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

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1 **Title:** From ocean sprawl to blue-green infrastructure – a UK perspective on an issue of global
2 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.

49 **1 Introduction**

50 **1.1 Ocean sprawl: proliferation and impacts**

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

66 The potential environmental impacts of artificial structures in the marine environment have become an
67 issue of great concern. Aside from the loss of and disturbance to natural habitats and species within
68 their physical footprint (“placement loss”; Heery et al., 2017), indirect local- and regional-scale
69 consequences may arise from altered coastal and oceanographic processes and altered connectivity (see
70 Bishop et al., 2017; Firth et al., 2016b; Heery et al., 2017 for reviews). Furthermore, artificial habitats
71 are known to support different and often less diverse communities of marine life, compared with natural
72 rocky habitats (Chapman and Bulleri, 2003; Firth et al., 2013b; 2016c; Glasby, 1999; Moschella et al.,
73 2005; Sheehan et al., 2013; Wilhelmsson and Malm, 2008). They have also often been seen to support
74 invasive non-native species and can act as stepping stones for species to spread into new areas (Airolidi

75 et al., 2015; Bulleri and Airoidi, 2005; Firth et al., 2013a; Mineur et al., 2012; Sammarco et al., 2004).
76 In light of these potential negative environmental implications of ocean sprawl, and to satisfy
77 international conservation commitments, it is increasingly important to incorporate ecologically-
78 sensitive design into marine and coastal developments.

79 The concepts of ecological engineering (or eco-engineering) and green infrastructure are not new
80 (Benedict and McMahon, 2002; Bergen et al., 2001). In terrestrial and freshwater systems, incorporating
81 environmental enhancements and natural capital (i.e. the assets from which ecosystem services are
82 derived) into engineered developments is well established. For example, green roofs (Brenneisen,
83 2006), motorway wildlife passages (Berthinussen and Altringham, 2012; Mata et al., 2008), coir rolls
84 on river walls (Hoggart and Francis, 2014) and bird/mammal nest boxes (Arnett and Hayes, 2000) have
85 all been widely implemented, allowing some evaluation of their efficacy in practice. There has also
86 been research into the optimal design of culverts and dams for fish migration (Newbold et al., 2014).
87 Consequently, the principles of eco-engineering and green infrastructure are embedded in urban
88 planning practice for terrestrial and freshwater development projects and restoration initiatives (e.g.
89 Brenneisen, 2006; Williams, 2010). In marine planning, however, eco-engineering of *blue-green*
90 infrastructure remains an emerging concept. Although there has been an explosion of interest in
91 applying the concepts of green infrastructure to artificial structures in the marine environment since the
92 early 2000s, especially amongst researchers trialling marine eco-engineering techniques (see Strain et
93 al., 2017b), it is not yet implemented as routine practice.

94 In this note, we consider the potential for proliferating ocean sprawl to be eco-engineered into blue-
95 green infrastructure. Specifically, we consider this in terms of enhancing biodiversity on artificial
96 marine and coastal structures (such as sea defences, port/harbour walls, energy infrastructure and others
97 listed above). We exclude artificial reefs from our considerations and focus instead on structures that
98 are necessary and appropriate for some primary function other than their ecological effects. We briefly
99 outline the evidence base for enhancing biodiversity on artificial marine structures. We then provide a
100 UK-perspective on this internationally-significant issue, emphasising that, despite a clear policy
101 recommendation and strong cross-sectoral stakeholder support, there are still few examples of truly and

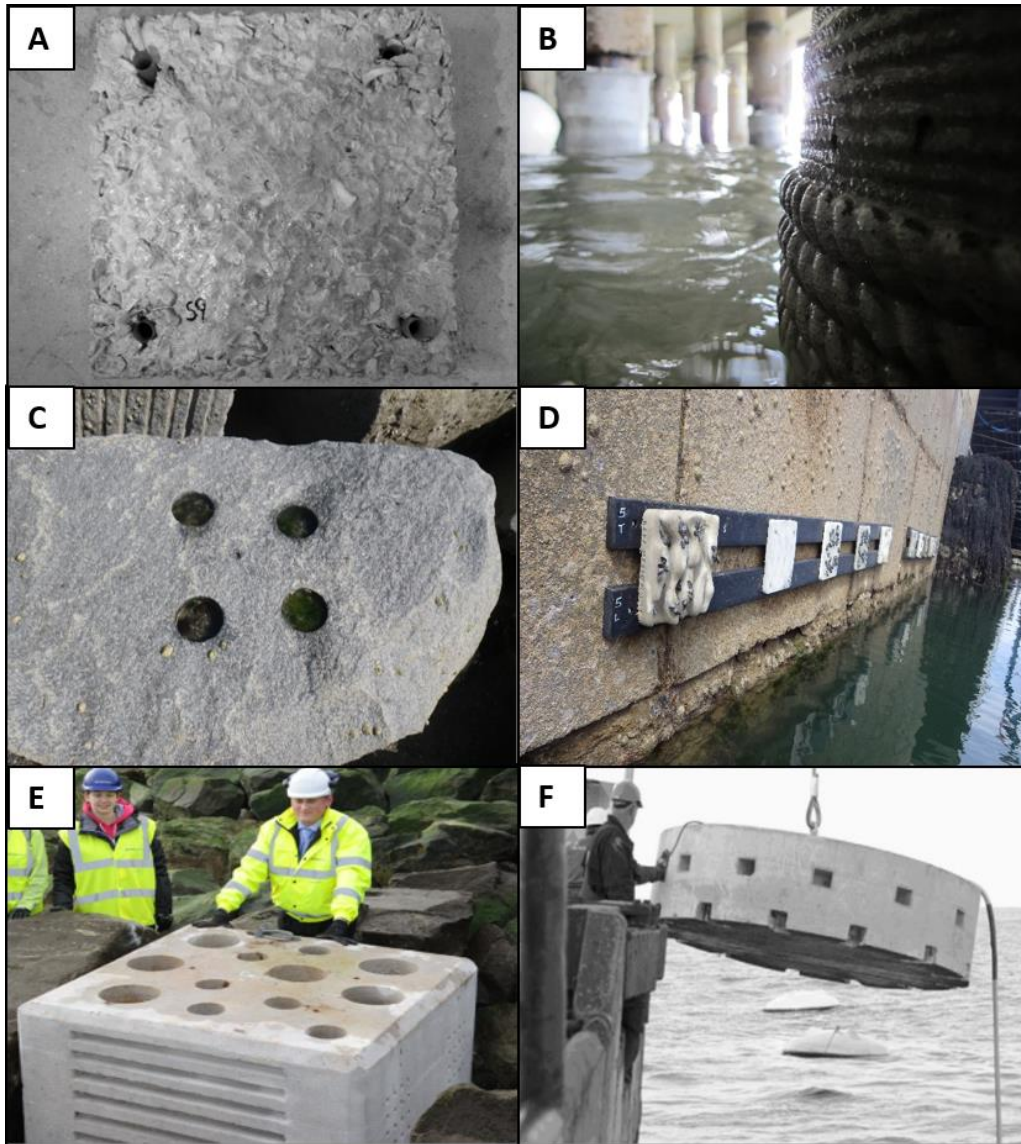
102 purposefully-designed blue-green infrastructure. We discuss what the barriers to achieving this are and
103 propose a strategy towards effective implementation, providing valuable insight to other nations
104 working towards this same goal.

105 **1.2 Evidence base for enhancing biodiversity on artificial marine structures**

106 Much progress has been made in recent years in identifying potential interventions for enhancing
107 biodiversity and natural capital on artificial structures in the marine environment (see Strain et al., 2017a
108 for review). Diversity deficits relative to natural rocky habitats have often been attributed to low
109 topographic complexity of structures (Aguilera et al., 2014; Chapman, 2003; Firth et al., 2013b; 2016c;
110 Wilhelmsson and Malm, 2008), particularly a lack of water-retaining features in intertidal structures.
111 Many marine eco-engineering trials have, therefore, attempted to enhance biodiversity on structures
112 through increasing their habitat complexity (see Figure 1 for examples). This has been tested at the
113 micro (μm - mm) scale by creating textured surfaces (Coombes et al., 2015; Perkol-Finkel and Sella,
114 2016; Sella and Perkol-Finkel, 2015), at the small-to-medium (mm - cm) scale by adding artificial pits,
115 crevices and pools (Browne and Chapman, 2014; Chapman and Blockley, 2009; Evans et al., 2016;
116 Firth et al., 2014; 2016a; Hall et al., 2018; Martins et al., 2010; Morris et al., 2017), and at the macro
117 (cm - m) scale by incorporating pre-cast habitat units into structure designs (Firth et al., 2014; Langhamer
118 and Wilhelmsson, 2009; Perkol-Finkel et al., 2017; Perkol-Finkel and Sella, 2016; Scyphers et al., 2015;
119 Sella and Perkol-Finkel, 2015). Researchers have also investigated alternative construction materials to
120 improve the habitat quality of structures and/or to reduce their environmental footprints (Collins et al.,
121 2015; Cuadrado et al., 2015; Dennis et al., 2017; McManus et al., 2017; Perkol-Finkel and Sella, 2014;
122 Sella and Perkol-Finkel, 2015). Others have trialled transplanting target species directly onto structures
123 to support threatened populations (Ng et al., 2015; Perkol-Finkel et al., 2012).

124 The enhancements that can be achieved through the design modifications described above include
125 increased biodiversity (Browne and Chapman, 2014; Chapman and Blockley, 2009; Dennis et al., 2017;
126 Evans et al., 2016; Firth et al., 2014; Loke and Todd, 2016; Perkol-Finkel and Sella, 2016; Sella and
127 Perkol-Finkel, 2015) and/or increased abundances of target species (Langhamer and Wilhelmsson,

128 2009; Martins et al., 2010; Ng et al., 2015; Perkol-Finkel et al., 2012; Strain et al., 2017a) on artificial
129 structures. It is important to point out that such increases should only be considered as enhancements
130 of the ecological condition of the structures themselves, when evaluated against the condition of those
131 same structures without any design modification. It would be incorrect to consider these as net
132 enhancements in the context of the wider environment; the effect of enhancements on the wider
133 environment (i.e. spillover effects) would be difficult to measure and has rarely been assessed (but see
134 Morris et al., 2017; Toft et al., 2013). In most cases, the net impact of introducing artificial structures
135 to the natural environment – enhanced or not – would still likely be negative (see discussion of impacts
136 above). Such enhancements can, nevertheless, support myriad ecosystem services (see Table 2 in Firth
137 et al., 2016b for summary of services supported by biodiversity associated with artificial marine
138 structures). For example, increasing abundances of macroalgae and corals could increase primary and
139 secondary production (Mann, 2009). Promoting high abundances of filter-feeders could improve local
140 water quality (Hawkins et al., 1999; Layman et al., 2014). Environmental improvements can, in turn,
141 lead to societal and economic benefits. For example, through increased food provision, fisheries yield
142 and stock sustainability (Langhamer and Wilhelmsson, 2009; Martins et al., 2010; Scyphers et al., 2015;
143 Toft et al., 2013; Wehkamp and Fischer, 2013), or through enhanced tourism and recreation (Airoldi et
144 al., 2005; Firth et al., 2013a; Lamberti and Zanuttigh, 2005). Improvements in public health are also
145 possible – both as a knock-on effect from environmental and social improvements, and on account of
146 the wellbeing associated with direct contact with nature and knowing that the natural environment is in
147 a healthy, well-managed condition (Clark et al., 2014).



148

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

159 **1.3 A UK perspective on this internationally-significant issue**

160 **1.3.1 The legislative landscape and ‘policy pull’ in the UK**

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

185 these policy documents clearly advocate multi-functional marine and coastal structures that are
186 engineered to support enhanced biodiversity (i.e. blue-green infrastructure).

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

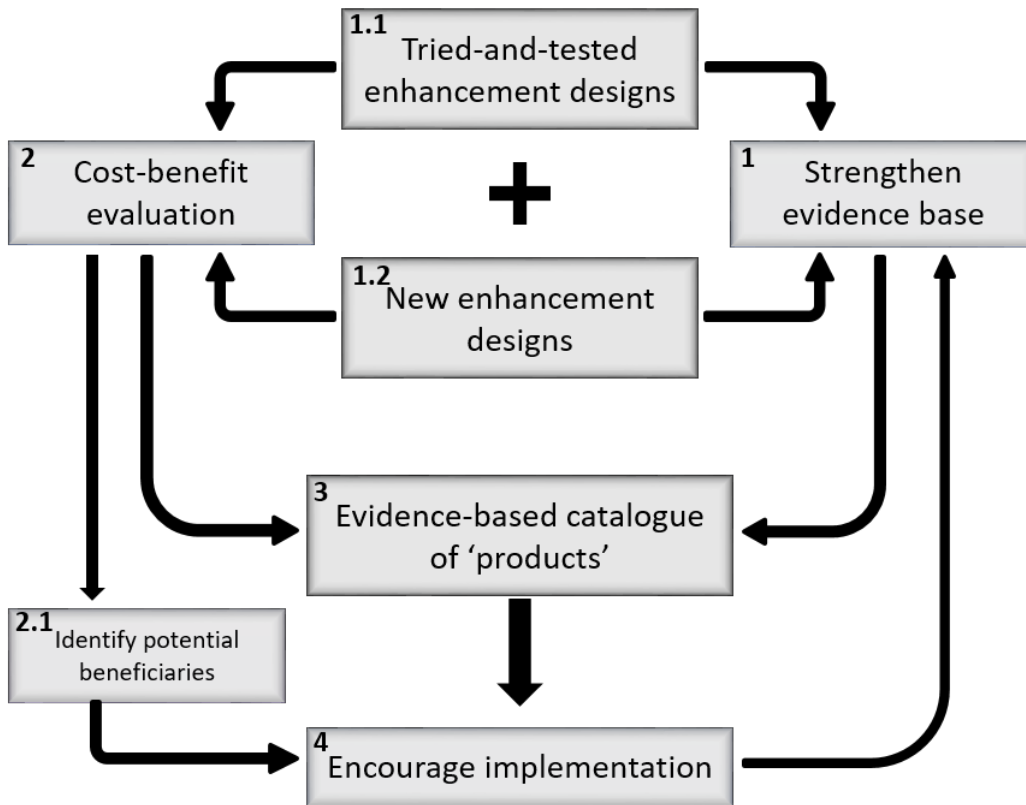
193 **1.3.2 Stakeholder support in the UK**

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

211 **2 Barriers and strategy towards blue-green infrastructure in the UK and beyond**

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

231



232

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

237

238 *Step 1: Further experimental trials to strengthen the evidence base*

239 Although there is a wealth of proof-of-concept evidence to support methods of enhancing artificial
 240 marine structures for environmental, social and economic benefit (discussed in 1.2 above), Evans et al.
 241 (2017) found that UK stakeholders perceived a lack of evidence to be a key barrier to implementation.
 242 It appears, therefore, that there is limited awareness of and/or confidence in the available evidence
 243 amongst practitioners. We suggest it is both of these things.

244 *Awareness of* the evidence base for enhancing artificial structures is certainly growing amongst
 245 practitioners, policy-makers and regulators in the UK. This has been the product of concerted efforts by
 246 researchers to raise its profile through targeted discussions and events – facilitated by key individuals

247 in the different sectors. As the evidence base grows, however, this approach is likely to become
248 unsustainable and knowledge will need to be transferred in more passive ways. This does not mean
249 reverting to the “loading dock approach” (Cash et al., 2006), however – i.e. simply publishing research
250 in journal articles and expecting it to be used as intended. Holmes and Clark (2008) highlighted the
251 importance of transferring scientific knowledge in a “useful form” to make it visible to and usable by
252 practitioners (see also McNie, 2007; Weichselgartner and Kasperson, 2010). A number of
253 industry/practice-facing documents have been produced in recent years that do translate some of the
254 marine eco-engineering evidence base in a useful form, both from the UK (e.g. CIRIA, 2015; Naylor et
255 al., 2017a) and elsewhere (e.g. Adams, 2002; Dyson and Yocom, 2015; NSW Government, 2012).
256 These tend to be broad and general in scope, however, with more of a focus on eco-engineering in
257 estuarine and vegetated systems than hard artificial marine structures. There is not yet a comprehensive
258 detailed resource specifically to support evidence-based decision-making for enhancing biodiversity on
259 artificial marine structures. This is discussed further in *Step 3* below.

260 *Confidence* in the evidence base for enhancing artificial structures appears to be a key barrier in the
261 UK. Researchers have been careful not to oversell their evidence in an effort to avoid it being misused
262 to facilitate or ‘green-wash’ potentially harmful developments – and rightly so. Many interventions in
263 the literature have only been trialled experimentally in a single location at a single point in time (e.g.
264 Chapman and Blockley, 2009; Firth et al., 2014; Perkol-Finkel and Sella, 2016). At present, therefore,
265 there is limited confidence in the predicted effects of these interventions when applied to different
266 development projects and environmental contexts. Even when interventions have been trialled more
267 than once, variation in experiment design, context and observed effects means there is still uncertainty
268 about how they would perform in different scenarios. For example, in the UK small drilled pits have
269 been trialled several times as a way of increasing microhabitat availability in intertidal structures, with
270 consistently positive effects on intertidal communities (Firth et al., 2014; Hall et al., 2018; Naylor et
271 al., 2011). In different experiments, however, different effects were observed. Drilled pits (25 mm depth
272 x 14 and 22 mm diameter, spaced 100 mm apart) installed in an offshore breakwater in the southwest
273 of England supported 33 intertidal species, whereas pits (25 mm depth x 25 mm diameter, spacing not

274 reported) installed in a sheltered seawall in the same region supported only 5 (Firth et al., 2014). Pits
275 (20 mm depth x 16 mm diameter, spaced 70 mm apart) installed in coastal rock armour in the northeast
276 of England supported 8 species, whereas the same pits in similar rock armour in the south of England
277 supported 19 (Hall et al., 2018). The magnitudes of differences between treatments (i.e. with pits) and
278 controls (i.e. no pits) in each case were also different. Given the variation in experimental designs and
279 contexts of each trial, it is not possible to know whether depth, diameter, spacing, context and/or local
280 species pool could have been responsible for the different effects observed. It would, therefore, be
281 difficult to predict the effects of installing drilled pits in any given structure in any given location in the
282 UK, let alone in different biogeographical regions (e.g. see Martins et al., 2010; 2016). Furthermore,
283 the length of time after installation that different interventions have been monitored in the literature
284 varies – from less than a year (e.g. Browne and Chapman, 2014; Strain et al., 2017a) to over two years
285 (e.g. Firth et al., 2016a; Martins et al., 2016). The timing and duration of monitoring will almost
286 certainly affect the evaluation of intervention success (e.g. see Firth et al., 2016a). Monitoring surveys
287 can, in most cases, only provide snapshots along non-linear successional trajectories. Although there is
288 no correct length of time over which interventions should be monitored, it is important that their effects
289 are evaluated over timeframes appropriate to the envelope of natural variability of the system in which
290 they are installed.

291 Unlike ecologists who are accustomed to working with uncertainty and variability in natural systems,
292 developers, engineers and decision-makers want to balance costs and benefits with some level of
293 confidence that predicted outcomes will be realised (Evans et al., 2017; Knights et al., 2014). It will
294 always be difficult to predict the precise ecological outcomes of an intervention in any given
295 development, but the more trials that are undertaken and reported (whether successful or not, e.g. see
296 Firth et al., 2016a), the greater our understanding of their potential. There is, therefore, a need for far
297 more thorough and controlled testing of existing interventions – to refine physical design parameters
298 and trial them more extensively, over longer timeframes and in a variety of biogeographic and
299 environmental contexts (Figure 2: Step 1.1; see discussion in Chapman et al., 2017). An effective way
300 of achieving this would be for researchers to collaborate by testing the same designs in reciprocal

301 locations – an approach the World Harbour Project (www.worldharbourproject.org) has pioneered,
302 replicating seawall enhancement trials across 15 cities around the world. We are working to encourage
303 this collaborative approach in the UK and Ireland through the newly-established BioMAS (Biodiversity
304 of Marine Artificial Structures) network.

305 In addition to further testing of existing interventions, there also remains a need for development and
306 testing of new enhancement designs (Figure 2: Step 1.2). Most interventions for intertidal structures
307 have focused on providing suitable habitat for rocky shore communities, especially refuge habitat
308 during the tide-out phase. There may be many alternative designs, yet to be tested, that can achieve this
309 same goal more effectively and/or more economically in different situations. There may also be further
310 opportunities to incorporate suitable habitat for target species during the tide-in phase (e.g. Morris,
311 2016; Toft et al., 2013), and to create space for sedimentary habitats, such as mudflats and saltmarsh,
312 to develop amongst engineered structures (e.g. Bilkovic and Mitchell, 2013; Chapman and Underwood,
313 2011). There are far fewer existing tried-and-tested designs for subtidal developments than there are for
314 intertidal ones – this is another key knowledge gap (but see Langhamer and Wilhelmsson, 2009; Perkol-
315 Finkel and Sella, 2016; 2017; Sella and Perkol-Finkel, 2015). Techniques that work in the intertidal
316 may not apply in the subtidal where different processes and stresses prevail. New enhancement
317 interventions may be possible on scour protection, cable mattresses, jetty pilings and other subtidal
318 structures that are becoming common features of the seabed and water column.

319 *Step 2: Cost-benefit evaluation*

320 Ultimately, existing and new evidence will need to be translated into an evolving catalogue of
321 enhancement options (or ‘products’; see *Step 3* below) to enable planners to incorporate ecologically-
322 sensitive design in artificial marine structures. This catalogue would ideally include some evaluation of
323 the costs and intended benefits of implementing each design (Figure 2: Step 2). Yet a considerable
324 amount of further research is necessary to reliably assess the cost-benefits of tried-and-tested
325 enhancement designs. To date, enhancements have been trialled primarily for experimental purposes –
326 small-scale pilot projects, mostly designed, manufactured, installed and funded on a bespoke basis by

327 researchers and their contracted industry partners. This has made it difficult to make direct comparisons
328 of the costs and benefits of different enhancements, and furthermore, to predict their implementation
329 costs and benefits when scaled-up in practice.

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

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

354 something we are aiming to do in the UK and Ireland as part of the EU-funded Ecostructure Project
355 (www.ecostructureproject.eu).

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

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

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

376 Lessons can be learned from the enterprise and product development in terrestrial and freshwater
377 systems. Tried-and-tested enhancements, such as insect, bird and mammal boxes, have progressed from
378 the research and development stage to become commercialised products. These can be purchased as
379 integrated habitat units (e.g. see www.habibat.co.uk) and built-in to developments to fulfil certain

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

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

429 *Step 4: Encouraging implementation in practice*

430 The support that Evans et al. (2017) found amongst UK stakeholders for implementing blue-green
431 infrastructure in 2014 persists today. We are beginning to see the start of a gradual shift from research-
432 driven experimentation to practice-driven implementation. Naylor et al. (2017b) report an example of
433 practice-driven implementation of ecologically-sensitive design in a coastal defence scheme in the
434 northeast of England. The implementation was driven by the local authority and regulators, who sought

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

462 Liability could relate to structural integrity (e.g. if enhancement units affect the stability of the structure
463 or if the units themselves require repair/replacement), public safety (e.g. children climbing on units
464 attached to seawalls), or protected species (e.g. implications for maintenance regimes if a species of
465 conservation concern colonises a structure). The recent “Greening the Grey” report by Naylor et al.
466 (2017a) goes some way to reassure people regarding potential impacts on structural integrity, having
467 been reviewed by an independent engineering expert whose opinion was that the eco-engineering
468 designs described within would be unlikely to have any effect. Nevertheless, the effect of designs on
469 structural integrity have not been tested experimentally to find the critical size/amount of modification
470 that could be supported by different structures without risk. There are also many other designs that were
471 not assessed as part of this exercise. We recommend that as well as strengthening the evidence base for
472 the ecological effects of enhancement designs (*Step 1*), experimentally testing their effect on
473 engineering integrity would increase confidence amongst asset owners and engineers to implement
474 them in their structures. The latter two liability issues (public safety and protected species) are legal
475 matters that need to be clarified by regulators to give developers confidence to engage with the potential
476 for building biodiversity enhancements into their plans.

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

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

496 **3 Concluding remarks**

497 Despite a growing evidence base, a clear policy steer, and broad cross-sectoral support, there are few
498 examples in the UK of truly blue-green infrastructure, designed to deliver ecological and/or socio-
499 economic secondary benefits. We are starting to witness the beginning of a gradual shift from research-
500 driven trials to practice-driven implementation of biodiversity enhancements in artificial marine
501 structures. Yet a number of barriers to wider routine implementation remain, most importantly: a lack
502 of confidence in the evidence base for the likely effect of enhancements in different scenarios; the ability
503 to balance predicted benefits with associated costs; a lack of a comprehensive evidence-based catalogue
504 of enhancement products; and clarity regarding post-installation liability. We have presented here a
505 strategy towards: (1) strengthening the evidence base; (2) improving clarity on the predicted costs and
506 benefits; (3) packaging the evidence in a useful form to support evidence-based planning and decision-
507 making; and (4) encouraging implementation as routine practice. Although we present this as a 4-step
508 process, it is important to note that this is not a linear process and we are not starting from the beginning
509 of Step 1. Recent reviews highlight the wealth of proof-of-concept evidence that already exists to
510 support methods of enhancing marine structures for biodiversity (Firth et al., 2016b; Strain et al.,
511 2017b). There is also a lot of work already happening to translate evidence in useful practice-facing
512 documents (e.g. CIRIA, 2015; Naylor et al., 2017a), to make products available commercially and to
513 encourage implementation (all discussed in Section 2). Crucially, researchers must focus on
514 strengthening the evidence base to provide a broader tool kit of eco-engineering solutions and increase
515 our confidence in predicting their effects in any given development. Specific evidence gaps are

516 highlighted in our strategy, including: understanding the effects of enhancements under different
517 biogeographic and environmental contexts; understanding the density-dependent effects of
518 enhancements at the structure scale (i.e. how much enhancement is enough?); understanding
519 enhancement options for subtidal structures; understanding the effects of enhancements on ecosystem
520 functioning and services; and understanding the effects of enhancements on structure integrity.
521 Generating this comprehensive and rigorous evidence base will not be easy. Scaled-up experimentation
522 is expensive and replicate structures are not always available for experimental control at the structure
523 scale. Collaboration between researchers to maximise research budgets and trial enhancements in
524 reciprocal locations will help towards this goal. Ultimately, we recommend that the Conservation
525 Evidence project provides a best-practice template for collating existing and new evidence into an
526 evidence-based catalogue of options to support decision-making in practice.

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

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

541

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