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From ocean sprawl to blue-green infrastructure - A UK perspective on an issue of global significance

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Abstract

Artificial structures are proliferating in the marine environment, resulting in 'ocean sprawl'. In light of the potential environmental impacts of this, such as habitat loss and alteration, it is becoming increasingly important to incorporate ecologically-sensitive design into artificial marine structures. The principles of eco-engineering and green infrastructure are embedded in urban planning practice for terrestrial and freshwater development projects. In marine planning, however, eco-engineering of *blue-green* infrastructure remains an emerging concept. This note provides a UK perspective on the progress towards uptake of eco-engineering approaches for enhancing biodiversity on artificial marine structures. We emphasise that, despite a clear 'policy pull' to incorporate biodiversity enhancements in marine structures, a range of proof-of-concept evidence that it is possible to achieve, and strong cross-sectoral stakeholder support, there are still few examples of truly and purposefully-designed blue-green artificial structures in the UK. We discuss the barriers that remain and propose a strategy towards effective implementation. Our strategy outlines a step-wise approach to: (1) strengthening the evidence base for what enhancements can be achieved in different scenarios; (2) improving clarity on the predicted benefits and associated costs of enhancements; (3) packaging the evidence in a useful form to support planning and decision-making; and (4) encouraging implementation as routine practice. Given that ocean sprawl is a growing problem globally, the perspective presented here provides valuable insight and lessons for other nations at their various states of progress towards this same goal.

Keywords: Artificial structures; Biodiversity enhancement; Conservation; Ecological engineering; Marine management; Science-policy interface.

1 Introduction

1.1 Ocean sprawl: proliferation and impacts

Artificial structures are proliferating in the marine environment globally, in what has been termed "ocean sprawl" (Duarte et al., 2013; see Firth et al., 2016b for review). Coastal defence structures (e.g. breakwaters, groynes, seawalls) have become common features along shorelines to retain land and protect expanding urban developments from predicted sea level rise and extreme weather. Structures associated with marine renewable energy generation (e.g. turbine pilings, scour protection, lagoon walls) are also increasingly prevalent as nations attempt to reduce greenhouse gas emissions. Meanwhile, platforms for offshore oil and gas exploration still operate in their thousands worldwide – in some places forming "steel archipelagos" (Villareal et al., 2007). A variety of other residential, commercial and recreational activities also introduce artificial structures to the seabed and water column, such as trestles and enclosures for mariculture, pontoons, docks and buoys for transport and navigation, recreational piers and artificial reefs. Shortage of valuable ocean-front land has led to the construction of entire artificial islands, such as the Palm Islands off the coast of Dubai (Hvidt, 2009) and island projects off Malaysia (Chee et al., 2017). The increasing extent of these types of developments in recent years has been highlighted as one of the top 15 global marine conservation issues of our time (Sutherland et al., 2016).

The potential environmental impacts of artificial structures in the marine environment have become an issue of great concern. Aside from the loss of and disturbance to natural habitats and species within their physical footprint ("placement loss"; Heery et al., 2017), indirect local- and regional-scale consequences may arise from altered coastal and oceanographic processes and altered connectivity (see Bishop et al., 2017; Firth et al., 2016b; Heery et al., 2017 for reviews). Furthermore, artificial habitats are known to support different and often less diverse communities of marine life, compared with natural rocky habitats (Chapman and Bulleri, 2003; Firth et al., 2013b; 2016c; Glasby, 1999; Moschella et al., 2005; Sheehan et al., 2013; Wilhelmsson and Malm, 2008). They have also often been seen to support invasive non-native species and can act as stepping stones for species to spread into new areas (Airoldi et al., 2015; Bulleri and Airoldi, 2005; Firth et al., 2013a; Mineur et al., 2012; Sammarco et al., 2004). In light of these potential negative environmental implications of ocean sprawl, and to satisfy international conservation commitments, it is increasingly important to incorporate ecologically-sensitive design into marine and coastal developments.

The concepts of ecological engineering (or eco-engineering) and green infrastructure are not new (Benedict and McMahon, 2002; Bergen et al., 2001). In terrestrial and freshwater systems, incorporating environmental enhancements and natural capital (i.e. the assets from which ecosystem services are derived) into engineered developments is well established. For example, green roofs (Brenneisen, 2006), motorway wildlife passages (Berthinussen and Altringham, 2012; Mata et al., 2008), coir rolls on river walls (Hoggart and Francis, 2014) and bird/mammal nest boxes (Arnett and Hayes, 2000) have all been widely implemented, allowing some evaluation of their efficacy in practice. There has also been research into the optimal design of culverts and dams for fish migration (Newbold et al., 2014). Consequently, the principles of eco-engineering and green infrastructure are embedded in urban planning practice for terrestrial and freshwater development projects and restoration initiatives (e.g. Brenneisen, 2006; Williams, 2010). In marine planning, however, eco-engineering of *blue-green* infrastructure remains an emerging concept. Although there has been an explosion of interest in applying the concepts of green infrastructure to artificial structures in the marine environment since the early 2000s, especially amongst researchers trialling marine eco-engineering techniques (see Strain et al., 2017b), it is not yet implemented as routine practice.

In this note, we consider the potential for proliferating ocean sprawl to be eco-engineered into blue-green infrastructure. Specifically, we consider this in terms of enhancing biodiversity on artificial marine and coastal structures (such as sea defences, port/harbour walls, energy infrastructure and others listed above). We exclude artificial reefs from our considerations and focus instead on structures that are necessary and appropriate for some primary function other than their ecological effects. We briefly outline the evidence base for enhancing biodiversity on artificial marine structures. We then provide a UK-perspective on this internationally-significant issue, emphasising that, despite a clear policy recommendation and strong cross-sectoral stakeholder support, there are still few examples of truly and purposefully-designed blue-green infrastructure. We discuss what the barriers to achieving this are and propose a strategy towards effective implementation, providing valuable insight to other nations working towards this same goal.

1.2 Evidence base for enhancing biodiversity on artificial marine structures

Much progress has been made in recent years in identifying potential interventions for enhancing biodiversity and natural capital on artificial structures in the marine environment (see Strain et al., 2017a for review). Diversity deficits relative to natural rocky habitats have often been attributed to low topographic complexity of structures (Aguilera et al., 2014; Chapman, 2003; Firth et al., 2013b; 2016c; Wilhelmsson and Malm, 2008), particularly a lack of water-retaining features in intertidal structures. Many marine eco-engineering trials have, therefore, attempted to enhance biodiversity on structures through increasing their habitat complexity (see Figure 1 for examples). This has been tested at the micro (μm-mm) scale by creating textured surfaces (Coombes et al., 2015; Perkol-Finkel and Sella, 2016; Sella and Perkol-Finkel, 2015), at the small-to-medium (mm-cm) scale by adding artificial pits, crevices and pools (Browne and Chapman, 2014; Chapman and Blockley, 2009; Evans et al., 2016; Firth et al., 2014; 2016a; Hall et al., 2018; Martins et al., 2010; Morris et al., 2017), and at the macro (cm-m) scale by incorporating pre-cast habitat units into structure designs (Firth et al., 2014; Langhamer and Wilhelmsson, 2009; Perkol-Finkel et al., 2017; Perkol-Finkel and Sella, 2016; Scyphers et al., 2015; Sella and Perkol-Finkel, 2015). Researchers have also investigated alternative construction materials to improve the habitat quality of structures and/or to reduce their environmental footprints (Collins et al., 2015; Cuadrado et al., 2015; Dennis et al., 2017; McManus et al., 2017; Perkol-Finkel and Sella, 2014; Sella and Perkol-Finkel, 2015). Others have trialled transplanting target species directly onto structures to support threatened populations (Ng et al., 2015; Perkol-Finkel et al., 2012).

The enhancements that can be achieved through the design modifications described above include increased biodiversity (Browne and Chapman, 2014; Chapman and Blockley, 2009; Dennis et al., 2017; Evans et al., 2016; Firth et al., 2014; Loke and Todd, 2016; Perkol-Finkel and Sella, 2016; Sella and Perkol-Finkel, 2015) and/or increased abundances of target species (Langhamer and Wilhelmsson, 2009; Martins et al., 2010; Ng et al., 2015; Perkol-Finkel et al., 2012; Strain et al., 2017a) on artificial structures. It is important to point out that such increases should only be considered as enhancements of the ecological condition of the structures themselves, when evaluated against the condition of those same structures without any design modification. It would be incorrect to consider these as net enhancements in the context of the wider environment; the effect of enhancements on the wider environment (i.e. spillover effects) would be difficult to measure and has rarely been assessed (but see Morris et al., 2017; Toft et al., 2013). In most cases, the net impact of introducing artificial structures to the natural environment – enhanced or not – would still likely be negative (see discussion of impacts above). Such enhancements can, nevertheless, support myriad ecosystem services (see Table 2 in Firth et al., 2016b for summary of services supported by biodiversity associated with artificial marine structures). For example, increasing abundances of macroalgae and corals could increase primary and secondary production (Mann, 2009). Promoting high abundances of filter-feeders could improve local water quality (Hawkins et al., 1999; Layman et al., 2014). Environmental improvements can, in turn, lead to societal and economic benefits. For example, through increased food provision, fisheries yield and stock sustainability (Langhamer and Wilhelmsson, 2009; Martins et al., 2010; Scyphers et al., 2015; Toft et al., 2013; Wehkamp and Fischer, 2013), or through enhanced tourism and recreation (Airoldi et al., 2005; Firth et al., 2013a; Lamberti and Zanuttigh, 2005). Improvements in public health are also possible – both as a knock-on effect from environmental and social improvements, and on account of the wellbeing associated with direct contact with nature and knowing that the natural environment is in a healthy, well-managed condition (Clark et al., 2014).

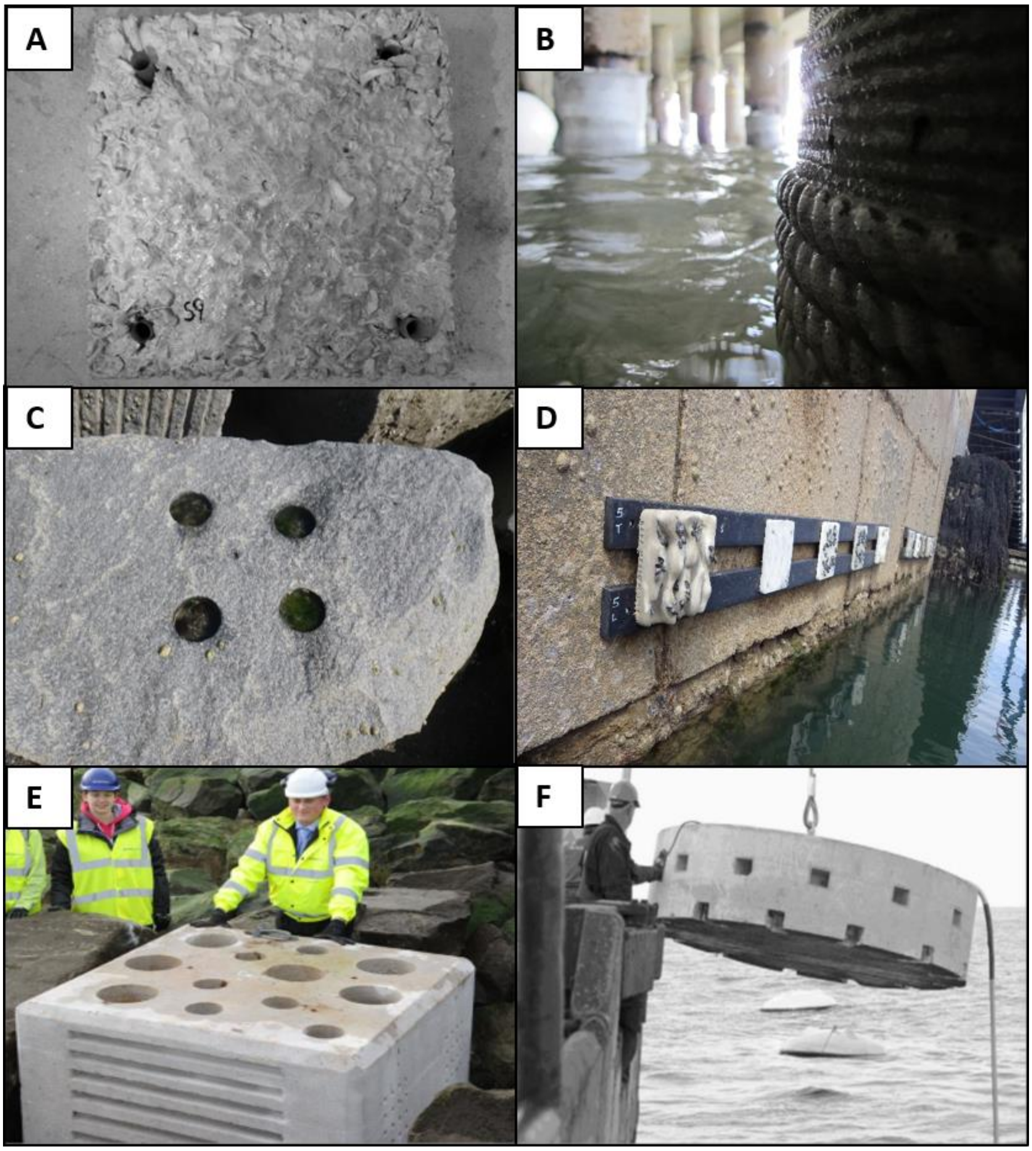

Figure 1 Examples of tried-and-tested ecological enhancement interventions for artificial marine structures: A] Textured concrete settlement tile (photo: Harry Dennis); B] ECOncrete® pier piling encasement in New York, USA (photo: Shimrit Perkol-Finkel); C] Drill-cored rock pools on a breakwater in Wales, UK (photo: Ally Evans); D] World Harbour Project mussel-seeded tiles on a seawall in Plymouth, UK (photo: Kathryn O'Shaughnessy); E] BIOBLOCK unit in a groyne in Wales, UK (photo: David Roberts); F] Perforated wave power foundation in Lysekil, Sweden (photo: Olivia Langhamer). Each of these designs has been shown experimentally to enhance biodiversity on artificial structures, i.e. there is 'proof-of-concept' evidence that they can work (see Section 1.2 for summary of the evidence base). More thorough testing is needed, however, to be able to predict their performance in wider implementation (see Section 2 for assessment of the evidence gaps).

1.3 A UK perspective on this internationally-significant issue

1.3.1 The legislative landscape and 'policy pull' in the UK

The 2010 review of the Convention on Biological Diversity (CBD) (UNEP, 2011) recognised that there has been broad international failure to meet biodiversity targets. Post-2010 targets reflect the need for urgent and proactive action to halt biodiversity loss and secure essential ecosystem services (www.cbd.int/sp/targets). In Europe, these targets have been translated into strong policy drivers to support incorporation of biodiversity enhancements in marine plans and projects. These were summarised by Naylor et al. in 2012. The EU Biodiversity Strategy (2011), for example, lays out requirements for member states to not only protect, but also to value and restore biodiversity and its associated natural capital. Targeted actions include more use of green infrastructure (Target 2, Action 6) and the No Net Loss biodiversity initiative, which champions restoration or "functional re-creation" of lost or degraded habitats (Target 2, Action 7). At the domestic level, EU member states have been required to define national targets (www.cbd.int/nbsap/targets) and develop national policies and initiatives to implement the strategy. In the UK, national targets promote a more proactive approach to planning, which is reflected in tangible policy guidance. For example, the UK's CBD targets include encouraging greener construction designs to enable development projects to enhance natural networks (Priority action 3.4). The UK Marine Policy Statement (2011) followed, advising that new marine developments should not only minimise environmental impacts, but may also provide "opportunities for building-in beneficial features for marine ecology [and] biodiversity […] as part of good design; for example, incorporating use of shelter for juvenile fish alongside proposals for structures in the sea" (Section 2.6.1.4). More recently, translation of this policy into regional planning guidelines has been even more specific. The Draft Welsh National Marine Plan (2017), for example, states that "proposals should demonstrate how they contribute to the protection, restoration and/or enhancement of marine ecosystems". It specifically recommends that "small changes to intertidal structures that allow the formation of crevices in walls or pools at low tide […] can provide additional environment for […] species that would otherwise be unable to exist there.". Although not prescribing definitive obligations, these policy documents clearly advocate multi-functional marine and coastal structures that are engineered to support enhanced biodiversity (i.e. blue-green infrastructure).

Countries all over the world are facing similar challenges with regard to marine urbanisation, and many have national policies that advocate protecting and enhancing the natural environment (see recent review by Dafforn et al., 2015b). Specific policies to encourage implementation of blue-green infrastructure, however, are lacking outside of Europe (discussed by Dafforn et al., 2015a). There is a duty on the UK, therefore, to utilise this 'policy pull' to pioneer the transition from research-driven experimentation of biodiversity enhancements into routine practice in marine planning.

1.3.2 Stakeholder support in the UK

In the absence of clear management objectives from authorities in the past, there has been uncertainty regarding *whether*, and if so, *what type of* multi-functional design enhancements would be considered desirable for marine developments (discussed by Chapman and Underwood, 2011; Firth et al., 2013a; Moschella et al., 2005). Evans et al. (2017) investigated UK stakeholder opinions regarding multi-functional design of coastal defences in 2014. In general, participants felt that the most desirable secondary benefits that could be built-in to coastal structures were ecological – prioritised over social, economic and technical ones. Specifically, provision of habitat for natural rocky shore communities, species of conservation interest, and commercially-exploited species (through provision of refuge for population conservation, rather than for fisheries benefit). There was also consensus, however, that it is more important to avoid or minimise negative impacts than it is to create and maximise positive ones. As previously discussed by Bulleri and Chapman (2010) in an international context, UK stakeholders further strongly believed that any built-in secondary benefits must be designed and evaluated in the context of the local environment and communities in question, and be tailored to the requirements of the specific target species or services desired. Nevertheless, Evans et al. (2017) found unanimous support across a number of sector groups, including academics, ecologists, engineers, local authorities, statutory bodies, conservationists and members of the public, for implementing multi-functional engineered structures (i.e. blue-green infrastructure) in place of traditional single-purpose ones.

2 Barriers and strategy towards blue-green infrastructure in the UK and beyond

Despite a wealth of proof-of-concept evidence, a clear policy pull and cross-sectoral support (all discussed in **1.2** and **1.3** above), there have been few examples of non-research-driven implementation of blue-green artificial structures in the UK (but see Naylor et al., 2017b), or indeed globally (but see Harris, 2003; Perkol-Finkel and Sella, 2016; Scyphers et al., 2015; Toft et al., 2013). So what are the barriers that remain? Evans et al. (2017) discussed some of the issues that stakeholders in the UK perceived to be barriers to ecologically-sensitive design of coastal defence structures in 2014. These barriers included cost and funding priorities, lack of evidence that biodiversity enhancements could be achieved (but see **1.2** above), lack of policy drive and legislative support (but see **1.3** above), and poor communication between sectors during planning. Based on this information, they proposed a step-wise approach to wide-scale and effective implementation of multi-functional coastal defences. We build on their suggestions here, taking a slightly wider scope to include hard artificial marine structures more generally (i.e. including port/harbour walls, energy infrastructure, recreational piers, etc., as well as coastal defences), with new insights gained through discussions with key UK stakeholders. We outline the progress that has already been made to overcoming some of the barriers identified, highlight the barriers that remain, and present a strategy to drive wider implementation of blue-green marine structures, both in the UK and globally (Figure 2). Unless otherwise stated, information presented in this section has derived from targeted discussions between 2012 and 2018 with a variety of UK policy-makers, regulators, practitioners and engineers involved in planning and decision-making for marine and coastal development projects.

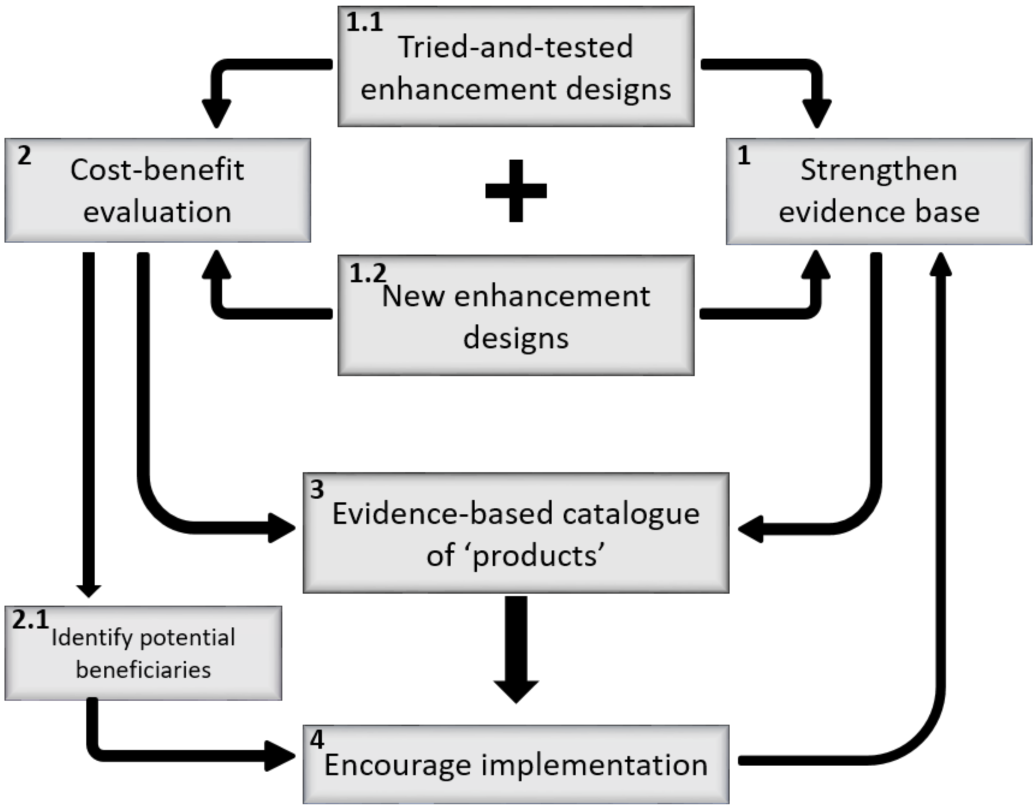

Figure 2 Schematic diagram illustrating necessary steps to effective implementation of blue-green infrastructure to maximise natural capital of artificial marine structures through design or engineering intervention. Importantly, stakeholder feedback should be sought and incorporated at each stage of the process.

Step 1: Further experimental trials to strengthen the evidence base

Although there is a wealth of proof-of-concept evidence to support methods of enhancing artificial marine structures for environmental, social and economic benefit (discussed in **1.2** above), Evans et al. (2017) found that UK stakeholders perceived a lack of evidence to be a key barrier to implementation. It appears, therefore, that there is limited awareness of and/or confidence in the available evidence amongst practitioners. We suggest it is both of these things.

Awareness of the evidence base for enhancing artificial structures is certainly growing amongst practitioners, policy-makers and regulators in the UK. This has been the product of concerted efforts by researchers to raise its profile through targeted discussions and events – facilitated by key individuals in the different sectors. As the evidence base grows, however, this approach is likely to become unsustainable and knowledge will need to be transferred in more passive ways. This does not mean reverting to the "loading dock approach" (Cash et al., 2006), however – i.e. simply publishing research in journal articles and expecting it to be used as intended. Holmes and Clark (2008) highlighted the importance of transferring scientific knowledge in a "useful form" to make it visible to and usable by practitioners (see also McNie, 2007; Weichselgartner and Kasperson, 2010). A number of industry/practice-facing documents have been produced in recent years that do translate some of the marine eco-engineering evidence base in a useful form, both from the UK (e.g. CIRIA, 2015; Naylor et al., 2017a) and elsewhere (e.g. Adams, 2002; Dyson and Yocom, 2015; NSW Government, 2012). These tend to be broad and general in scope, however, with more of a focus on eco-engineering in estuarine and vegetated systems than hard artificial marine structures. There is not yet a comprehensive detailed resource specifically to support evidence-based decision-making for enhancing biodiversity on artificial marine structures. This is discussed further in *Step 3* below.

Confidence in the evidence base for enhancing artificial structures appears to be a key barrier in the UK. Researchers have been careful not to oversell their evidence in an effort to avoid it being misused to facilitate or 'green-wash' potentially harmful developments – and rightly so. Many interventions in the literature have only been trialled experimentally in a single location at a single point in time (e.g. Chapman and Blockley, 2009; Firth et al., 2014; Perkol-Finkel and Sella, 2016). At present, therefore, there is limited confidence in the predicted effects of these interventions when applied to different development projects and environmental contexts. Even when interventions have been trialled more than once, variation in experiment design, context and observed effects means there is still uncertainty about how they would perform in different scenarios. For example, in the UK small drilled pits have been trialled several times as a way of increasing microhabitat availability in intertidal structures, with consistently positive effects on intertidal communities (Firth et al., 2014; Hall et al., 2018; Naylor et al., 2011). In different experiments, however, different effects were observed. Drilled pits (25 mm depth x 14 and 22 mm diameter, spaced 100 mm apart) installed in an offshore breakwater in the southwest of England supported 33 intertidal species, whereas pits (25 mm depth x 25 mm diameter, spacing not reported) installed in a sheltered seawall in the same region supported only 5 (Firth et al., 2014). Pits (20 mm depth x 16 mm diameter, spaced 70 mm apart) installed in coastal rock armour in the northeast of England supported 8 species, whereas the same pits in similar rock armour in the south of England supported 19 (Hall et al., 2018). The magnitudes of differences between treatments (i.e. with pits) and controls (i.e. no pits) in each case were also different. Given the variation in experimental designs and contexts of each trial, it is not possible to know whether depth, diameter, spacing, context and/or local species pool could have been responsible for the different effects observed. It would, therefore, be difficult to predict the effects of installing drilled pits in any given structure in any given location in the UK, let alone in different biogeographical regions (e.g. see Martins et al., 2010; 2016). Furthermore, the length of time after installation that different interventions have been monitored in the literature varies – from less than a year (e.g. Browne and Chapman, 2014; Strain et al., 2017a) to over two years (e.g. Firth et al., 2016a; Martins et al., 2016). The timing and duration of monitoring will almost certainly affect the evaluation of intervention success (e.g. see Firth et al., 2016a). Monitoring surveys can, in most cases, only provide snapshots along non-linear successional trajectories. Although there is no correct length of time over which interventions should be monitored, it is important that their effects are evaluated over timeframes appropriate to the envelope of natural variability of the system in which they are installed.

Unlike ecologists who are accustomed to working with uncertainty and variability in natural systems, developers, engineers and decision-makers want to balance costs and benefits with some level of confidence that predicted outcomes will be realised (Evans et al., 2017; Knights et al., 2014). It will always be difficult to predict the precise ecological outcomes of an intervention in any given development, but the more trials that are undertaken and reported (whether successful or not, e.g. see Firth et al., 2016a), the greater our understanding of their potential. There is, therefore, a need for far more thorough and controlled testing of existing interventions – to refine physical design parameters and trial them more extensively, over longer timeframes and in a variety of biogeographic and environmental contexts (Figure 2: Step 1.1; see discussion in Chapman et al., 2017). An effective way of achieving this would be for researchers to collaborate by testing the same designs in reciprocal locations – an approach the World Harbour Project (www.worldharbourproject.org) has pioneered, replicating seawall enhancement trials across 15 cities around the world. We are working to encourage this collaborative approach in the UK and Ireland through the newly-established BioMAS (Biodiversity of Marine Artificial Structures) network.

In addition to further testing of existing interventions, there also remains a need for development and testing of new enhancement designs (Figure 2: Step 1.2). Most interventions for intertidal structures have focused on providing suitable habitat for rocky shore communities, especially refuge habitat during the tide-out phase. There may be many alternative designs, yet to be tested, that can achieve this same goal more effectively and/or more economically in different situations. There may also be further opportunities to incorporate suitable habitat for target species during the tide-in phase (e.g. Morris, 2016; Toft et al., 2013), and to create space for sedimentary habitats, such as mudflats and saltmarsh, to develop amongst engineered structures (e.g. Bilkovic and Mitchell, 2013; Chapman and Underwood, 2011). There are far fewer existing tried-and-tested designs for subtidal developments than there are for intertidal ones – this is another key knowledge gap (but see Langhamer and Wilhelmsson, 2009; Perkol-Finkel and Sella, 2016; 2017; Sella and Perkol-Finkel, 2015). Techniques that work in the intertidal may not apply in the subtidal where different processes and stresses prevail. New enhancement interventions may be possible on scour protection, cable mattressing, jetty pilings and other subtidal structures that are becoming common features of the seabed and water column.

Step 2: Cost-benefit evaluation

Ultimately, existing and new evidence will need to be translated into an evolving catalogue of enhancement options (or 'products'; see *Step 3* below) to enable planners to incorporate ecologically-sensitive design in artificial marine structures. This catalogue would ideally include some evaluation of the costs and intended benefits of implementing each design (Figure 2: Step 2). Yet a considerable amount of further research is necessary to reliably assess the cost-benefits of tried-and-tested enhancement designs. To date, enhancements have been trialled primarily for experimental purposes – small-scale pilot projects, mostly designed, manufactured, installed and funded on a bespoke basis by researchers and their contracted industry partners. This has made it difficult to make direct comparisons of the costs and benefits of different enhancements, and furthermore, to predict their implementation costs and benefits when scaled-up in practice.

Costs of enhancements are not always reported in the literature, and when they are, they are not often reported in consistent comparable ways. Costs have been reported in terms of people time and equipment for DIY installation (Firth et al., 2014; Hall et al., 2018), costs charged by a contractor/manufacturer (Firth et al., 2014; Naylor et al., 2017a), percentage of overall scheme costs (Naylor et al., 2011), and additional cost compared to "business as usual" (Naylor et al., 2017a). All are useful metrics but none are directly comparable, nor can they be directly extrapolated for scaled-up implementation in practice, since economies of scale would be likely when designs are manufactured industrially. We encourage more researchers to report as much information as possible on the costs associated with their experimental trials. The costs of enhancements will become clearer as experimental designs are commercialised into products (see *Step 3* below).

There is also limited understanding of the value of potential *benefits* of enhancements, particularly non-use value such as the provision of habitat for species of conservation importance (Nunes and Van den Bergh, 2001). A number of valuation tools have been developed to quantify the benefits of biodiversity and green infrastructure (summarised in Natural England, 2013). These ideas have very recently been applied to artificial coastal and marine structures (Naylor et al., 2018). It was suggested by stakeholders in the UK that there may be opportunities to attract partnership funding to pay for interventions, if beneficiaries of enhancement outcomes could be identified (Evans et al., 2017; see also the 'Payment for Ecosystem Services' (PES) approach described by Forest Trends and The Katoomba Group, 2010) (Figure 2: Step 2.1). But again, although beneficiaries of interventions with clear socio-economic benefits (such as enhanced fisheries yield) may be readily identified, beneficiaries of non-use enhancement outcomes would be less obvious and potentially harder to attract (see barriers to the PES approach in Defra, 2011). We encourage researchers to go beyond reporting the effects of enhancement trials in terms of changes in biodiversity, to measure effects on ecosystem function and the services they support. This may lead to more effective evaluation of enhancement interventions. This is something we are aiming to do in the UK and Ireland as part of the EU-funded Ecostructure Project (www.ecostructureproject.eu).

When balancing the cost-benefit of enhancement options it is also necessary to consider the key question of *how much enhancement is enough*? This is a question we have been asked time and again by developers and regulators considering ecological enhancement of artificial structures. It will be critical to understand density-dependent effects (e.g. Martins et al., 2010) of interventions when built-in to different types of structures, in order to ensure enhancements are proportionate to the scale of developments. There may be several alternative ways of defining what constitutes adequate and appropriate enhancement in different scenarios. For example, when installing artificial habitat units (such as artificial rock pools) it may be a reasonable aim to mimic the density of that feature in nearby natural rocky habitats. If the objective was to promote target species, however, then it may be more appropriate to consider scale in terms of population size and reproductive viability. This is another major knowledge gap which needs to be addressed through carefully-designed experiments that can effectively assess the scale of enhancement effects in relation to the structure being tested on.

Step 3: Translation from experimental designs into a catalogue of products

We suggested in *Steps 1* and *2* that the evidence base for enhancing biodiversity on artificial marine structures would be usefully communicated to end-users through an evolving evidence-based catalogue of off-the-shelf enhancement products (Figure 2: Step 3). Such a tool would not only raise and sustain awareness of the growing evidence base into the future; it would also greatly support evidence-based decision-making. Products could be selected and evaluated for implementation on the basis of their predicted effects on biodiversity, their scope of application, their cost, and an indication of confidence that intended benefits would be realised.

Lessons can be learned from the enterprise and product development in terrestrial and freshwater systems. Tried-and-tested enhancements, such as insect, bird and mammal boxes, have progressed from the research and development stage to become commercialised products. These can be purchased as integrated habitat units (e.g. see www.habibat.co.uk) and built-in to developments to fulfil certain planning or licencing requirements and provide space for nature. The existing evidence base for marine enhancement interventions summarised above appears to be no less convincing than the evidence for such terrestrial and freshwater equivalents (e.g. see synopses at www.conservationevidence.com). For example, bat gantries have been widely installed in the UK to help bats cross roads safely, despite there being little evidence that they will work in all scenarios (Berthinussen and Altringham, 2012). There appears to be more caution in implementing tried-and-tested marine enhancements in the UK based on the existing evidence, which we wholly support on account of the knowledge gaps that remain (see discussion in *Steps 1* and *2* above). We stand by our call for the evidence base to be strengthened through further experimentation. Nonetheless, translating marine enhancement designs into commercialised products would enable more efficient and cost-effective implementation – both for scaled-up experimentation and for implementation in practice. It would also provide a more realistic evaluation of their cost (see *Step 2* above). There is a growing number of companies that can and do provide off-the-shelf enhancement products for marine structures, as well as bespoke designs, both in the UK (e.g. Artecology www.artecology.space, ARC Marine www.arcmarine.co.uk, Salix www.salixrw.com) and internationally (e.g. ECOncrete® www.econcretetech.com, Reef Design Lab www.reefdesignlab.com). This is a positive step towards cost-effective implementation, as long as there is adequate transparency regarding the evidence base underpinning products. There are numerous ways of creating artificial rock pool products for intertidal structures, for example, with different materials, colours, textures, shapes and sizes, incorporating cost, aesthetic and educational concerns as well as their functionality (e.g. Sydney Harbour's flowerpots: Browne and Chapman, 2014; Artecology's Vertipools: Hall, 2017; ECOncrete®'s Tide Pools: Perkol-Finkel and Sella, 2016; or a drill-coring service: Evans et al., 2016). An evidence-based catalogue would need to evidence how variation in physical design parameters would be expected to affect their ecological performance in a given context. It would also need to contain evidence of how the number, configuration and timing of installation of rock pool habitat, more generally, would be expected to affect ecological outcomes. In some scenarios, cost, aesthetics and/or educational concerns may be as or more important than ecological effects; there should nevertheless be transparency regarding the strength of evidence for what the ecological effects are likely to be if implemented in the name of biodiversity enhancement.

Through discussions with practitioners and policy-makers in the UK, we gathered some suggestions on how an evidence-based catalogue of enhancement products might look. They told us that to be effective and useful, a catalogue should be a streamlined, user-friendly (e.g. drop-down boxes and filters) online resource, which is maintained to ensure content is up-to-date and complete. Information would be layered, with high-level philosophies of interventions at the initial stage of browsing – perhaps making use of a "TripAdvisor"-style scoring system to indicate effectiveness, confidence and peer-review rating. Then by clicking through layers, users may access medium-level information about the principles and objectives, via brief synopses and bullet points. Full detailed evidence, with links to publications and researcher contact details, would be available at the deepest catalogue layer. Although practitioners may not wish to (or have time to) read the primary evidence underpinning products, knowledge that it exists and is accessible if needed is important and instils confidence in using higher-level information. Based on this description, we suggest that the Conservation Evidence project, administered by the University of Cambridge (www.conservationevidence.com), provides an existing template that is fit-for-purpose. The project follows a rigorous peer-reviewed protocol for collating and translating evidence of the efficacy of conservation interventions into printed and online synopses to support decision-making by practitioners (Sutherland et al., 2018). Conservation Evidence synopses are already available for a number of terrestrial and freshwater species and habitats, and are used by practitioners working in terrestrial and freshwater conservation in the UK. We suggest this would be an effective way of translating experimental evidence for biodiversity enhancement options on marine structures (outlined in Section 1.2) into an evidence-based catalogue of products for blue-green engineering solutions, which would be relevant to practice in the UK and globally.

Step 4: Encouraging implementation in practice

The support that Evans et al. (2017) found amongst UK stakeholders for implementing blue-green infrastructure in 2014 persists today. We are beginning to see the start of a gradual shift from research-driven experimentation to practice-driven implementation. Naylor et al. (2017b) report an example of practice-driven implementation of ecologically-sensitive design in a coastal defence scheme in the northeast of England. The implementation was driven by the local authority and regulators, who sought advice from the researchers. Although a positive step forwards, there were some limitations in terms of the enhancements delivered in the scheme, apparently on account of some of the barriers described above. "Passive" enhancement measures (i.e. "smart" positioning of rock armour units to maximise function of existing surface complexity) were eventually implemented in the rock revetment over "active" measures that were proposed (i.e. using alternative construction materials and installing retrofit rock pools). This was reportedly based on cost implications (Naylor et al., 2017b). Further examples of the shift from research-driven trials to practice-lead implementation in the UK have stemmed from experiments undertaken by Hall (2017) and Hall et al. (2018). They undertook experimental trials of rock pool units installed on a seawall in the south of England (Hall, 2017) and drilled pits and grooves in coastal armouring in the northeast of England (Hall et al., 2018). These trials provided location- and context-specific evidence needed by the developers – a ferry port and a local authority, respectively – to predict the likely effect of these enhancements if scaled-up in practice (A. Hall, pers. comms.). As a result, both enhancement designs have been implemented by the developers in practice in subsequent projects. Furthermore, the local authority was able to attract funding from The Environment Agency (a national public body) to implement and monitor the scaled-up enhancement under their commitment to create intertidal habitat as part of the government's 25 Year Environment Plan (Defra, 2018). Another local authority has subsequently approached Hall for advice with the aim of following the same approach in a large capital project in their region (A. Hall, pers. comms.). Government advisors and private developers in Wales have similarly approached Evans, Moore and Ironside about incorporating enhancements in a number of coastal and offshore development projects. Yet the majority of these discussions to date have *not* resulted in implementation – again because of the various barriers outlined in this paper. During these discussions, a new barrier has emerged that will need to be overcome in order to encourage wider implementation in practice. We have found that developers and asset owners are generally willing to facilitate research-driven enhancement trials on marine structures under their responsibility. In many cases, they are eager, even, to be part of this progressive movement. When it comes to implementing enhancements as part of their own practice, however, a recurring concern has arisen regarding liability of interventions post-construction.

Liability could relate to structural integrity (e.g. if enhancement units affect the stability of the structure or if the units themselves require repair/replacement), public safety (e.g. children climbing on units attached to seawalls), or protected species (e.g. implications for maintenance regimes if a species of conservation concern colonises a structure). The recent "Greening the Grey" report by Naylor et al. (2017a) goes some way to reassure people regarding potential impacts on structural integrity, having been reviewed by an independent engineering expert whose opinion was that the eco-engineering designs described within would be unlikely to have any effect. Nevertheless, the effect of designs on structural integrity have not been tested experimentally to find the critical size/amount of modification that could be supported by different structures without risk. There are also many other designs that were not assessed as part of this exercise. We recommend that as well as strengthening the evidence base for the ecological effects of enhancement designs (*Step 1*), experimentally testing their effect on engineering integrity would increase confidence amongst asset owners and engineers to implement them in their structures. The latter two liability issues (public safety and protected species) are legal matters that need to be clarified by regulators to give developers confidence to engage with the potential for building biodiversity enhancements into their plans.

It is important that researchers continue to take a pro-active role in communicating and encouraging implementation of current and future enhancement options to end-users (Figure 2: Step 4). We suggested above (*Step 1*) that continuous knowledge transfer through direct discussions and events may be unsustainable as the evidence base grows. We suggested, instead, that an evolving catalogue of enhancement options/products as described in *Step 3* would support more sustainable knowledge transfer ongoing. But this resource would still need to be promoted to end-users as it evolves to ensure it remains fit-for-purpose and used in practice. Amplifier organisations (also referred to as 'knowledge brokers': Naylor et al., 2012, 'interpreters': Holmes and Clark, 2008, and 'boundary organisations': McNie, 2007) have an extremely important role in connecting researchers with industry, environmental managers and policy-makers. In the UK, the independent non-profit body CIRIA (the Construction Industry Research and Information Association, www.ciria.org) has emerged as an effective intermediary group in the field of eco-engineering and green infrastructure. Their Coastal and Marine

Environmental Site Guide (CIRIA, 2015), outlining best practice guidelines for marine and coastal construction work, includes a case study of an experimental trial of artificial rock pools for marine structures (Evans et al., 2016). This promotion and endorsement has generated interest for implementation from developers and statutory bodies in the UK and internationally. CIRIA is based in the UK but operates more widely. We recommend that researchers and practitioners involved in implementing blue-green infrastructure around the world engage with them and other amplifier organisations.

3 Concluding remarks

Despite a growing evidence base, a clear policy steer, and broad cross-sectoral support, there are few examples in the UK of truly blue-green infrastructure, designed to deliver ecological and/or socio-economic secondary benefits. We are starting to witness the beginning of a gradual shift from research-driven trials to practice-driven implementation of biodiversity enhancements in artificial marine structures. Yet a number of barriers to wider routine implementation remain, most importantly: a lack of confidence in the evidence base for the likely effect of enhancements in different scenarios; the ability to balance predicted benefits with associated costs; a lack of a comprehensive evidence-based catalogue of enhancement products; and clarity regarding post-installation liability. We have presented here a strategy towards: (1) strengthening the evidence base; (2) improving clarity on the predicted costs and benefits; (3) packaging the evidence in a useful form to support evidence-based planning and decision-making; and (4) encouraging implementation as routine practice. Although we present this as a 4-step process, it is important to note that this is not a linear process and we are not starting from the beginning of Step 1. Recent reviews highlight the wealth of proof-of-concept evidence that already exists to support methods of enhancing marine structures for biodiversity (Firth et al., 2016b; Strain et al., 2017b). There is also a lot of work already happening to translate evidence in useful practice-facing documents (e.g. CIRIA, 2015; Naylor et al., 2017a), to make products available commercially and to encourage implementation (all discussed in Section 2). Crucially, researchers must focus on strengthening the evidence base to provide a broader tool kit of eco-engineering solutions and increase our confidence in predicting their effects in any given development. Specific evidence gaps are highlighted in our strategy, including: understanding the effects of enhancements under different biogeographic and environmental contexts; understanding the density-dependent effects of enhancements at the structure scale (i.e. how much enhancement is enough?); understanding enhancement options for subtidal structures; understanding the effects of enhancements on ecosystem functioning and services; and understanding the effects of enhancements on structure integrity. Generating this comprehensive and rigorous evidence base will not be easy. Scaled-up experimentation is expensive and replicate structures are not always available for experimental control at the structure scale. Collaboration between researchers to maximise research budgets and trial enhancements in reciprocal locations will help towards this goal. Ultimately, we recommend that the Conservation Evidence project provides a best-practice template for collating existing and new evidence into an evidence-based catalogue of options to support decision-making in practice.

Given the rapid proliferation of ocean sprawl globally, and the associated impacts on the natural environment (Firth et al., 2016), it is critical that ecologically-sensitive engineering designs are widely, but appropriately, incorporated into both new and existing marine developments. It is also important, however, to recognise that ecological enhancements that can be built-in to engineered structures do not constitute mitigation or compensation for the loss of natural habitats and species. They must not be used to 'green-wash' potentially harmful developments. The provision of biodiversity enhancements from multi-functional structures, therefore, should not be prioritised over more sustainable and less invasive marine planning options. Where hard structures are considered appropriate and necessary, however, opportunities should be taken to maximise natural capital as well as to minimise environmental impacts.

We hope the strategy presented here provides some much-needed clarity on what can be done to maximise the natural capital of burgeoning ocean sprawl – in the UK and elsewhere. We finally encourage researchers and practitioners from other parts of the world to publish their own perspectives on this internationally-significant issue, to share best practice and lessons learned, and to support our collective global efforts and commitments under the Convention of Biological Diversity.

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