusing on one objective (Table 8.1).

Table 8.1 Overall thesis objectives

O1. (Paper 1)	To identify current management practices and attitudes towards marine wildlife by practitioners responsible for the conservation and management of maritime built heritage.
O2. (Paper 2)	To evaluate the impact of marine wildlife on the rates of deterioration of a material regularly used in the construction and repair of maritime built heritage.
O3. (Paper 3)	To determine whether communities of marine wildlife supported by historic maritime structures differ to those found on natural rocky cliffs and modern concrete infrastructure.
O4. (Paper 4)	To develop and apply a methodology for identifying joint priority areas for biodiversity and maritime heritage conservation at a regional scale.

8.1 How have the four objectives been met?

With regards to the main objectives, the findings in this thesis showed that:

O1. Attitudes towards marine growth are generally in agreement among practitioners in the UK irrespective of their occupation or the historic maritime structures they are responsible for managing. Perceptions of marine growth are mostly positive, but concerns exist regarding its impacts on maintenance regimes, the condition of mortar, and health and safety. Several biogeomorphological processes are perceived to contribute to the protection and/or deterioration of heritage sites. On the one hand, marine wildlife is perceived to enhance deterioration through

bioerosive effects. This includes direct forms of bioerosion caused by rasping, boring, burrowing, and rooting marine organisms as well as indirect bioerosion caused by bio-chemical weathering processes and colonising wildlife enhancing mechanical strain. On the other hand, marine wildlife is perceived to contribute to the direct and indirect protection of heritage assets by acting as a physical barrier against deteriorative erosional processes (e.g. wave action, abrasion, boat impacts, etc.) and reducing the efficiency of decay mechanisms through the moderation of near-surface microclimates. Most of the practitioners who were surveyed have interest in the conservation of marine wildlife, however, degrees of engagement vary. Several gaps in research, evidence, and guidance relating to the management of wildlife-heritage interactions were identified, and these include: (i) the impact of marine growth on built heritage conservation, (ii) the values associated with marine growth on heritage assets, (iii) effective ways of encouraging marine growth through ecological enhancement techniques and/or discouraging the colonisation of invasive species, and (iv) the ecological benefits associated with heritage assets (e.g. habitat provision).

O2. Seaweed does not significantly enhance the deterioration of natural cement-based mortar during the first few months of exposure. Instead, the experimental results presented in Paper 2 demonstrate that the net effects of seaweed cover may be broadly bioprotective due to its influence on near-surface microclimatic regimes; seaweed cover may enhance the curing process and structural integrity of mortar and limit surface breakdown associated with thermal variability under both warm (summer) and cold (winter) conditions. Preliminary temperature data used to compare the thermal behaviours of biotic (e.g. seaweed) and abiotic (e.g. crevices) microhabitats on natural and artificial substrates in Paper 3 further supports these findings as surfaces colonised by seaweed were found to remain relatively cool during low-tide periods compared to bare (uncolonised) substrate (Appendix Fig. C1).

O3. Historic masonry walls support more diverse ecological communities than modern concrete walls, but these communities differ to those found on nearby natural rocky cliffs. Patterns of species

richness are positively associated with the abundance of surface-colonising ecosystem engineers (e.g. canopy-forming seaweeds) and mm-scale topographic variability. In addition, the ecological value of these structures is associated with the provision of cryptic microhabitats (i.e. crevices), with historic masonry walls generally providing substantially more cryptic space than both concrete walls and rocky cliffs. The unique physical properties of historic masonry walls, therefore, make them a potentially important component of habitat diversity, particularly along highly developed coastlines.

O4. When considered alongside remote-sensing data and records of modern coastal defences, historical datasets can be used to develop a robust methodology for: (i) mapping maritime structures (including heritage assets) at a regional scale and (ii) identifying structures with the greatest potential for the joint conservation of built heritage and marine wildlife. By using the novel methodology developed in this thesis, it was possible to accurately map maritime structures on the Isles of Scilly and evaluate the ecological potential and heritage value of these structures. This allowed for the identification of 'conservation priority structures' and initial assessments of intervention opportunities for enhancing both heritage and biodiversity conservation. The results indicate that in certain regions of the UK (such as the Isles of Scilly), maritime built heritage represents a significant proportion of coastal infrastructure. Therefore, to avoid underestimation, evaluations of marine human development should consider records of built heritage assets.

8.2 Opportunities for advancing wildlife-heritage research and practical conservation

In addition to addressing the four main objectives, my research highlights several opportunities for improving understanding of wildlife-heritage interactions and developing practical solutions for the joint conservation of maritime built heritage and marine wildlife:

- Opportunity 1. Applying my research to other heritage sites.
- Opportunity 2. Using a multi-method approach to advance understanding of wildlife-heritage interactions.
- Opportunity 3. Developing practical solutions for joint wildlife-heritage conservation.

These opportunities cut across the four main objectives and build on the findings presented in each paper (Fig. 8.1). When considered together, they highlight the wider contributions of this thesis to the fields of geomorphology, heritage science, and marine ecology, and identify potential pathways for future research that aims to address the needs/concerns of asset managers and conservation practitioners.

8.2.1 Opportunity 1. Applying my research to other heritage sites.

By considering each paper in turn, the following section outlines the opportunities for applying the findings to other heritage sites and, more broadly, the implications of this research for heritage science and conservation.

Paper 1, Perception Study: Given the scope of the perception study and the number of participants that took part (i.e. >130), the results can be considered broadly applicable to other heritage sites in the UK with similar characteristics to those considered in this study (i.e. "historic blockwork or masonry maritime structures built pre-1960 that are regularly submerged and exposed by the tide", Chapter 4, p66). In contrast, the results may be less applicable to heritage sites not built of stone (e.g. shipwrecks) and ruined and/or decommissioned structures that no longer provide functional benefits, as values and management issues associated with these structures may differ. For instance, marine growth on decommissioned structures may be associated with fewer and/or less severe health and safety concerns relative to functioning assets that are regularly used and maintained. Furthermore, marine managers may be less concerned about biodeterioration and other forms of decay on decommissioned structures, especially those with no formal protection and/or where a certain degree of loss is expected and increasingly accepted in management strategies (e.g. managed decline, adaptive release; DeSilvey et al., 2021, 2022; DeSilvey and Harrison, 2020). Further work is also required to determine the extent to which my findings apply to heritage sites outside of the UK as the social values, priorities, and traditional practices of people may vary in other countries (Strain et al., 2019).

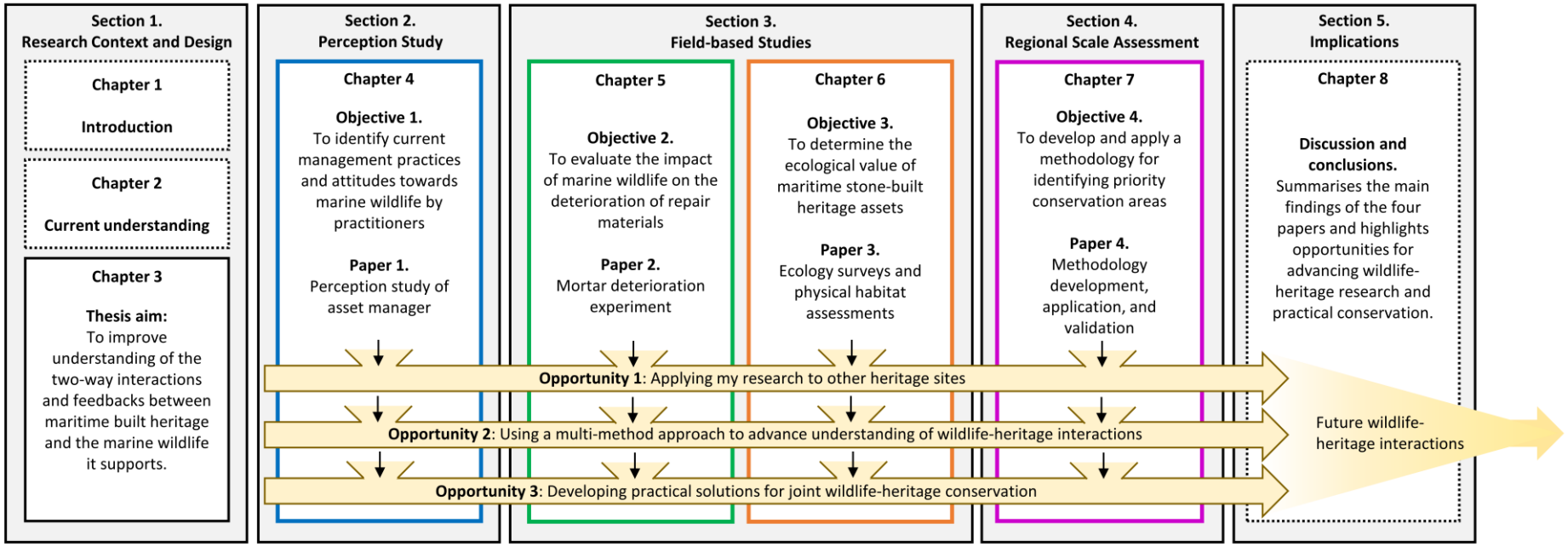


Fig 8.1. A schematic showing how the three opportunities discusses in Section 5 cut across with the thesis objectives. Developed with reference to Richards, 2020.

Paper 2, Mortar Deterioration Experiment: As discussed in Chapter 5 (Paper 2), natural-cement-based mortar has been used to construct built heritage assets throughout Europe since the middle of the nineteenth century and continues to be used as a repair material on maritime structures with traditional masonry designs. Consequently, the results of this thesis are broadly applicable to stone-built heritage assets constructed or repaired using natural cement (e.g. Vicat Prompt™) or other materials with comparable physical and chemical properties. In contrast, some caution should be taken when applying the findings to stone-built heritage assets constructed of materials with significantly different characteristics, as their susceptibility to environmental drivers of deterioration may differ (Artis et al., 2014; Figueiredo et al., 2018; Fusade and Viles, 2019). Furthermore, given that environmental conditions and the characteristics of colonising biota are known to influence biogeomorphological processes (Baxter et al., 2022; Coombes et al., 2013b), the findings are most applicable to (i) relatively wave-protected/sheltered heritage sites in the mid-to-low tidal range where seaweeds are most abundant and (ii) temperate climates. Currently, further work is needed to assess the influences of different biological covers on heritage materials and structures in more wave-exposed heritage sites as well as those located in warmer and colder climates.

Paper 3, Ecology Surveys and Physical Habitat Assessments: By assessing the ecological value of mortared and dry-jointed heritage assets in Chapter 6 (Paper 3) as well as ruined structures in Chapter 7 (Paper 4), this thesis builds on a growing body of research investigating the biodiversity of stone-built heritage assets (e.g. Chapter 2, Table 2.1). Given that mortared and dry-jointed stone walls represent a major component of several types of stone-built heritage assets in marine environments (e.g. stone-walled fish traps), the findings are relevant to other heritage sites that are similar in age and design (e.g. material and masonry configuration). Further work is needed, however, to examine heritage assets and other maritime structures that are much younger or have considerably different designs (e.g. WWII concrete pillboxes), as these structures may not provide the same characteristic features shown here to benefit marine organisms (i.e., cryptic microhabitat space and fine-scale surface complexity).

In addition to structure type, the results in Paper 3 indicate that location is an important factor influencing the composition of ecological communities on heritage assets. As indicated by previous studies, many complex, dynamic, and interacting environmental, biological, and anthropogenic factors shape marine communities on maritime structures (Chapter 2, Fig. 2.2, p14; Firth et al., 2016b). Nevertheless, a particular strength of this thesis is the broad geographical spread of field sites across the UK, which show that the ecological benefits associated with historic walls are comparable between different latitudes (e.g. from Cornwall to Scotland) and environmental settings (e.g. from estuarine to open coast). As such, the findings are considered broadly relevant to stone-built heritage assets in a variety of marine and coastal environments. This is further supported by evidence of other types of stone-built heritage sites—also located in other countries—providing similar ecological benefits (e.g. Favier Dubois et al., 2018; Kemp, 2006).

Paper 4, A Methodology for Regional-Scale Joint-Conservation Assessment: The results of Chapter 7 demonstrate that it is possible to use desk-based research to identify conservation priorities for more detailed, targeted assessments. While the methodology was developed specifically to identify and evaluate maritime structures on the Isles of Scilly, with minor adjustments, the approach taken can be used to identify priority structures elsewhere. For example, the scoring system can be easily modified to consider the particular suite of structures found in other locations, including those with unique design characteristics and those constructed from a broader range of materials (e.g. wood, metal, and plastic). As such, the application of the methodology to other regions around the UK should prove relatively straightforward given the increasing availability of high-resolution remote-sensing data (e.g. EA National LIDAR Programme) and detailed information stored in historical datasets alongside records of modern coastal infrastructure (e.g. EA Spatial Flood Defences Dataset). This includes, for example, records of built heritage assets in Scotland and Wales provided

by Historic Environment Scotland[16] and Cadw,[17] respectively. Beyond the UK, my novel methodology can also be applied where comparable and sufficiently detailed datasets are available.

8.2.2 Opportunity 2. Using a multi-method approach to advance understanding of wildlife-heritage interactions

This thesis drew on methods and understanding from geomorphology, heritage science, and marine ecology to gain a holistic understanding of the interactions between maritime built heritage and marine wildlife. Given the diverse range of methods used, this section (i) evaluates the effectiveness of the overall research approach, and (ii) highlights opportunities to improve understanding of wildlife-heritage interactions using an interdisciplinary, multi-method strategy.

First, this thesis highlights the benefits of developing a conceptual framework at the start of a research project. In previous studies, conceptual diagrams have been used to consolidate understanding of biophysical processes (e.g. Davidson et al., 2018; Naylor et al., 2012b; Sunamura, 1994; Viles and Coombes, 2022) and the complex interactions between built heritage and the environment (e.g. Coombes and Viles, 2021; Richards et al., 2019). Building on these examples, at the beginning of this project, a conceptual diagram of the interactions and feedbacks between maritime built heritage, marine wildlife, and asset managers was developed after reviewing the literature (Chapter 3, Fig. 3.1). Whilst developing this framework, it became evident that: (i) several gaps in research relating to wildlife-heritage interactions exist, and (ii) addressing these gaps required methods and understanding from a range of disciplines. Consequently, the conceptual diagram helped inform subsequent field- and desk-based research as it allowed the formulation of research objectives specifically designed to address gaps in evidence and understanding. Furthermore, by indicating the potential importance of both biophysical processes and human

[16] Accessed at: http://portal.historicenvironment.scot/
[17] Accessed at: https://cadw.gov.wales/

actors in moderating wildlife-heritage interactions, Figure 3.1 highlighted the potential benefits of adopting a multi-strategy/mixed-method approach.

Second, this thesis demonstrates the benefits and challenges of using a multi-method strategy to address research questions relating to wildlife-heritage interactions. Integrating and comparing data collected using different methods can present several challenges (Kinnebrew et al., 2021). For instance, interpreting data that is methodologically or topically dissimilar often requires an understanding of several statistical analysis techniques (Johnson and Onwuegbuzie, 2004; McKendrick, 2009). However, if these challenges are overcome, several benefits can be delivered. In the perception study, for example, a combination of methods was used to gain a depth of understanding not feasible through a single method alone (Chapter 4, Paper 1). Specifically, the opinions of a geographically dispersed target group were captured and compared using open-ended (i.e. qualitative) and scaled-response (i.e. semi-quantitative) questions in the online questionnaire. Complementary data collected through the semi-structured interviews then allowed key themes, concepts, and meaning to be teased out and developed. Thus, by combining qualitative and semi-quantitative data, the practices and opinions of asset managers were more effectively captured. More broadly, integrating methods from both the social and natural sciences in a mixed-method approach ensured that biophysical processes investigated throughout this thesis were considered within a social context (Castelló y Tickell, 2021). For instance, research gaps identified during the perception study were used to inform the field-based experiments and assessments (Paper 2–3). This ensured that the outcomes of the fieldwork directly addressed the concerns of practitioners and practical challenges associated with built heritage and wildlife conservation. Such an approach is crucial to ensure that applied academic research remains policy relevant and applicable to real-world challenges (Cooke et al., 2021; Martin et al., 2019).

In addition to informing field-based research, qualitative methods and desk-based research offers several practical benefits. As demonstrated in Paper 4, these techniques provide a means of

synthesising information stored in various formats to produce new datasets. This includes, for example, using historical datasets (e.g. historic maps, NHLE records) alongside remote-sensing data and records of modern defence structures to identify priority conservation areas. Desk-based research is also often less time-consuming and costly compared to field-based research. As such, for projects that are time- and cost-sensitive (including PhDs), desk-based research offers a practical means of addressing specific research objectives. Finally, as highlighted during the COVID-19 pandemic, desk-based research provides a safe means of collecting data when unexpected circumstances prevent field and laboratory research. For instance, during the UK National Lockdown in response to the COVID-19 pandemic, I was able to collect data for the perception study by distributing an online questionnaire and conducting remote interviews via video communication platforms.

This thesis also highlights the ethical and practical considerations required when investigating physical and ecological processes on heritage assets. Research investigating habitat provision on porous coastal defence structures (e.g. rock armour) has previously relied on the removal of external material during intrusive maintenance works to expose (internal) cryptic habitat (e.g. Sherrard et al., 2016). Sampling methods that can damage vulnerable surfaces, such as the Schmidt Hammer, have also been used to investigate the biogeomorphological functions of marine organisms on natural rocky shores (Baxter et al., 2022; Pappalardo et al., 2016, 2018). However, given the protected status of many heritage assets, similar methods could not be used in this thesis. Despite these limitations, this research has shown that non-destructive and non-invasive approaches can be successfully applied to investigate wildlife-heritage interactions on stone-built heritage assets. For example, in Chapter 5 (Paper 2), the field-block exposure trial allowed me to investigate the impact of seaweed growth on the deterioration of mortar using lab-based techniques (e.g. 3D microscopy) without the need for destructive sampling. Furthermore, in Chapter 6 (Paper 3), using a simple torch allowed me to illuminate and survey cryptic microhabitat features in historic walls, without having to remove any external stonework.

Finally, this thesis demonstrates the potential benefits and opportunities of combining relatively simple, low-cost methods with more advanced technologies when investigating wildlife-heritage interactions. In Paper 3, both low- and high-tech methods were used to conduct physical habitat assessments; the dimensions of (internal) cryptic microhabitats were measured using a metre ruler, while mm-scale surface complexity was recorded using SfM photogrammetry. Despite these methods differing in terms of cost and technological sophistication, both provided valuable information on the structural complexity of maritime structures. Using high-tech equipment in dynamic marine and coastal environments is also associated with several risks, including: (i) environmental hazards (e.g. precipitation, insolation, hot and cold weather conditions, seawater, sand, salt-laden air, etc.) that can easily damage technical equipment; (ii) the remote nature of many coastal locations, which means there is often limited capacity to conduct repairs; and (iii) dynamic tidal regimes that limit the time available for setting up/ packing away complicated equipment. As such, when investigating wildlife-heritage interactions in the marine zone, integrating low-cost, physically robust, and/or easily repaired low-tech methods with more advanced techniques will enhance the overall resilience of fieldwork (Viles, 2016), provided that sufficient quality of data can be achieved.

8.2.3 Opportunity 3. Developing practical solutions for joint wildlife-heritage conservation.

Over the last few decades, eco-engineering approaches have increasingly been developed to enhance marine biodiversity on maritime structures (e.g. Firth et al., 2016a; O'Shaughnessy et al., 2019; Strain et al., 2018). However, many of these techniques are not appropriate for heritage assets (e.g. listed buildings and Scheduled Monuments) as designations often prohibit significant physical modifications (Historic England, 2016a, b; O'Shaughnessy et al., 2019). This includes several eco-engineering techniques that are effective at encouraging the colonisation of marine wildlife on maritime structures, such as pre-cast artificial rockpools (e.g. Bone et al., 2022a; Browne and Chapman, 2011; Hall et al., 2019; Morris et al., 2017, 2018) and textured panels (e.g. Bishop et al.,

2022; Borsje et al., 2011; Clifton et al., 2022; Coombes et al., 2015; Cordell et al., 2017; Evans et al., 2021; Kosová et al., 2023; Loke et al., 2014; Loke and Todd, 2016; MacArthur et al., 2019; Moschella et al., 2005; Sheffield et al., 2022) that are attached/retrofitted to existing structures as well as drill-cored rock pools (e.g. Evans, 2016; Firth et al., 2014) and pits (e.g. Chapman and Underwood, 2011; Firth et al., 2014; Jackson, 2015; Martins et al., 2016, 2010).

As a way of reflecting on how the results of this project can contribute to practical opportunities for conserving marine wildlife and built heritage, this section outlines several management strategies that were considered/identified throughout this thesis (Table 8.2). This includes nature-based solutions that have the potential to unlock mutually beneficial outcomes for the conservation of cultural heritage and marine wildlife (Coombes and Viles, 2021), such as: (i) allowing and/or actively encouraging the growth of bioprotective species (e.g. seaweed) on heritage assets (as discussed in Paper 2); (ii) preserving architectural features that provide refuges from marine organisms (as discussed in Papers 3 and 4); and (iii) positioning eco-enhanced precast armouring units (e.g. ECOncrete Antifers; Perkol-Finkel and Sella, 2015) in front of heritage assets to provide scour protection (as discussed in Paper 4). Although some of these techniques are already in use (e.g. Fig. 8.2), Table 8.2 provides the first synthesis of strategies aimed at enhancing biodiversity on (specifically) stone-built heritage assets in marine environments. These strategies have been organised under three categories: (i) managing marine growth, (ii) repair work, and (iii) eco-enhancements. Given that many of these methods have not been thoroughly tested, rather than acting as a prescriptive guide for asset managers and heritage professionals, Table 8.2 is intended as a springboard to inform future research aimed at testing/developing novel strategies for joint wildlife-heritage conservation. In this way, Table 8.2 contrasts with other 'catalogues' of eco-engineering solutions for modern infrastructure that have been more thoroughly researched/tested and increasingly applied (e.g. Evans et al., 2021; ICE, 2023; Naylor et al., 2011, 2017a; O'Shaughnessy et al., 2019; Strain et al., 2018; Sutherland et al., 2021).

Table 8.2. Examples of management strategies with joint wildlife-heritage conservation goals. The potential advantages (+) and disadvantages (-) of each approach on marine wildlife and built heritage conservation are considered. Strategies that are likely to have negligible effects are also indicated (0). Papers from this thesis providing supporting evidence are stated in bold. Sections of the literature review (Chapter 2) with supporting evidence are stated in italics. A preliminary assessment of the relative degree of evidence available for each strategy is also provided: no evidence found ('NE', orange), some evidence available ('SE', yellow), comprehensive evidence available ('CE', blue).

	Approach	Potential Impacts on Heritage Assets			Potential Impacts on Marine Wildlife			Additional considerations
Managing Marine Growth	'Do nothing' approach (Marine growth)	+ - -	Marine growth can both enhance and retard the deterioration of heritage assets (**Paper 2**; *Section 2.3.1–2.3.3*), and positively and negatively impact a structure's appearance (**Paper 1**; *Section 2.4*). It can also make structural inspections more challenging (**Paper 1**; Cork and Chamberlain, 2015).	S E	+ - -	Low intervention approaches typically benefit marine wildlife (e.g. Airoldi et al., 2005; Crowe et al., 2000). However, where established, invasive species may also benefit from this approach, damaging native biodiversity.	S E	Intervention: None Cost: None, although untreated issues may cause higher long-term costs. Time: None
	Control or remove non-native or invasive species	0	If done using non-destructive techniques, this approach is unlikely to impact upon the conservation of heritage assets, unless the species being removed acts as a biogeomorphological agent.	N E	+	Removing invasive species from maritime structures may enhance native biodiversity, however, more work is required to directly evaluate the effectiveness of this intervention.	N E	Intervention: Low Cost: Low, periodic Time: Low, periodic
	Artificially seeding, transplanting, and/or gardening ecosystem engineers and/or bioprotective species.	+ - -	Species that form biotic covers and act as ecosystem engineers may also (i) exhibit bioprotective and/or bioerosive functions (**Paper 2**; *Section 2.3.1–2.3.3*), and (ii) make structural inspections more challenging (**Paper 1**; Cork and Chamberlain, 2015).	S E	+	Ecosystem engineers provide biogenic structural habitat for associated organisms and improve local biodiversity (**Paper 3**; Bertness et al., 1999; Umanzor et al., 2017).	C E	Intervention: Medium Cost: Medium, one-off Time: Medium, one-off
	Using eco-friendly products and avoiding damaging cleaning techniques	+	Pressure washing can negatively impact marine growth and damage mortar/stone (**Paper 1**; Historic England, 2017a). Therefore, avoiding its use may provide mutual benefits; however, the influence of eco-friendly cleaning products on materials used to construct and repair heritage assets is currently unknown and warrants additional research.	S E	+	Compared to conventional cleaning methods (e.g. bleach-based products), eco-friendly/biodegradable cleaning products are less damaging to marine wildlife.	S E	Intervention: Low Cost: Low, periodic Time: Low, periodic
	Avoiding the removal of bioprotective species	+ - -	Bioprotective species can protect built heritage assets from material decay (**Paper 2**; *Section 2.3.2–2.3.3*). However, some structural defects are only visible when colonising wildlife is removed and, therefore, could be missed (**Paper 1**).	S E	+	Retaining covers of canopy forming species maintains refuge provision for understory species (**Paper 3**; Burnaford, 2004; Watt and Scrosati, 2013).	C E	Intervention: Low Cost: None, although untreated issues may cause higher long-term costs. Time: Low, on-going
	Selective removal of bioerosive species	+	Some bioerosive species can damage heritage assets (*Section 2.3.1, 2.3.3*). Therefore, removing them from historic structures may improve built heritage conservation.	N E	-	Removing bioerosive organisms may negatively impact local biodiversity.	N E	Intervention: Low Cost: Low, periodic Time: Low, periodic

	Approach	Potential Impacts on Heritage Assets			Potential Impacts on Marine Wildlife			Additional considerations
Repair work	'Do nothing' approach (Building Conservation)	+ _	Over time, this approach will lead to the gradual deterioration of a feature/structure. Although loss is generally considered something to be avoided (DeSilvey and Harrison, 2020), the transformation of a structure through its gradual decay may also release new benefits (e.g. aesthetics, ecological, authenticity; Douglas-Jones et al., 2016; DeSilvey et al., 2021).	S E	+ _	Decay features can provide habitat for marine wildlife (**Paper 3**). However, material breakdown may also release pollutants (e.g. artificial materials, corrosion products) into the environment, negatively impacting marine ecosystems (Schmidt and Warner, 1989).	S E	Intervention: None Cost: None, although untreated issues may cause higher long-term costs. Time: None
	Indenting mortar joints or eliminating the use of mortar completely	+ _	This approach is unlikely to significantly impact the structural integrity of heritage assets. However, depending on the structure, indented mortar joints may either be in harmony or incongruent with the original design of a structure (Historic England, 2017b).	C H	+	Indented mortar joints create habitat space and refuges for marine organisms (**Paper 3**; Chapman and Underwood, 2011; Dugan et al., 2011; Firth et al., 2014; Naylor et al., 2012a; O'Shaughnessy et al., 2019).	C H	Intervention: Low Cost: Low, one-off Time: Low, one-off
	Selecting/positioning old/weathered stone to replace damaged or missing stonework.	+ _	Compared to newly quarried rock, old stone is more likely to be in keeping with the aesthetics of a historic structure. However, old/ pre-weathered stone may be more susceptible to damage due to years of exposure to mechanism of decay.	S E	+	Old stone is more likely to have surface features (e.g. weathering pits) that benefits marine wildlife compared to newly quarried rock and other engineered materials, such as concrete (**Paper 3;** Connell and Glasby, 1999; Coombes et al., 2011; Dodds et al., 2022; Herbert and Hawkins, 2006; Sempere-Valverde et al., 2018). Positioning stonework during repair work so that natural surface heterogeneities are exposed will maximise its ecological value (MacArthur et al., 2020)	C H	Intervention: Low–Medium Cost: Variable, one-off Time: Variable, one-off
	Using repair methods that retain rather than cover over or fill in cryptic habitat space	+	Repair methods that retain the characteristic features of dry-jointed heritage assets (e.g. crevices at the interstices on adjacent stones) will complement the general aesthetics of a historic structure. This includes traditional maintenance techniques, such as using wooden pegs, used to secure dislodged stonework, and contemporary methods, such as the 'stitching' solution described by Hine et al. (2015).	S E	+	Horizontal and vertical crevices that occur between adjacent stones in dry-jointed configurations provide cryptic habitat space and refugia for marine wildlife (**Paper 3**). Therefore, marine wildlife will likely benefit from using traditional repair methods that retain these features.	S E	Intervention: Variable Cost: Variable Time: Variable
	Scheduling maintenance and repair works to avoid important phonological events	0	This may not be possible if urgent repairs are needed, e.g. after a storm event.	S E	+	Low intervention approaches that minimise disturbance during the settlement of key species can benefit marine wildlife (e.g. Airoldi et al., 2005; Crowe et al., 2000).	S E	Intervention: Low Cost: Variable Time: Variable

	Approach	Potential Impacts on Heritage Assets			Potential Impacts on Marine Wildlife			Additional considerations
Eco-enhancement	Temporary eco-engineering solutions (e.g. tires, rope, ribbon, 'hulas'; Paalvast et al., 2012)	+ –	Unlike pre-cast artificial rockpools, several eco-engineering solutions do not require the permanent physical modification of heritage assets. For example, car tyres suspended from mooring rings via ropes or chains that act as fenders on historic walls can also provide ecological benefits (HR Wallingford, 2005). However, tyres are generally considered unsightly. Therefore, implementing this approach may negatively impact the aesthetic value of heritage sites.	S E	+ –	Tyres can resemble ecologically important water-retaining features, such as rockpools (Firth et al., 2013), and have been observed to support priority marine species (Firth et al., 2015a). However, tyres can release microplastics and other pollutants into marine environments as they decay (e.g. Collins et al., 1995; Baensch-Baltruschat et al., 2020; Heery et al., 2017; Wik and Dave, 2009).	C E	Intervention: Medium Cost: Low, one-off Time: Low, one-off
	Semi-permanent ('hard') eco-engineering solutions (e.g. pre-cast armouring units)	+ –	Several eco-enhancement techniques are designed to both enhance biodiversity and provide erosion protection. This includes artificial boulder fields (Chapman 2012, 2017), precast armouring units (e.g. BIOBlOCK, ECOncrete Antifers; Firth et al., 2014; Perkol-Finkel and Sella 2013, 2015; Sella and Perkol-Finkel, 2015), eco-engineered block mattresses (e.g. Sella et al., 2021), and low-terrace habitat benches (Toft et al., 2013). If implemented in front of heritage assets, these techniques may provide protection against erosional processes (O'Shaughnessy et al., 2019). However, they may also negatively impact the aesthetic value and authenticity of heritage assets and make structural inspections/repair work more challenging.	S E	+ –	If designed with passive and/or active eco-enhancements, habitat benches and armouring units may provide beneficial habitat for marine wildlife (e.g. MacArthur et al., 2020; Naylor et al., 2017b; Toft et al., 2013). However, careful consideration should be given when implementing this approach as it may alter the physical, chemical, and biological characteristics of the surrounding environment (Heery et al., 2017).	C H	Intervention: High Cost: High, one-off Time: High, one-off
	Clad a historic wall with new materials that are sensitive to the design of the original structure and have ecological enhancement benefits.	+ –	Constructing a new wall in front of an older structure or cladding an old wall with new material may protect it from deteriorative weathering and erosional processes (e.g. Southsea Coastal Scheme). However, this approach is relatively extreme and usually only suitable when a structure is under severe threat. Values associated with the structure (e.g. aesthetics) may be lost unless careful consideration is given to the design of the new wall (e.g. material, masonry configuration, etc.)	S E	+ –	Any ecological enhancement techniques incorporated into a new wall (e.g. indented mortar joints) should benefit biodiversity. However, habitat features associated with the old wall being replaced/covered will be lost. Constructing new walls is also likely to disturb local marine ecosystems (e.g. Heery et al., 2017).	S E	Intervention: High Cost: High, one-off Time: High, one-off
	Establishing a protected areas around a heritage site.	+ –	This approach may reduce the amount of anthropogenic disturbance caused to a heritage asset (e.g. boat impacts). However, not being able to directly interact with a heritage asset may either enhance or reduce the values and services people gain from the heritage site.	S E	+	Establishing a protected area will likely reduce the amount of anthropogenic disturbance to marine wildlife supported by a heritage asset.	S E	Intervention: High Cost: Variable, on-going Time: Variable, on-going



Fig. 8.2. Management strategies that have the potential to benefit marine wildlife and either enhance or have a negligible impact on built heritage conservation: (a) pre-cast artificial rockpools (ECOncrete Antifers) positioned in front of heritage assets as breakwater units (©ECOncrete); (b) rockpools formed by eroded limestone blocks on Plymouth Breakwater (Firth et al., 2013); (c) traditional methods used to secure dislodged material that retain cryptic habitat space (e.g. wooden pegs); (d) repositioning stone removed during maintenance work so that its textured surfaces face outwards; (e) tyres that retain water during low-tide; (f) an invasive Pacific oyster (*M. gigas*), and (g) an advert for an invasive-species culling event organised by Falmouth Marine Conservation.

As with other management solutions, those with joint wildlife-heritage conservation goals should be rigorously tested, analysed, and results published so there is confidence in the delivery of benefits for both ecology and cultural heritage (O'Shaughnessy et al., 2019). In the first instance, this will require more detailed assessments of the ecological value of maritime heritage assets, including historic masonry walls, but also other understudied heritage structures (e.g. stonewalled fish traps, clam gardens, etc.). Determining the ecological value of these structures will not only improve arguments for their continued conservation but also provide baseline data on which the success of enhancement techniques can be judged.

In addition to collecting baseline data, assessments of how and to what extent management practices influence asset performance, maintenance, and inspection are also required, including evaluations of whether the conservation techniques presented in Table 8.2 have a negative, neutral, or positive effect on asset resilience (Naylor et al., 2017a, 2018). Furthermore, future work is needed to determine any practical constrains, additional costs, and secondary benefits (e.g. socio-economic values) that may be associated with these techniques (Coombes and Viles, 2021; Naylor et al., 2011, 2017a, 2018) as well as stakeholder attitudes towards their implementation given that the views and perceptions of different users are likely to influence wider uptake (Evans et al., 2017; Kienker et al., 2018; Strain et al., 2019). The success of using a multi-method strategy in this thesis suggests that a similar approach could be usefully applied when carrying out these assessments. Finally, the extent to which these strategies meet legislation and policy instruments designed to protect and enhance cultural heritage (e.g. the Ancient Monuments and Archaeological Areas Act 1979) and the natural environment (e.g. the Water Framework Directive) must be considered (Naylor, et al., 2011, 2012a).

In terrestrial environments, nature-based solutions are increasingly being incorporated into heritage conservation and management strategies as a way of releasing co-benefits and tackling issues related to climate change, biodiversity loss, and unsustainable development (Coombes and Viles, 2021). Given that maritime built heritage and marine wildlife are both increasingly threatened by the effects of climate change (e.g. rising sea levels, increased storm frequency) and coastal urbanisation, now is the right time to extend these ideas to marine and coastal environments so that opportunities for joint wildlife-heritage conservation can be fully realised.

8.3 How might wildlife-heritage interactions transform in the future?

This penultimate section draws on the findings of the four papers to reflect on how wildlife-heritage interactions might transform in the future. This is important to consider given that the transformation of wildlife-heritage interactions may influence the direction of future research and

opportunities for developing effective solutions for practical conservation (Coombes and Viles, 2021). Specifically, this section considers future wildlife-heritage interactions in relation to the impact of coastal urbanisation and climate change on: (i) heritage assets as habitats for marine wildlife, and (ii) biogeomorphological processes operating on maritime built heritage. Alternative drivers of decay beyond biodeterioration are also briefly considered.

8.3.1 Heritage assets as habitats for marine wildlife

Over the next century, marine development is predicted to increase in response to coastal urbanisation and the threats associated with climate change (e.g. rising sea-levels, more frequent storm events; Bulleri and Chapman, 2010; Floerl et al., 2021; Thompson et al., 2002). In contrast, the availability of natural habitat is predicted to decline as more and more artificial structures are built in marine and coastal environments (Dugan et al., 2011). The growing threat of coastal squeeze means that heritage assets may become increasingly important hotspots for marine biodiversity, especially along heavily developed coastlines dominated by vertical concrete infrastructure where historic masonry walls might provide some of the only suitable habitat for marine organisms, particularly cryptic species. Refuges provided by heritage assets may also protect marine organisms from some of the most damaging effects of climate change. As shown using infra-red imagery collected during physical habitat assessments in Chapter 6 (Paper 3, Appendix Fig. C1), during low-tide periods, microhabitat features remain relatively cool compared to external surfaces exposed to direct insolation. In the future, with incidences of extreme warm weather (e.g. heatwaves) predicted to increase (Arias et al., 2021), refuges provided by (internal) cryptic microhabitats will become increasingly important for marine species at risk of desiccation (Garrity, 1984; Williams and Morritt, 1995). Marine wildlife may particularly benefit from habitat features provided by ruined sites and assets with dry-jointed constructions because, as shown in this thesis, these structures generally have the greatest availability of cryptic habitat space (Paper 3). Over longer time periods, climate migrants and/or invasive species whose geographical ranges shift in response to changing

temperatures, sea-level rise, and ocean acidification may use stone-built heritage assets as stepping-stones, along with shipwrecks (e.g. Paxton et al., 2019b; Soares et al., 2016, 2020) and other forms maritime infrastructure (e.g. wind turbines, oil and gas platforms, rock armour; Adams et al., 2014; Airoldi et al., 2015; Mineur et al., 2012).

Under future climate scenarios, the frequency and intensity of storms are also predicted to increase (Arias et al., 2021). As with other forms of cultural heritage (e.g. shipwrecks, archaeological sites, artefacts), sediment that is reworked during storm and flood events may bury stone-built heritage assets (Daly, 2013; Pearson and Williams, 1996), resulting in the loss of any associated values (e.g. cultural heritage, ecology). Alternatively, storm events may reveal historic structures that were previously buried (Harkin et al., 2020), thereby enabling the colonisation of these structures by marine wildlife. Whilst storm damage and other forms of deterioration present several challenges to heritage conservation (see Sesana et al., 2021 for a recent review), resultant changes to the physical structure of maritime assets may release new ecological benefits (DeSilvey, 2017; DeSilvey et al., 2021, 2022; DeSilvey and Harrison, 2020). For example, ruined and disused heritage assets can function as natural reefs long after losing any functional benefits (e.g. Hill et al., 2021; Lymperaki et al., 2022). Furthermore, as shown in Paper 3, voids created by dislodged stonework on historic masonry walls can provide unique habitats for marine organisms in the intertidal zone. Consequently, processes of decay may result in the transformation of values associated with stone-built heritage assets form those associated with cultural heritage and functional benefits to those associated with marine biodiversity. At the same time, marine managers may implement more extreme and/or invasive maintenance techniques to enhance the resilience of heritage assets to climate change, with potentially detrimental consequences for marine wildlife. This may include, for example, using concrete or cement to repair microhabitat features that are deemed structurally unsafe or vulnerable. Heritage designations may provide some protection against unsympathetic repairs, although this is threatened by a current lack of professional guidance on the management and adaptation of historic buildings in marine environments (Wyatt and Prizeman, 2018).

Rising sea-levels and coastal erosion are also likely to transform interactions between heritage assets and marine wildlife as more and more historic structures become submerged by the tide. This includes coastal assets not previously located in the tidal zone and others that will become permanently submerged (e.g. Sacco Perasso and Ricci, 2019). As heritage assets gradually transition between supra-, high-, mid-, low-, and sub-tidal zones, so will the composition of the ecological communities that are supported by these structures. Work is now needed to better understand the resilience of existing ecological communities on heritage assets as well as the mechanisms, rates, and endpoints of likely community transitions with sea-level rise.

8.3.2 Biogeomorphological processes operating on maritime built heritage

Biogeomorphological processes operating on maritime built heritage will also transform in response to a changing climate. For instance, an increase in the incidence of extreme weather events, such as heatwaves, may mean that the shading and water-retaining effects of canopy forming species will have greater bioprotective significance for vulnerable materials. This is linked to the occurrence and efficacy of thermal weathering, wetting–drying, and salt crystallisation in the intertidal zone and on heritage structures, all of which might be expected to be enhanced under a warning climate (Benavente et al., 2008; Trenhaile, 2014; Viles, 2002). A combination of longer-term field monitoring, laboratory simulation, and modelling could usefully help explore these issues (Viles, 2002). As storm events are also predicted to increase over the next century (Arias et al., 2021), the potential for seaweed and other biotic covers to act as a physical barrier, by reducing wave action and mortar wash-out, should be explored. At the same time, heatwaves and storms are linked to seaweed disturbance and loss (e.g. Haring et al., 2002), which, in turn, will impact any associated protective and/or deteriorative effects (Coombes et al., 2013b). Over longer periods of time, changing temperatures, sea-level rise, and ocean acidification are expected to cause range shifts for many intertidal organisms (de la Hoz et al., 2019; Pineiro-Corbeira et al., 2018; Wilson et al., 2019). Consequently, the structure of the biological communities that develop on maritime built heritage

may also change, along with their biogeomorphological functions (Sesana et al., 2021; Viles and Cutler, 2012). Future research is now needed to determine in greater detail how the biogeomorphological roles of seaweed and other biological covers will change during the twenty-first century so that practitioners can continue to make informed decisions about how to manage marine growth on heritage assets.

8.3.3 Other drivers of stone-built heritage deterioration

In addition to biogeomorphological processes, several other factors threaten maritime built heritage. These factors relate to the bioerosive effects of non-marine species, environmental conditions, human activity, and natural hazards (Table 8.3). Unlike wildlife-heritage interactions, many of these factors are already considered in professional guidelines on how to manage stone-built heritage assets in marine environments, such as the CIRIA report on 'Old Waterfront Walls' (Cork and Chamberlain, 2015). As highlighted in the perception study (Paper 1), asset managers are generally more concerned about the impacts of these threats than colonising wildlife. Consequently, management strategies with joint biodiversity and built heritage conservation goals should be considered within the wider context of these factors. Work is now needed to update current guideline to ensure that information on the bioprotective and/or bioerosion potential of marine organisms becomes more widely available to asset managers and conservation practitioners. This includes, for example, information on how marine organisms may enhance and/or protect against the threats in Table 8.3, and how these interactions might transform in the future.

Table 8.3. Drivers of deterioration on stone-built heritage located in the intertidal zone. Those in bold were discussed by respondents in the perception study (Paper 1).

Driver	Deterioration process
Biogeomorphological	
- **Woody vegetation**	The growth of woody vegetation (e.g. bushes, saplings, trees) can render a wall vulnerable to water penetration and frost action. Plants can affect the water content of adjacent soils, destabilising the foundations of walls, and can concentrate scour causing the erosion of susceptible materials (e.g. mortar joints). Furthermore, the roots of woody vegetation can penetrate cracks, accelerate mortar deterioration, and transfer wind loads to a wall via 'wind rock' (Cork and Chamberlain, 2015; English Heritage, 2014).
- Biofilms and lichen	Biofilms and lichen provide both bioprotective and bioerosive functions on stone-built heritage assets through the moderation of physical and chemical weathering processes (Carter and Viles, 2005; Gadd and Dyer, 2017; Liu et al., 2022).
- **Birds**	Bird droppings can negatively impact the appearance of historic structures and can enhance the deterioration of masonry through chemical weathering processes (Bassi and Chiatante, 1976; Channon, 2004; Spennemann et al., 2017).
- **Burrowing animals**	Burrowing animals, including mammals, amphibians, reptiles, and invertebrates, can undermine the integrity of a wall by eroding its foundations and internal structure (Cork and Chamberlain, 2015; Davidson et al., 2018).
Environmental	
- Temperature	Fluctuations and extremes in temperature can cause the gradual deterioration of masonry through mechanical weathering processes (Doehne and Price, 2010; Smith et al., 2008).
- **Moisture (Precipitation)**	On sections of wall not directly exposed to the sea (i.e. areas above the high-tide mark), precipitation and sea spray enables mechanical and chemical weathering processes driven by moisture, including freeze–thaw, wetting–drying, and salt weathering (Morillas et al., 2020; Mottershead, 1997, 2000).
- Moisture (Tides)	On sections of wall that are periodically submerged by the tide, mechanical weathering processes (e.g. salt weathering, wetting–drying) are enhanced.
- **Wave action**	Wave action causes the gradual erosion of susceptible material (e.g. joint mortar). Sediment suspended within waves can enhance erosion through abrasion. During storm events, high-intensity waves can cause stonework to be dislodged and removed resulting in greater destruction (e.g. Brown, 2013). Furthermore, scour at the front of a structure can cause structural instability, leading to the failure of a wall (Allsop, 2010; Oumeraci, 1993).
Human	
- Neglect	Compared to historic infrastructure located inland, specific guidance on the management of stone-built maritime heritage is limited (although see Cork and Chamberlain, 2015). Furthermore, the costs (i.e. financial and time) associated with maintaining historic maritime infrastructure are often considerably greater than those associated with similar structures in terrestrial environments. Consequently, stone-built maritime heritage is vulnerable to unsympathetic alterations and/or neglect that can lead to its gradual deterioration and/or a loss of cultural values (Wyatt, 2017; Wyatt and Prizeman, 2018).
- Vertical and horizontal loads	Human activity can increase vertical loads (e.g. via road traffic and vibrations, mobile cranes, stacked shipping containers, etc.) and horizontal loads (e.g. via dredging wires, moored vessels) on walls making them vulnerable to failure (Cork and Chamberlain, 2015).
- Pollution	Oil can stain building materials and has the potential to accelerate decay (e.g. Chin and Church, 2010). Microorganisms that have the ability to digest oil produce acids that can cause the chemical weathering of sensitive materials.
- **Boats**	Accidental impacts by vessels can damage historic structures. Waves produced by vessels may also cause the erosion of susceptible materials at the tideline. Furthermore, propeller wash and bow thrusters can cause scour and undermine wall foundations (Cork and Chamberlain, 2015).
- **Maintenance**	Maintenance techniques used to manage and remove marine growth (e.g. pressure washing) can accelerate mortar and stone deterioration (Historic England, 2017a).
Natural hazard	
- Earthquakes	Primary (e.g. seismic waves) and secondary (e.g. liquefaction) hazards associated with earthquakes can cause the structural failure of historic maritime structures (e.g. Yasuda et al., 2012).
- Storm surges/ Tsunamis	Tsunamis (e.g. Willems and van Schaik, 2015) and storm surges (Wyatt and Prizeman, 2018) can cause severe damage to historic maritime structures.
- Lightning	Lightening can dislodge stonework from historic masonry structures, including maritime built heritage assets (Historic England, 2019).
- Landslides	Landslides and cliff erosion can destabilise the foundations of maritime structures such as seawalls (Adams and Heidarzadeh, 2021) and coastal fortifications (Bromhead and Ibsen, 2006).

8.4 Conclusions

The overall aim of this thesis was to improve scientific understanding of the two-way interactions and feedbacks between maritime built heritage and the marine wildlife it supports. By addressing this aim, this thesis provides the first assessment of the ecological and biogeomorphological aspects of wildlife on maritime built heritage. In addition, this thesis makes a number of original contributions to the fields of biogeomorphology, heritage science, and marine ecology, and the practical conservation of built heritage and marine wildlife. These are summarised below:

i. Understanding practices and attitudes towards marine growth, and the identification of gaps in evidence, research, and guidance relating to wildlife-heritage interactions

   For the first time, this research identifies how marine growth is perceived and managed by practitioners responsible for the conservation of maritime heritage assets. In doing so, it highlights practical conservation techniques used to remove and encourage marine wildlife on heritage assets as well as perceived gaps in research, evidence, and guidance relating to wildlife-heritage interactions. An improved understanding of the concerns of practitioners allows conservation planning and implementation to be more effective. Furthermore, as demonstrated in this thesis, such understanding can be used to guide future field- and desk-based research that aims to inform practical conservation.

ii. Understanding the biogeomorphological impact of seaweed cover on materials used to construct and repair stone-built heritage assets

   Although previous research has investigated the impacts of marine wildlife on natural rock and engineered materials (e.g. concrete), this thesis was one of the first to analyse the biogeomorphological effects of marine growth on a material used to construct and repair stone-built heritage assets (Paper 2). As such, this research provides a novel contribution to a growing field of study investigating the biogeomorphological functions of marine

organisms on engineered maritime assets (e.g. Bone et al., 2022b). In addition, by directly addressing the concerns of practitioners identified in the perception study—notably, the perception that seaweed can cause damage to mortar—this research contributes to the practical conservation of heritage assets.

iii. Understanding the ecological value of historic masonry walls in marine environments

The results of Paper 3 address several gaps in understanding relating to the impacts of maritime heritage assets on marine biodiversity (Appendix Table E1). Notably, the findings suggest that the unique physical properties of historic masonry walls make them an important component of habitat diversity along developed coastlines. By improving understanding of the ecological value of stone-built heritage assets, this thesis builds on previous studies investigating the biodiversity of other forms of cultural heritage in marine environments (e.g. stone-walled fish traps, shipwrecks) as well as maritime infrastructure in general.

iv. The application of field approaches to assess biogeomorphological processes on repair materials

This thesis demonstrates the value of using a field-bock exposure trial to determine the biogeomorphological effects of marine wildlife on engineered materials, including those used to build and repair stone-built heritage assets. Furthermore, this work shows how relatively simple, low-cost methods (e.g. microclimate monitoring) can be combined with more advanced technology (e.g. 3D microscopy, optical profilometer) to improve our understanding of deteriorative processes acting on built heritage assets.

v. The application of field approaches to assess the ecological value of heritage assets

This thesis used an innovative range of field methods to assess and compare the biodiversity and physical habitat provision of maritime structures and natural rocky substrate,

combining relatively simple methods (e.g. metre ruler, quadrat) with more advanced technology (e.g. SfM photogrammetry). Notably, this research highlights the value of surveying the outer, seaward-facing surfaces of maritime structures in combination with internal void space and other cryptic microhabitats in order to gain a full understanding of the ecological communities that are supported by a structure.

vi. The development of a methodology to identify priority conservation areas and sites for future research

In this thesis, a novel methodology for the rapid and remote identification of priority conservation areas for both built heritage and marine biodiversity was developed, applied, and tested. Given that the methodology can be easily adapted and requires relatively low computational costs, it has the potential to inform conservation strategies in many regions of the UK and around the world.

vii. Evidence-based recommendations for wildlife and built heritage conservation

The research presented in this thesis has several implications for the practical conservation of built heritage and marine wildlife. Findings in Paper 3 imply that wherever possible, cryptic microhabitats and other characteristic features associated with heritage assets should be preserved for the benefits they provide marine wildlife. Furthermore, findings in Paper 2 indicate that seaweed growth has a negligible impact on repair mortars used to conserve valued heritage assets. By considering the results of this thesis alongside evidence from previous studies, series of practical conservation strategies were evaluated in Table 8.2. This helps address the desire of asset managers for more guidance on how to best manage wildlife-heritage interactions in marine environments (e.g. Paper 1). Given the potential benefits of nature-based solutions for built heritage conservation (Coombes and Viles, 2021), the results of this thesis highlight an urgent need for further research into the effectiveness of these strategies as well as any unintended consequences they might have.

viii. Wider application of research approach

Beyond marine and coastal environments, the approach adopted in this thesis can contribute to research on wildlife-heritage interactions in different environmental settings. This includes, for example, studies investigating the two-way relationships between built heritage assets (e.g. historic buildings) and colonising wildlife (e.g. vascular plants) in urban environments. As demonstrated here, an interdisciplinary, mixed-method approach can enable: (i) the identification of current management practices and attitudes towards wildlife colonisation, and gaps in evidence that warrant additional research attention; (ii) the investigation of biogeomorphological, and (iii) ecological processes and interactions to be assessed in the field, (iv) the development of a methodology to identify priority areas for conservation, and (v) evaluations of different management approaches and interventions specifically aimed at delivering co-benefits for biodiversity and cultural heritage.

Considering the outcomes of this thesis, future work should aim to (i) enhance understanding of the two-way interactions between marine wildlife and built heritage beyond historic masonry walls and (ii) identify/develop opportunities for joint wildlife-heritage conservation. In particular, future research should:

i. Establish the benefits, services, and values associated with wildlife-heritage interactions by a greater diversity of stakeholders who interact with built heritage assets and the marine wildlife it supports

This could involve, for example, community members, policy-makers, heritage professionals, and structural engineers who manage and/or use historic maritime structures as well as practitioners involved in the conservation of marine wildlife. An improved understanding of the services (and disservices) would enable us to: (i) determine whether certain services are valued more than others; and (ii) identify opportunities for enhancing services that benefit humans.

ii. Investigate in greater detail the biogeomorphological impacts of wildlife on maritime heritage assets

This could involve a balanced assessment of the biodeteriorative and/or bioprotective effects of different biological covers on built heritage assets and whether biogeomorphological processes vary with cover type, location, environmental conditions, the type of material being colonised (stonework, plastic, wood, metal, etc.), and over different spatial/temporal scales. For instance, more work is needed to determine whether: (i) the thermal insulating effects of seaweed and other biotic covers can protect heritage assets against damaging freeze–thaw events during cold weather; (ii) seaweed holdfast attachments cause damage to underlying substrate; and (iii) biotic covers facilitate chemical forms of decay due to enhanced moisture retention at the surface. The effects of marine growth on repair materials, including natural cement, also needs to be examined over longer periods of time and under changing climatic conditions (i.e. those associated with climate change predictions). An improved understanding of the magnitude and directionality of biogeomorphological processes operating on historic maritime structures will help address the concerns of practitioners, including those identified in the perception study (Paper 1), allowing them to make more informed management decisions.

iii. Evaluate and compare the potential ecological value of different types of maritime built heritage

This could include, for example, different types of stone-built heritage assets (e.g. clam gardens, fish traps, ruined/decommissioned masonry structures) that until now have been relatively understudied as well as structures built of different materials that have also received little research attention, including intertidal shipwrecks, historic piers, and concrete pillboxes. Future work could not only evaluate the ecological communities that grow directly on the surfaces of these structures (e.g. sessile organisms) but also mobile

species such as fish, marine mammals, and swimming invertebrates as is being increasingly done for non-heritage assets (e.g. Hall et al., 2021). More work is also needed to better understand whether the deterioration status of heritage assets influences the ecological communities they support, as this is a relatively under-explored variable. Species and community dynamics on built heritage assets (e.g. colonisation rates, disturbance regimes and patch dynamics, trophic interactions, and community resilience in response to environmental change) should also be explored in greater detail, especially in comparison to other asset types and natural rocky habitats that have been more thoroughly researched. More broadly, advances in marine ecology and related fields (e.g. ecological engineering) should continue to be applied to built heritage assets to provide a more holistic understanding of interactions and feedbacks in marine environments.

iv. Adapt and apply the methodology developed in Paper 4 to other geographical areas

This could include, for example, modifying the scoring system so that the methodology can be applied to areas beyond the Isles of Scilly. In particular, it would be useful to apply and test the methodology in heavily urbanised areas where artificial structures dominate the foreshore and natural habitats are rare, given that heritage assets may represent important refuges for marine wildlife in these locations.

v. Evaluate management strategies designed to deliver joint wildlife-heritage conservation goals

This could include, for example, testing and analysing the management strategies detailed in Table 8.2. In particular, these strategies should be investigated to determine their effectiveness in delivering benefits for cultural heritage and marine biodiversity alongside their practicality and cost (i.e. financial, time). As with other eco-enhancement techniques, these strategies should be tested on various structure types, in different locations (with varying in exposure, surrounding substrate type, latitude, etc.), and over varying timescales.

Given that coastal urbanisation is predicted to increase into the twenty-first century, future studies should also explore in greater detail how construction features associated with built heritage may help guide the future design of coastal infrastructure and ecological enhancement techniques.

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Appendices.

Appendix A: Author Contribution

The vast majority of work completed in this thesis was done by the candidate. As all four submitted papers were co-authored, both the contributions of the candidate (underlined) and the co-authors are outlined below.

Paper 1 (Chapter 4): T. Baxter, M. Coombes, and H. Viles contributed to the conception and design of the study. T. Baxter distributed the online questionnaire, conducted the interviews, and analysed the data. T. Baxter wrote the original draft, with T. Baxter, H. Viles, and M. Coombes reviewing and editing the manuscript.

Paper 2 (Chapter 5): T. Baxter, M. Coombes, and H. Viles contributed to the conception and design of the study. T. Baxter conducted the field block exposure trial and collected the data. T. Baxter also conducted the analysis and drafted the initial manuscript. M. Coombes and H. Viles provided supervision. All authors discussed the results and reviewed and edited drafts of the manuscript.

Paper 3 (Chapter 6): This study was conceptualized and designed by T. Baxter, M. Coombes, and H. Viles. T. Baxter collected the data, conducted the analysis, and drafted the initial manuscript. M. Coombes and H. Viles provided supervision. All authors discussed the results and reviewed and edited drafts of the manuscript.

Paper 4 (Chapter 7): This study was conceptualized and designed by T. Baxter, M. Coombes, and H. Viles. T. Baxter developed the methodology with advice from M. Coombes and H. Viles. T. Baxter conducted the desk-based research and ground-truthing fieldwork on the Isles of Scilly. T. Baxter analysed the data and drafted the initial manuscript. All authors read and approved the final version of the manuscript.

By signing the Statement of Authorship, you are certifying that the candidate made a substantial contribution to the publications, and that the description above is accurate.

Signed (Timothy Baxter):  Date: 27.02.2023

Signed (Martin Coombes):  Date: 27.02.2023

Signed (Heather Viles):  Date: 27.02.2023

Appendix B: Supplementary Material for Paper 1 (Chapter 4)*

Table B1. Characteristics of the questionnaire respondents and interviewees: occupation and location of work.

Category	Occupation	Questionnaire	Interview
Harbour Managers (n = 82)	Harbourmaster	68 (51%)	7 (25%)
	Harbour Board Member, Chairperson or Trustee	14 (11%)	2 (7%)
Engineer (n = 20)	Asset Manager or Engineer	12 (9%)	3 (10%)
	Structural, Maritime or Civil Engineer (Consultant)	6 (5%)	4 (13%)
	Contractor	2 (1%)	0 (0%)
Enviro. or Biodiversity Managers (n = 12)	Environment or Sustainability Manager	8 (6%)	7 (25%)
	Marine or Biodiversity Officer	4 (3%)	2 (7%)
Heritage and Conservation Managers (n = 11)	Heritage Officer or Advisor	6 (5%)	1 (3%)
	National Trust Manager	5 (4%)	2 (7%)
Other (n = 7)	Other Interested Parties	4 (3%)	1 (3%)
	Unknown	3 (2%)	0 (0%)
Total		132	29

Location	Questionnaire	Interview
England	49 (37%)	14 (48%)
Scotland	40 (30%)	8 (28%)
Wales	13 (10%)	5 (17%)
N. Ireland	6 (5%)	2 (7%)
Unknown	24 (18%)	0 (0%)

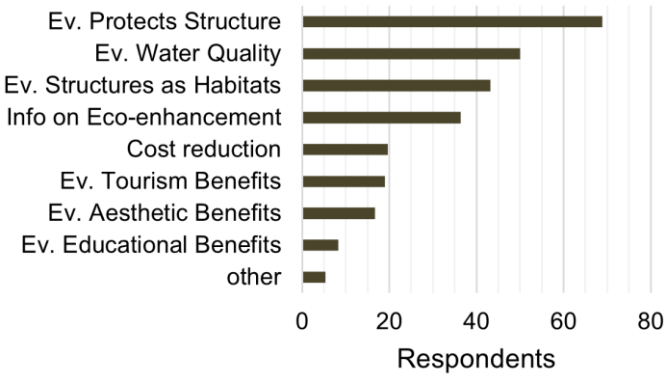


Figure B2. Reasons identified by respondents that would make them more likely to encourage marine growth.

* Published version available at: https://www.frontiersin.org/articles/10.3389/fmars.2022.913972/full#supplementary-material

Appendix C: Supplementary Material for Paper 3 (Chapter 6)[*]

An infrared camera was used to compare temporal and spatial thermal variability on three types of habitat (historic masonry wall, concrete wall, and rocky cliff) during a single low-tide period at Aberdour, Scotland (Fig. C1). For each habitat type, thermal images of a representative 60 × 45 cm area were collected at 1 h intervals over 3 h on a relatively clear, dry day on 14th May 2021. The area recorded on each habitat type was at approximately mean tide level. The infrared images were taken using a Teledyne FLIR C3-X thermal camera and subsequently analysed using FLIR Tools. The thermal camera can measure the temperature of objects between -10 to 150°C with an accuracy of ±2°C. Following previous studies that have analysed rocky substrate using thermal imagery, emissivity values were set at 0.95.

[*] Published version available at: https://doi.rg/10.1016/j.marpolbul.2023.114617

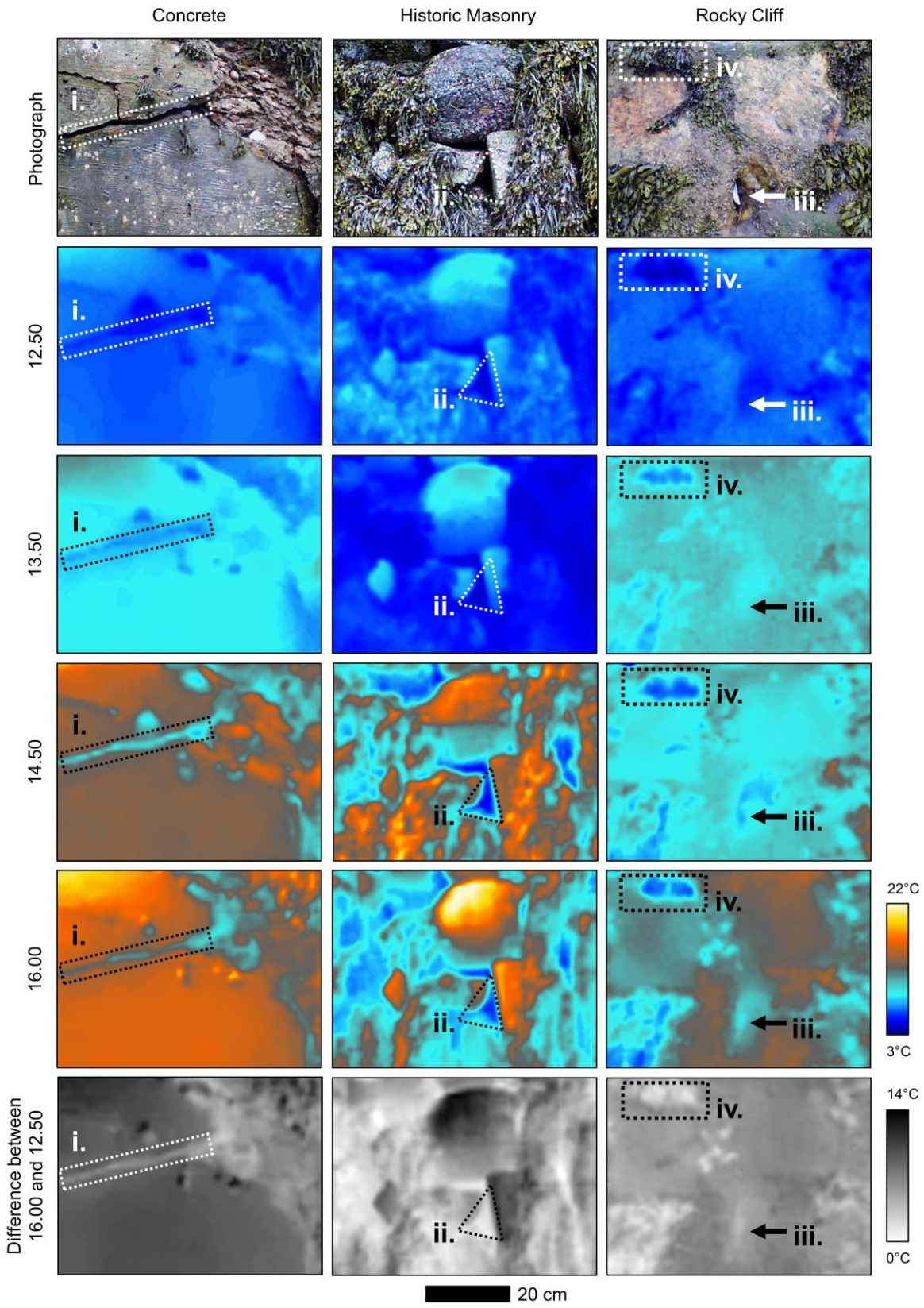


Fig. C1. Infra-red thermal images (second to fifth rows) showing the surface temperature (°C) of a concrete wall (left column), a historic masonry wall (middle column), and rocky cliff habitat (right column) at Aberdour, Scotland, taken at low-tide between 12.50 and 16.00 on 14th May 2021. Differences in temperature between the structures at 16.00 and 12.50 are also shown (sixth row). Microhabitat features including cracks (i) and crevices (ii. and iii.) are labelled, along with areas of substrate covered by seaweed (iv).

Table C1. Presence of species on the outer surfaces (S) and within cryptic microhabitats (C) on concrete ('Con.'), historic masonry ('Mas.'), and rocky cliff ('Roc.') habitats at each location.

	Portsoy						St Andrews						Aberdour						Cockenzie						Tenby						Falmouth						St Mary's					
	Con.		Mas.		Roc.		Con.		Mas.		Roc.		Con.		Mas.		Roc.		Con.		Mas.		Roc.		Con.		Mas.		Roc.		Con.		Mas.		Roc.		Con.		Mas.		Roc.	
	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C
Cnidaria																																										
Actinia equina				x					x	x	x	x				x														x							x	x	x		
Dynamena pumila				x					x	x	x	x				x				x						x	x									x	x	x		
Arthropoda																																										
Anurida maritima	x		x	x	x	x	x	x	x	x	x	x	x		x		x		x	x	x				x		x	x							x	x	x	x			
Carcinus maenas			x	x					x	x	x	x			x						x					x		x			x				x	x	x	x			
Chthamalus montagui																															x	x	x	x	x		x	x	x	x		
Dynamene bidentata																																							x			
Gammaridea spp.	x		x	x	x		x	x	x	x	x	x		x	x		x															x		x			x				
Idotea granulosa											x																															
Ligia oceanica			x	x		x	x		x	x					x	x															x						x	x			
Neomolgus littoralis			x				x		x							x		x																							
Semibalanus balanoides	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x							
Strigamia maritima							x		x																																	
Mollusca																																										
Acanthochitona spp.																											x	x										x				
Cingula trifasciata																																						x	x			
Peringia ulvae													x			x																										
Littorina littorea			x	x	x			x	x		x	x	x	x		x			x		x	x	x				x				x	x									
Littorina obtusata			x																														x	x		x	x	x			
Littorina saxatilis			x	x			x		x	x		x	x			x											x		x		x	x		x							
Melarhaphe neritoides	x	x	x		x	x		x	x	x			x		x	x	x		x		x				x		x		x		x	x	x			x	x				
Mytilus edulis	x		x	x	x	x	x	x	x	x		x			x	x	x	x	x	x	x	x				x	x	x			x	x	x			x	x				
Nucella lapillus	x			x	x	x				x	x					x		x		x	x	x	x				x	x				x	x								
Phorcus lineatus																														x		x	x	x				x	x	x		
Patella spp.	x	x	x	x	x	x	x	x	x	x		x			x	x	x	x	x	x	x	x	x	x		x	x	x	x	x		x	x	x		x		x	x	x		
Steromphala umbilicalis																																	x	x	x			x	x	x		
Tritia incrassata																x		x																				x	x	x		
Annelida																																										
Eulalia viridis																x					x	x			x	x		x														
Nephtyidae spp.								x																																		
Spirobranchus spp.					x																	x					x	x									x		x		
Spirorbis spirorbis				x						x		x				x		x															x		x	x	x	x		
Porifera																																										
Halichondria panicea				x		x																					x														x
Hymeniacidon perlevis																									x	x	x	x			x						x	x	x		
Bryozoa																																										
Alcyonidium hirsutum																																						x		x		
Flustrellidra hispida				x						x		x			x	x								x		x													x		
Schizoporella unicornis				x						x																	x											x			
Watersipora subtorquata																																							x			
Chordata																																										
Dendrodoa grossularia																																							x			
Lipophrys pholis					x																						x		x									x			
Chlorophyta																																										
Cladophora spp.	x		x	x	x	x			x	x	x	x				x	x								x		x										x				
Chaetomorpha spp.																				x																						
Ulva spp.			x	x	x	x			x	x	x	x	x			x	x	x		x		x		x	x	x	x	x			x	x		x		x	x	x			
Rhodophyta																																										
Bangia fuscopurpurea																																						x	x			
Catenella caespitosa										x													x	x		x		x													
Ceramium spp.					x						x	x							x	x	x	x																			
Chondrus crispus				x						x				x	x	x			x	x																	x				
Corallina officinalis				x		x									x					x																					
Corallinaceae spp.												x								x																		x			
Dementia contorta						x															x																				
Encrusting red seaweed										x															x			x									x		x		
Gelidium spp.																x																									
Lomentaria articulata				x		x				x	x	x				x											x											x			
Mastocarpus stellatus	x		x	x	x	x																																				
Membranoptera alata																x		x																								
Osmundea spp.	x		x		x	x				x									x	x	x				x	x	x	x													
Palmaria palmata	x			x		x															x							x													
Plocamium lyngbyanum				x																																					
Plumaria plumosa				x		x					x	x											x																		
Porphyra spp.			x		x											x	x	x					x																		
Pterothamnion plumula																x																									
Rhodochorton purpureum										x																															
Vertebrata fucoides																	x								x		x	x													
Vertebrata lanosa				x						x																						x					x		x		
Ochrophyta																																										
Ascophyllum nodosum									x		x	x	x	x	x																	x					x	x	x		
Elachista spp.			x	x	x																				x	x		x											x		
Filamentous browns																																		x								
Fucus serratus											x															x	x	x									x				
Fucus spiralis			x	x	x		x	x	x	x	x	x	x	x	x	x	x								x		x							x			x				
Fucus vesiculosus										x	x	x																				x		x		x			x		
Leathesia marina	x					x																																				
Pelvetia canaliculata																																x										
Ascomycota																																										
Tephromela atra																x		x																								
Total	12	3	19	28	15	21	10	9	18	21	22	21	10	4	12	27	12	11	6	0	11	15	13	8	7	4	13	14	18	21	5	0	5	15	15	6	10	0	20	29	21	11

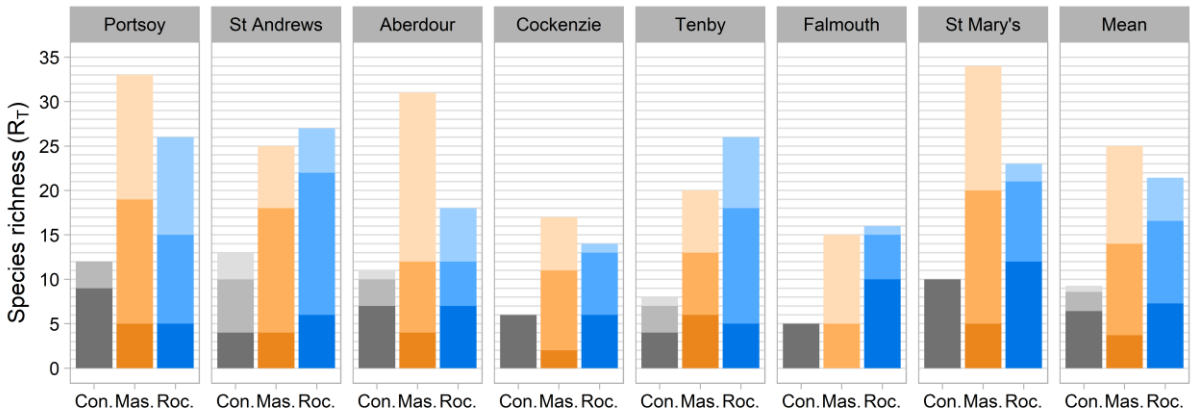


Fig. C2. Total numbers of species found on concrete walls (grey, 'Con.'), historic masonry walls (orange, 'Mas.), and rocky cliff (blue, 'Roc.') habitats at seven location in the UK. This includes species found uniquely on outer surfaces (darkest shades) and within cryptic microhabitats (lightest shades) as well as those observed within both environments. Mean values across all locations are also shown.

Appendix D: Supplementary Material for Paper 4 (Chapter 7)*

Table D1. Presence and absence of native and non-native species observed on the surfaces of structures during quadrat surveys (*) and within the microhabitat features of structures during timed searches (+).

	Structure	HTQ	OTQ	CT	PHQ	CNQ	HTSR	OTSL	HTO	PMRA	PCRA	HTSW	PHO	OTSW
	EPS	3	3	2.5	2.5	2	1.5	1.5	1.5	1.5	1.5	1	1	1
Group	Species													
Mollusca	*Patella* spp.	*	*	*	*	*	*	*	*	*	*	+		
	Melarhaphe neritoides	*	*	*	*		*	*	*	*			*	*
	Littorina obtusata	*	*	*	*	*	*	*	*					
	Littorina compressa			*	+	*				+				*
	Littorina saxatilis				*							+	*	
	Nucella lapillus		+	*	+									
	Steromphala umbilicalis	*	*	*	*	*	+	*						
	Steromphala cineraria		*											
	Phorcus lineatus	*	*		*	*		*		*	*	+	*	
	Calliostoma zizphinum			*										
	Cingula trifasciata	+												
	Acanthochitona crinita	+		*										
	Mytilus edulis	+		*			+							
Anthropoda	*Chthamalus montagui*	*	*	*	*	*	*	*	*	*	*	*		*
	Perforatus perforatus			*										
	Carcinus maenas	*		*	*		*	*						
	Ligia oceanica	*			*					*				
	Echinogammarus marinus				*		*		*	*		*		
	Anurida maritima	*										*		
Annelida	*Spirorbis spirorbis*	*	*	*	+	*	*	*	*					
	Spirobranchus triqueter	*												
Echinoderm	*Asterina gibbosa*		+	*										
Algae	*Fucus serratus*	*	*	*		*	*							
	Fucus Vesiculosus	*	*	*	*	*	*	*	*					
	Fucus spiralis		*		*		*	*	*	+			*	
	Ascophyllum nodosum	*	*		*		*							
	Leathesia marina		+	*										
	Pelvetia canaliculata				*					*	*	*		
	Filamentous browns	*	*	*	+	*	*		*					
	Lomentaria articulata	*	*	*	*	*	+							
	Palmaria palmata		*	*										
	Osmundea spp.		*	*										
	Mastocarpus stellatus			*										
	Corallina officinalis			*										
	Corallinaceae crusts	*	*	*		*								
	Halurus equisetifolius			*										
	Rhodochorton purpureum	*		*										
	Chondrus crispus	*		*										
	Vertebrata fruticulosa							*						
	Vertebrata lanosa	*	*		*		*							
	Gelidium pusillum			*			*							
	Catenella caespitosa				*		*							
	Ulva spp.	*	*	*		*	*	*	*			*	*	
	Cladophora spp.			*										
	Chaetomorpha linum			*				*						
Cnidaria	*Dynamena pumila*	*	*	*	*		*							
	Actinia equina	+	*		+			*		+	+			
Bryozoa	*Schizoporella unicornis*	*	*	*			*							
	Alcyonidium gelatinosum			*										
	Alcyonidium hirsutum			*			*							
	Watersipora subatra†	*		*			*							
	Flustrellidra hispida	*		*			*							
	Amathia spp.	*												
Porifera	*Ophlitaspongia papilla*			*										
	Halichondria panicea			*										
	Halichondria bowerbanki	*	*	*			*							
	Hymeniacidon perlevis	+		*										
Chordata	*Dendrodoa grossularia*	*	+											
	Diplosoma spongiforme	*												
	Lipophrys pholis	+					+							
Number of Species observed within Quadrat		29	23	41	19	13	22	14	10	7	4	5	5	3
Number of Species unique to Crevices		6	4	0	4	0	4	0	0	3	1	3	0	0
Total Number of Species		35	27	41	23	13	26	14	10	10	5	8	5	3

†Non-native species

* Published version available at: https://doi.org/10.1016/j.ocecoaman.2022.106288

Appendix E: Supplementary Material for Chapter 8

Table E1. Hypotheses presented in Chapter 2 (Table 2.2) and how they were addressed in this thesis. These hypotheses relate to the impact of historic masonry structures on marine wildlife.

Factor	Hypotheses presented in Chapter 2, Table 2.2 and tested in this thesis	Supported by findings?	Section (Paper)
Age	Due to their age, historic masonry walls have a greater density of weathering features and support more diverse marine communities than structures more recently built.	**Supported**—Historic masonry walls were found to have a greater density of mm-scale weathering features and supported more diverse ecological communities than modern structures.	Section 3 (Paper 3) Section 4 (Paper 4)
- Material	Historic masonry walls constructed of natural rock have rougher surfaces and support greater abundances of marine species compared to modern coastal infrastructure constructed of concrete.	**Supported**—Historic masonry walls were found to have significantly greater rougher surfaces than concrete walls and support greater abundances of marine species.	Section 3 (Paper 3)
- Surface texture	Given that they have experienced years of degradation due to weathering and erosional processes, the availability of fine-scale surface features is higher on historic walls compared to other forms of coastal infrastructure.	**Supported**—Historic masonry walls were found to have significantly greater mm-scale surface complexity than concrete walls.	Section 3 (Paper 3)
- Structural complexity	The availability of meso-scale habitat features is greater on walls with traditional masonry configurations compared to other forms of coastal infrastructure.	**Supported**—The availability of meso-scale habitat features was found to be significantly greater on historic masonry walls compared to concrete walls.	Section 3 (Paper 3)
- Availability of cryptic habitats	The availability of (internal) cryptic habitat space is greater on historic masonry walls compared to other forms of coastal infrastructure. These features provide novel habitat for marine organisms.	**Supported**—The availability of cryptic habitat space was found to be significantly greater on historic masonry walls compared to concrete walls. Historic masonry walls also supported significantly more cryptic species.	Section 3 (Paper 3)
Maintenance regime	Marine wildlife is managed differently on historic masonry walls compared to other forms of coastal infrastructure.	**Undetermined**—Although some practitioners indicated that they managed marine wildlife differently on historic masonry walls, others did not.	Section 2 (Paper 1)