

1 Sunken worlds: The past and future of human-made reefs in marine
2 conservation
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20 **Abstract:**

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Structures submerged in the sea by humans over millennia provide hard and longstanding evidence of anthropogenic influence in the marine environment. Many of these human-made reefs (HMRs) may provide opportunities for conservation despite having been created for different purposes such as fishing or tourism. In the midst of controversy around the costs and benefits of HMRs, a broad analysis of biodiversity and social values is necessary to assess conservation potential. This requires: (1) reframing HMRs as social-ecological systems, moving beyond comparisons with “natural” coral or rocky reefs to consider their roles as ecosystems in their own right, (2) creating frameworks to track their type, number, size, units, location, characteristics, origins, social uses and associated biodiversity locally and worldwide, and (3) applying systematic assessment of conservation benefits in relation to stated conservation intentions. This integrative approach can catalyse learning, identify conservation opportunities, and inform positive management of HMRs into the future.

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38 **A rising tide**

39 Human influence reaches into all ecosystems, and is increasing globally in the marine
40 realm (Vitousek et al. 1997; Halpern et al. 2015). By one estimate, only about 13% of the
41 ocean remains “wild” or under low impact from factors such as climate change,
42 overfishing, pollution and benthic structures (Jones et al. 2018). In a conservation
43 context, human activities have historically been considered undesirable; however, some
44 have proposed an alternate framing of a two-way, multi-layered and dynamic
45 relationship between “people and nature” (Mace 2014). Additionally, some
46 conservationists suggest the prevailing sense of “doom and gloom” around human
47 activities may stymie practical action to study them or transform them into conservation
48 opportunities (Duarte et al. 2015; Balmford & Knowlton 2017).

49 The creation of human-made reefs (HMRs) – which we define as hard, persistent
50 structures placed intentionally or accidentally in the ocean by humans – has received
51 limited attention in the conservation sphere. These diverse structures result from
52 human activities such as fishing (Turner et al. 1969; Headley 2017), shipping (Simon et
53 al. 2013), oil and gas extraction (Claisse et al. 2014), tourism (Stolk et al. 2007; Oh et al.
54 2008; Kirkbride-Smith et al. 2013), conservation (Seaman 2007; Dupont 2008) and
55 coastal management including storm protection, erosion reduction (Silva et al. 2016)
56 and the creation of surf beaches (Rendle 2015). One study mapping global human
57 impacts on the marine environment estimated anthropogenic “benthic structures” in
58 coastal regions affect an area of 300,000 square kilometres (Halpern et al. 2008), the

approximate size of Italy. A process of “marine urbanisation” is said to be underway (Dafforn et al. 2015). Though HMRs have been called “tremendously popular” (Bohnsack & Sutherland 1985) and the claim has long been made that they are “increasing exponentially” (Schuhmacher & Schillak 1994), there is currently no centralised way of tracking their spread, leading to calls for comprehensive databases (Bohnsack & Sutherland 1985; Seaman 2007). In cases where HMRs have been quantified on a global level, analyses have generally been limited to one type of structure emerging from a specific industry, such as oil and gas (Halpern et al. 2008; Jones et al. 2018).

Nonetheless, there are indications that HMRs of diverse origins are present in large numbers and proliferating rapidly. By 2007, the Reef Ball Foundation claimed over half a million of its patented concrete structures had been deployed underwater in over 59 countries (Naik 2007). In a single Mexican bay, Headley (2017) estimates that 27,152 artificial shelters have been created for lobster fishing. UNESCO estimates three million shipwrecks lie on the ocean floor, some of which may be thousands of years old (UNESCO 2009). Establishment of HMRs in French coastal waters has accelerated; of the 93,982 m³ of material deployed since 1968, 50% was deployed since 2000 (Tessier et al. 2015). The Florida Fish and Wildlife Conservation Commission has distributed over \$26 million dollars in funds for public projects and estimates 70-100 sites are built annually off the Florida coast, adding to the 3,330 established since the 1940s (FWCC 2018). Given their diverse origins, HMRs can vary greatly in size, number of units, reasons for creation, and materials; however, considering them as a group can illuminate the scale at which humans are transforming marine ecosystems.

Ecosystem services provided by HMRs are likely to be both substantial and underestimated. For example, an evaluation of a five-county area in North Florida estimated the value of spending on goods and services related to the use of HMRs at \$414 million dollars in 1997-1998 (Bell et al. 1998). Scuba diving on HMRs can generate substantial tourism revenue – for example, Oh et al. (2008) estimated willingness to pay for scuba diving on HMRs at \$101 per trip – while potentially diverting pressure away from natural coral or rocky reefs. Following the deployment of a decommissioned ship as an AR in Florida, Leeworthy et al. (2006) tracked a 3.7% overall increase in local dive charter business, which bolstered local income by \$961,800 and created 68 new jobs. As business grew, pressure on surrounding natural reefs was alleviated; the total number of AR users grew by 118.1% while total users on natural reefs declined by 13.7%. These figures only begin to evaluate economic benefits that could accrue from HMRs; further measures of provisioning, regulating and cultural services are necessary (Schut 2013). In particular, cultural values of HMRs may be considerable and unique. For example, the cultural value of shipwrecks includes providing clues into forgotten aspects of human history and contributing to a sense of cultural identity (Krumholz & Brennan 2015). The process of constructing HMRs can also create opportunities for community bonding and participation (Trialfhianty & Suadi 2017) or unique avenues for education about the marine environment.

Claims of conservation benefit have arisen for a wide variety of HMRs, which commonly state or imply that the provision of new substrate for marine life to grow, take shelter and feed on leads to the creation of productive new ecosystems (Lee et al.

2018) or that the structures can relieve pressure on nearby coral reefs (Leeworthy et al. 2006). These claims have related to accidental shipwrecks (James & Hibbert 1994; Krumholz & Brennan 2015), rock piles (Fox et al. 2019), purposefully sunk naval ships or subway cars (Leeworthy et al. 2006), underwater sculptures referred to as “the art of conservation” (MUSA 2016), decommissioned oil rigs (Claisse et al. 2014), coastal engineering structures (Silva et al. 2016), industrial mitigation projects (Dupont 2008) and even piles of old tyres (Allen 2007). In some cases, conservation is explicitly emphasised to justify creation of structures or halt their scheduled removal from the marine environment (Olsen 2016; Fowler et al. 2018). However, beyond a few high-profile cases of success or failure, these conservation claims have not been widely tracked or questioned. Given indications that HMRs could be altering marine ecosystems on a massive scale, it is imperative that critical attention is paid to their conservation impacts. While scientific interest in HMRs is rising, the number of relevant papers in the conservation literature remains low (Figure 1).

A controversial history

A searing debate over the purposeful use of HMRs in fisheries and marine conservation has risen and fallen for almost half a century, spanning scientific, regulatory, and even moral realms (Meier et al. 1989; Fronda & French 2015). In fisheries and ecology, this debate has often culminated in the question of “attraction versus production” – whether HMRs contribute to increasing overall marine biomass or

124 biodiversity, or simply aggregate it by drawing it away from natural reefs (Bohnsack &
125 Sutherland 1985). The answer to this question is difficult to determine in most cases,
126 and is unlikely to be binary (Pickering & Whitmarsh 1997). Attraction has almost
127 universally been posited as a harmful process which makes fish more vulnerable to
128 exploitation, but recent work indicates some attraction could be beneficial for some
129 species as dispersion could make fish harder to catch (Smith et al. 2015). Regardless of
130 whether they are diverting biomass from natural structures or increasing it overall,
131 HMRs are capable of sheltering high levels of biomass and biodiversity (Turner et al.
132 1969; Claisse et al. 2014), though they may vary in trophic structure from natural reefs
133 (Simon et al. 2013). Another concern regards the facilitation of invasion by invasive or
134 non-native species, as new hard substrate provided by HMRs could provide footholds
135 for establishment (Simkanin et al. 2012). Finally, the assumption that new hard
136 substrate is preferable to the ecosystems it can replace or transform – such as soft
137 sediment communities, which can be highly biodiverse and play a crucial role in nutrient
138 cycling – has been challenged (Heery et al. 2017).

139 In a wider sense, the debate around when, why and by whom HMRs should be
140 created is deeply divided, with HMRs often framed as either hopeful innovations or
141 intrusions on a natural order. On the one side there are warnings of a potential “ocean
142 junk pile whose major value has been as a promotional gimmick” (Turner et al. 1969), a
143 fisheries management tool that has been “grossly misused” by unqualified people
144 (Meier et al. 1989) and “slapping the seas with the big almighty hand of humankind and
145 damaging yet another part of the earth” (Fronza & French 2015). Meanwhile,

146 proponents of HMRs have spoken of “bastions for marine life” (Fronza & French 2015),
147 “one of the richest marine ecosystems on the planet” (Olsen 2016), sites which are
148 “among the most productive marine fish habitats globally” (Claisse et al. 2014) and
149 “tremendous potential for habitat enhancement” (Bohnsack & Sutherland 1985). Many
150 arguments in this debate are implicitly based on the perception that HMRs are relatively
151 recent additions to marine ecosystems.

152 However, the practice of building or sinking structures in the sea can be observed
153 over thousands of years across a wide range of cultures, particularly with regard to
154 fishing and aquaculture. In Mexico, hook-shaped structures made of stone are believed
155 to have been used by pre-Hispanic Mayan fishers to herd schools of fish and manatees
156 (Garduño Argueta & Caballero Pinzón 1998). Intertidal rock walls and terraces in British
157 Columbia, built to increase clam production, may have been in use for up to 5000 years
158 (Groesbeck et al. 2014). Ancient Hawaiian marine fish ponds were built 1500-1800 years
159 ago with stones, with walls extending over 100m in length (Costa-Pierce 1987). In
160 traditional Palauan fishing, permanent stone structures were used to trap fish with the
161 tides (Johannes 1981). However, the long history of HMRs has not been sufficiently
162 acknowledged in the scientific literature; many studies continue to cite the first
163 emergence of these structures in Japan in the 17th or 18th century (Bohnsack &
164 Sutherland 1985; Lee et al. 2018).

165 Once HMRs have been deployed, there is often a lack of clarity around responsibility
166 for their impacts, and this has been complicated by the idea that structures can benefit

167 marine life. “Rigs-to-reefs” programmes present a clear example, affecting the fate of
168 over 7,500 oil and gas platforms worldwide, for which complete removal is currently
169 standard practice (Techera & Chandler 2015; Fowler et al. 2018). Costs for removal
170 worldwide have been estimated at \$210 billion dollars, and some sites have been
171 identified as highly productive for marine life, leading to suggestions for partial removal
172 and monitoring on a case-by-case basis (Claisse et al. 2014; Fowler et al. 2018).
173 Generally, while conservation concerns initially revolved around the insertion of new
174 structures, they have now expanded to consider the risks of removing habitat and of
175 maintaining structures with potentially negative impacts (Allen 2007). This opens up
176 crucial questions around best practice for managing HMRs once they exist, underscoring
177 the importance of monitoring and clear metrics for conservation benefit.

178

179 **What’s in a name?**

180 In order to understand the global prevalence of HMRs, and their potential positive
181 and negative outcomes, there is a need for clarity around terminology. Several terms
182 have emerged from different disciplines, including “artificial reefs”, “human-made
183 reefs”, “anthropogenic reefs”, “underwater structures” and “anthropogenic structures
184 at sea”, some of which may bias perceptions and assessment of HMRs.

185 Though the word “reef” is now most commonly associated with ecosystems based
186 around coral or rocks, its origins and definitions reveal a focus on hard substrate in the
187 ocean, regardless of composition. The Oxford English Dictionary (2009) defines reef as

188 “a ridge or bank of rock, sand, shingle, etc., lying just above or just below the surface of
189 the sea or another body of water, usually in such a way as to pose a hazard to shipping”.
190 In English, the word is believed to be derived from the Old Norse *rif*, simply meaning
191 “ridge in the sea” (Dögg Friðriksdóttir 2014). For centuries, reefs were primarily
192 associated with a risk of shipwreck; for example, the term *abrolhos*, marking a reef on a
193 Portuguese 16th century map, is believed to be derived from the command to sailors to
194 “keep your eyes open!” (Bowen 2015 p. 3).

195 Though the term “artificial reef” is most widespread in the scientific literature and
196 media, Pitcher & Seaman Jr (2000) recommend “human-made reef” since use of the
197 word “artificial” can imply HMRs are an inferior substitute for “natural” reefs . The use
198 of categories that implicitly privilege “natural” systems over ones created or influenced
199 by humans has been challenged more widely in conservation. One could argue the
200 distinction between “natural” and human-influenced systems has been blurred to the
201 point of irrelevance because human influence has become so pervasive (Vitousek et al.
202 1997). Additionally, “novel ecosystems” created or influenced by humans have
203 increasingly been recognised and are not necessarily worse for the species involved
204 (Hobbs et al. 2014). Ultimately, conceptualising HMRs as imitations of natural reefs may
205 limit our ability to perceive the unique costs, benefits and opportunities they present.
206

207 **Lines in the sand**

208 Beyond nomenclature, dominant definitions in current use for HMRs are also
209 obstructing a full view of the heterogeneity and scale of human presence in marine
210 ecosystems. These definitions are often tied to normative judgments around the role of
211 human influence and the legitimacy of ecosystems transformed by it. Criteria for
212 inclusion as an artificial or human-made reef often hinge on factors that are challenging
213 to ascertain in practice, such as a structure’s purpose or its ecological similarity to
214 natural reefs. These normative judgments have perpetuated a lack of nuance in the
215 debate around HMRs and a lack of widespread assessment around conservation claims.
216 By excluding structures from initial assessment through resource-intensive qualification
217 processes and feeding into biases around “natural” systems, these criteria may be
218 limiting learning for conservation.

219

220 *The role of purpose*

221 Purpose-based definitions for HMRs require particular intentionality; for example,
222 for an object to have been “deployed purposefully on the seafloor to influence physical,
223 biological or socioeconomic processes related to marine living resources” (Seaman &
224 Jensen 2000 p. 5). Purpose is a key element in the construction and assessment of
225 HMRs, and a purpose-based approach has the benefit of a benchmark by which to
226 measure outcomes. However, as an initial filter it may frustrate attempts to assess
227 structures for which the initial purpose cannot be confirmed, and exclude unexpected

228 examples of success or failure. In this scenario, a shipwreck or oilrig harbouring high
229 levels of biodiversity would not be assessed for its conservation benefit. Purposes are
230 often not formalised; a meta-analysis of HMRs in fisheries found a clear purpose had
231 only been articulated in 62% of cases (Becker et al. 2018). Purposes can be difficult to
232 ascertain as they are subjective and multifaceted, may change over time, and may
233 require access to stakeholders who cannot be reached or choose to claim a different
234 purpose. HMRs are increasingly being designed with multiple purposes (Dafforn et al.
235 2015) or can gain new purposes if their uses change.

236 Statements of purpose can provide valuable information about social uses and
237 conservation opportunities, and are particularly relevant given the international
238 legislation that governs sinking of anthropogenic structures in the ocean. The London
239 Convention of 1972 and Protocol of 1996, established by the International Maritime
240 Organisation, regulates marine dumping and counts 87 States as its parties. It defines
241 dumping as “any deliberate disposal at sea of vessels, aircraft, platforms or other man-
242 made structures at sea” and states that dumping does not include the “placement for a
243 purpose other than the mere disposal thereof” (IMO 2006 pt. 4.2.2). Therefore, the
244 sinking of anthropogenic structures in marine environments with claims of any purpose
245 other than disposal – for example, conservation – is permitted so long as the placement
246 is not contrary to the aims of the protocol, though individual cases are still subject to
247 local national law (Techera & Chandler 2015). By this logic, the submersion of 2 million
248 tyres off the coast of Fort Lauderdale, Florida, in 1972 – now partially retrieved, at great
249 expense, following disintegration and pollution – was acceptable as it was done with

250 conservation in mind (Allen 2007). Although international guidelines now specifically
251 disavow the use of tyres (London Convention and Protocol/UNEP 2009), proposals for
252 their use in HMRs are still emerging, most recently in Guam (Cerbo 2018).

253

254 *The role of outcome*

255 Outcome-based definitions for HMRs set down specific requirements in terms of
256 how associated communities develop, such as being “colonised by plant and animal
257 communities resembling those of a naturally occurring reef” (Storrie & Morrison 2003)
258 or inciting “the development of productive habitat in an otherwise unproductive
259 location” (Brock 1994). These definitions face two challenges: they are resource-
260 intensive to assess, particularly as ecological communities may continue to change over
261 time, and they reinforce an irrelevant hierarchy by requiring similarity to “natural” reefs.
262 Again, outcomes are key to conservation assessment, but creating initial thresholds
263 excludes opportunities to learn from structures which fail to generate particular
264 outcomes.

265 Functional comparisons between natural and human-made reefs can contribute to a
266 greater understanding of ecological context, regional biodiversity, and succession. Such
267 comparisons are particularly relevant in cases where HMRs are deployed in an effort to
268 rehabilitate, restore or mitigate damage to coral or rocky reefs. However, HMRs vary
269 hugely in terms of materials, structural complexity, age, location and size, which can

270 make straightforward comparisons with coral or rocky reefs difficult (Carr & Hixon
271 1997).

272 The more fundamental problem with outcome-based definitions is that they drive
273 unhelpful biases by focusing on resemblance to natural reefs, implying that equivalence
274 is possible and deviation is undesirable, blocking the perception of unique contributions.
275 One author states: “the natural world is far better at generating the services ecosystems
276 provide than we are at engineering them” (Roberts 2012, p. 19). This viewpoint
277 perpetuates the idea that HMRs aim to substitute natural reefs, either immediately or as
278 soon as some technological threshold is passed. In some cases, its basic premise can
279 create hope or confusion about the potential for replacing coral reefs in light of the
280 profound losses these ancient, complex ecosystems are facing. Comparisons may also
281 direct attention away from a shared marine context; after all, life on HMRs is no more
282 likely to succeed than life on natural reefs if surrounding environmental conditions are
283 dismal (Dupont 2008). A more forward-thinking approach would be to focus on
284 understanding the unique and separate ecological functions, ecosystem services and
285 values provided by HMRs, considering them as ecosystems in their own right rather than
286 as pale imitations of natural reefs. This is particularly relevant in cultural terms, given
287 the potential of HMRs to hold historical or educational meaning for humans. This
288 function-oriented approach to assessing HMRs would not preclude comparison with
289 coral or rocky reefs in relevant cases, but it would avoid using them as a limiting
290 benchmark, and promote a less biased comparison for the purpose of future HMR
291 management.

292

293 **The 5 W's and How**

294 In order to plan for a conservation future that can harness and direct this rising tide
295 of HMRs, it would be helpful to move beyond narrow inclusion criteria and instead to
296 assess a large pool of structures of diverse origins (Figure 2). The initial categorisation of
297 a structure as an HMR should be made regardless of purpose or outcomes, as long as
298 anthropogenic origins can be confirmed. In practice, purpose and outcomes are not
299 currently assessed on a routine basis, and are impossible to assess for every structure.
300 Despite being highly valuable for learning, these more targeted assessments are
301 therefore more appropriate as secondary stages of analysis.

302 As a first step towards conservation assessment, it will be necessary to collate
303 information on the basic characteristics of HMRs, first locally and then potentially
304 worldwide. At the local scale, tracking of HMRs can inform management plans by
305 providing a fuller picture of marine landscapes and a sense of how stakeholders interact
306 with or transform them. The process could be usefully structured according to the “5
307 W's and How”, taught as tools for basic information gathering in primary schools,
308 journalism seminars and police training worldwide: where HMRs are; what they are
309 made of; when, why and by whom they were established; and how they are used
310 socially and ecologically. Basic variables could include location, size, number of units,
311 and materials, with information on origin (such as the creator and date of creation),
312 biodiversity and known purpose or social uses being included if available. If collected

313 systematically, available information at the local level could later be submitted to a
314 global database, providing a rough sense of trends worldwide. At various scales, these
315 initial data gathering exercises will be instrumental to assessing the conservation impact
316 of HMRs as a whole, and generating best practice guidelines in the context of their
317 accelerating use worldwide.

318 Collating information on HMRs is challenging; they may be established informally or
319 even illegally, and people may be unwilling to disclose locations if they believe others
320 could damage or derive value from them (as with fishing spots or archaeological sites).
321 Some HMRs are located in inaccessible areas, such as the deep sea, and most are
322 difficult to find given they are underwater, though some can be identified through
323 satellite imagery. Databases may be enabled by permitting processes, in the case of
324 NOAA or the Florida Fish and Wildlife Conservation Commission, or through the
325 administration of patents, as in the case of the Reef Ball Foundation. However, this
326 information may not always be made public, and the focus on regulation means that
327 accidental, informal or illegal HMRs are not included. Given that HMRs are created for
328 many reasons, systematic local surveys of diverse stakeholder groups could provide
329 information on their location and uses.

330 Collection of local information on HMRs should be prioritised, given its direct
331 relevance to marine management and the effort required for data gathering; however,
332 gaining a sense of how HMRs are shaping ecosystems at regional and global levels is also
333 important. The creation of databases at larger scales would undoubtedly entail

334 significant logistical challenges – among them the allocation of time, effort and funding.
335 However, it could be carried out by combining a meta-analysis of the scientific
336 literature, collation of databases maintained by state or national agencies, and vetting
337 of information submitted on a voluntary basis. Models could include databases such as
338 conserveareas.org, and data could be included on open access maps of marine change
339 such as that curated by the OcToPUS initiative (octopus.zoo.ox.ac.uk).

340

341 **Moving towards a typology of human-made reefs**

342 Once initially identified and located, the characteristics of a structure can be
343 expressed in a typology, providing an anchor for the collection of available information
344 on conservation-relevant variables (Table 1, Figures 2 and 3). Four categories provide a
345 framework for collating information on the structure in question – its mode of
346 production, known purposes and social uses, conservation intention and conservation
347 benefits. Mode of production is intended as a category which a trained observer could
348 assess through easily visible characteristics without contacting the original creator of the
349 HMR. The category on purposes and uses is intended to broaden understanding of the
350 multiple social values of HMRS beyond a singular purpose, since information on human
351 uses is important but often lacking (Becker et al. 2018). Conservation intention
352 represents statements of purpose from a conservation standpoint, and indicates
353 potential for conservation management through resources or willingness to take action.
354 Evidence of conservation intention could be derived from planning applications or

355 interviews with the creators of reefs. Conservation benefits could be assessed through
356 various metrics appropriate to a particular context, including diversity and abundance of
357 target species or functional groups.

358 This is not the first typology suggested for HMRs; Stolk et al. (2007) proposed one
359 for recreational structures based on the intention to simulate, replicate or transform
360 natural reefs. The use of the broader typology which we propose, encapsulating a
361 variety of structures, would instead record the diverse uses and conservation impacts of
362 HMRs on marine ecosystems.

363

364 **The road to conservation assessment**

365 Conservation science is a value-based discipline that seeks to benefit people and
366 biodiversity through the use of natural and social science to manage the environment
367 (Kareiva & Marvier 2012). These goals are key to assessing the contribution of HMRs to
368 conservation, since they guide the social and ecological metrics by which success is
369 measured. Previous performance metrics proposed for HMRs range from the suggestion
370 that performance can only be assessed according to the purpose for which a structure
371 was built (Carr & Hixon 1997), to a “reef performance scale” ranging from -3 to +3, with
372 scores based on the fulfilment of desired objectives (Baine 2001).

373 A different approach would be to determine a set of metrics of conservation benefit
374 and apply them to a diverse selection of HMRs regardless of original purpose, or to a

375 single HMR across time. Ecological metrics could be “targeted” according to
376 conservation goals, and chosen in consultation with relevant stakeholders – for
377 example, measuring presence or abundance of an endangered, invasive or commercially
378 important species – or “general”, measuring variables such as diversity of sessile
379 organisms or fish diversity. In conjunction, measurements of social benefit could take
380 place – for example, consideration of tourism revenue as in Leeworthy et al. (2006), or
381 analysis of ecosystem services such as that carried out by Kirkbride-Smith et al. (2013)
382 and Schut (2013). Such a combined, holistic approach to assessment of HMRs could
383 begin to broadly capture the breadth of social-ecological processes of value to
384 conservation, thereby supporting management decisions.

385 Relevant metrics for conservation benefit could be assessed in relation to
386 conservation intention to manage existing HMRs and guide their future creation, in the
387 context of social and cultural benefits (Figure 4). Structures could be held up to greater
388 scrutiny if explicitly designed for conservation, but this process could also allow new
389 insights to emerge from HMRs designed by and for other sectors. In many cases,
390 conservation will be just one of a set of stated objectives (Lee et al. 2018), or it may
391 emerge subsequently. However, if any intention has been expressed, treating the
392 structure as conservation-motivated could help to avoid greenwashing in order to gain a
393 licence to operate (Rendle 2015). It could also indicate availability of resources for
394 conservation monitoring and management. For example, statements of conservation
395 benefit in the press or on documents such as permit applications could be a valuable
396 tool for setting specific goals and holding creators of HMRs to account. Importantly,

neither “conservation intention” nor “conservation benefits” are static; the creation and monitoring of realistic, measurable conservation-relevant goals could imbue intention, and a structure’s conservation benefits could vary with changes in relevant metrics.

The matrix of conservation benefits and intention (Figure 4) can be used to identify opportunities and guide decisions around permissions and policy for future HMRs, supplementing existing guidance (Baine 2001; London Convention and Protocol/UNEP 2009). It could aid in decision-making around the protection and management of high-performing conservation structures, as well as about the transformation or removal of structures which actively harm marine ecosystems. Though some elements of success are likely to be localised (Baine 2001), analysing a wide pool of HMRs can help guide understanding of their use and conservation potential across sectors worldwide. The identification of HMRs generating conservation benefits in different contexts will make it increasingly possible to envision and coordinate a future in which these structures help to maintain diverse, functional marine ecosystems, allowing nature and people to co-exist.

Into the future

As ocean landscapes continue to change, conservationists have an opportunity to manage HMRs in a conscious and integrated way, by mapping and monitoring these structures locally and worldwide, deepening understanding of the values they provide, providing guidelines for best practice, and considering whether some might qualify for

418 protection. Acknowledging the longstanding use of HMRs could helpfully inform the
419 debate around their future deployment and management, if only by clarifying they have
420 existed far longer than a few hundred years.

421 In many parts of the world, there is very little management or oversight of HMRs.
422 Local and global registries and targeted systematic conservation assessment (as outlined
423 in Table 1 and Figure 2) could inform management decisions (Figure 4), using basic
424 information to answer larger conservation questions. For example, Pitcher & Seaman Jr
425 (2000) suggested extending protections afforded to some natural coral or rocky reefs to
426 highly productive HMRs. The marine communities that develop on HMRs are far from
427 immune to damage by humans; one study found 55% lower species richness, 57% lower
428 abundance and 41% lower diversity on heavily trawled shipwrecks than ones classed as
429 “pristine” (Krumholz & Brennan 2015). Some HMRs could qualify for protection as sites
430 of underwater cultural heritage, or be used as a targeted management tool: one study
431 suggests treating natural reef habitats as “crown jewels” and deploying HMRs to offload
432 diving pressure and create additional habitat (Oh et al. 2008). Questions over structure
433 removal are also shaping policy and practice across sectors (Fowler et al. 2018)

434 HMRs can defy categorisation, since they represent a mixture of cultural and
435 biological patrimony. However, similar questions arise around land-based structures,
436 such as buildings managed for human use as well as the conservation of endangered
437 species such as bats (Voigt et al. 2016). More broadly, a range of human-made

438 ecosystems are recognised for their conservation value, including heathlands and chalk
439 grassland in the UK, and more recently some urban environments.

440 In the last century, human-made reefs have taken many forms in the cultural
441 imagination: mysterious time capsules filled with treasure, evidence of pollution and
442 corporate greed, siren calls to marine organisms that create bountiful fishing grounds to
443 the detriment of the individual organisms and their species, and symbols of
444 regeneration and hope in an ocean under threat. The “seductive spell of artificial reefs”
445 (Meier et al. 1989) – the glow of satisfaction that can result from seeing marine life
446 accumulate on a structure built and left bare months before – has sparked their
447 construction and worldwide debates. It is now time for conservationists to assess their
448 potential role in the oceans of the future. First, it will be important to count and
449 categorise: How many HMRs exist, what lives on them, who uses them, and at what rate
450 are these structures proliferating? Second, to consider: What opportunities and threats
451 do these novel ecosystems provide in a conservation context? Finally, to suggest policies
452 that can steer this growing tide toward a productive future, not only for the ocean but
453 for ourselves.

454

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Figures & Tables

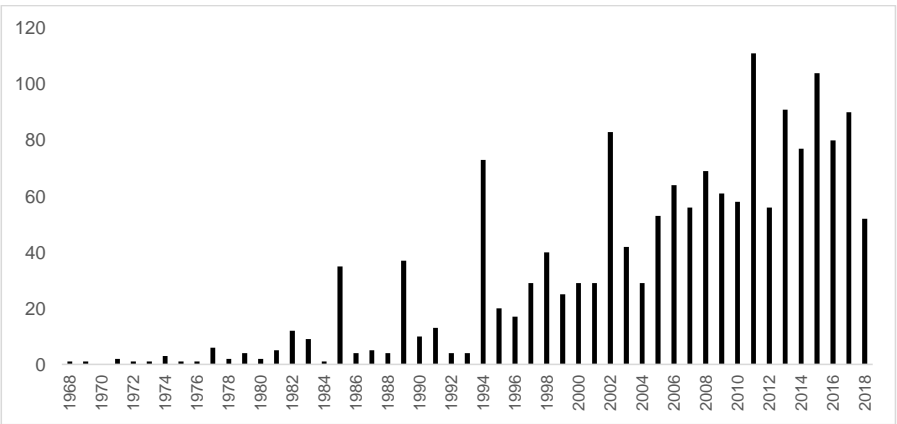


Figure 1. Scientific publications (n=1,606) containing the terms “artificial reef” or “human-made reef*” or “anthropogenic reef*” from 1945-2018 on the Web of Knowledge database. Only 2.1% of these publications are categorised under the research area “Biodiversity conservation” with the bulk of this literature starting in 2005. Of the remaining publications, 52.8% are categorised under “Marine freshwater biology”, 33.4% under “Oceanography” and 24.4% under “Fisheries.” (Web of Knowledge, August 2018).*

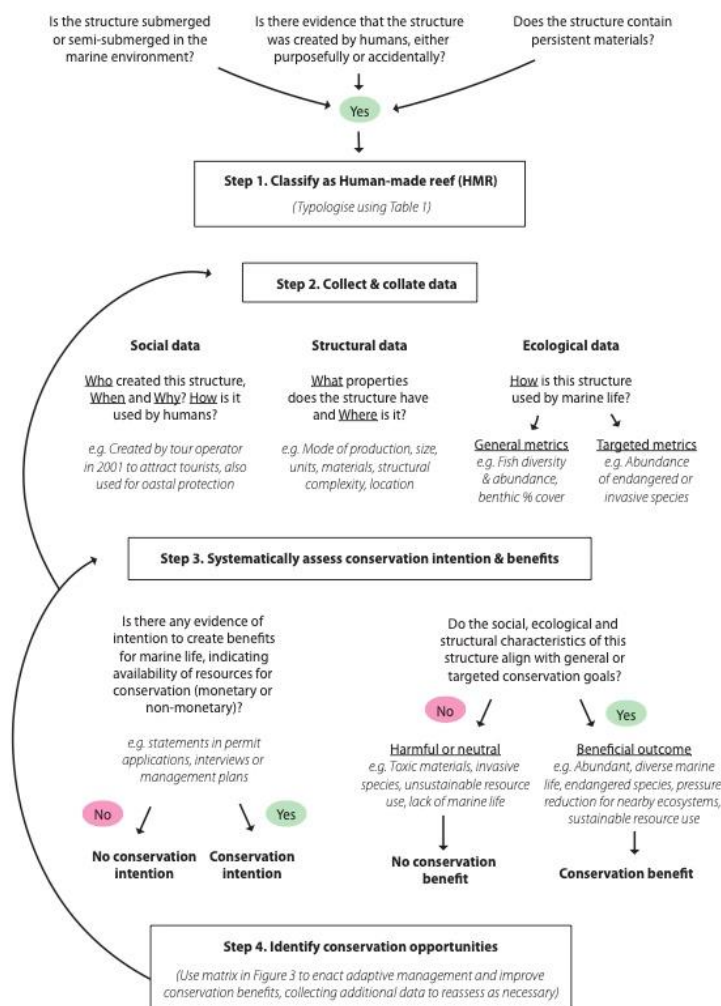


Figure 2. A key providing guidance on how to identify a diverse initial pool of HMRs at a local or global level, conduct data collection around the “5W’s and How”, and carry out systematic assessment of conservation intention and benefits to identify conservation opportunities.



Figure 3. Examples of diverse HMRs categorised according to typology in Table 1. Clockwise from top left: a. Artworks; b. Prefabricated modules; c. Sunken artefacts; d. Infrastructure; e. Traditional structures. All photos taken by SCT in Cozumel, Mexico (2019).

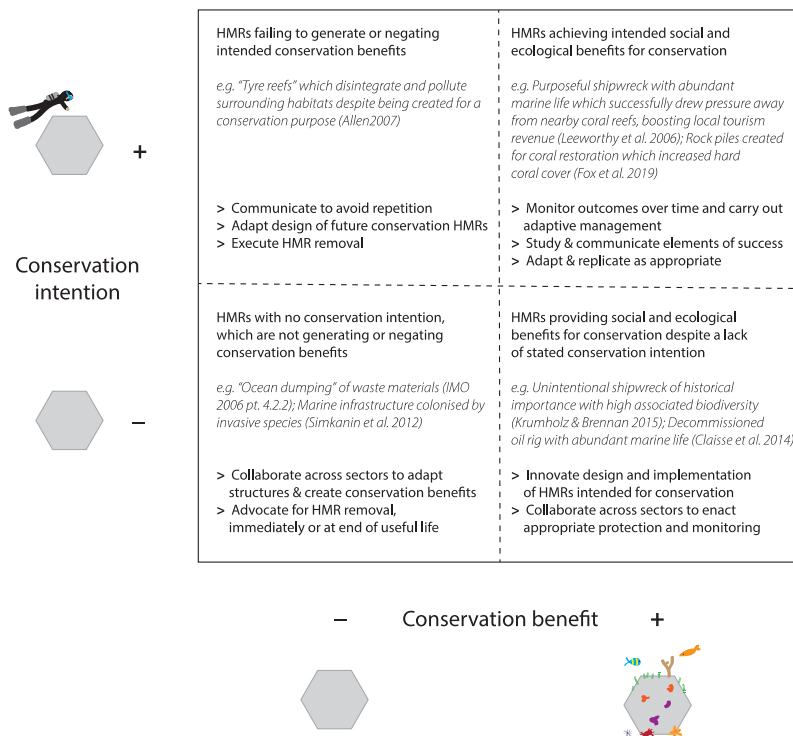


Figure 4. Matrix of conservation opportunities for diverse human-made reefs, based on assessment of conservation intention and benefits. Intention and benefits may change over time, meaning that the matrix can be used to track changes on one HMR or to compare across HMRs. Conservation intention is considered either present or absent, based on whether any statement on intended or actual conservation benefit from the HMR has been made (regardless of whether other uses are also intended). Outcomes with respect to conservation benefits are on a continuous scale and assessed through general metrics (such as fish diversity) or targeted metrics (such as presence of an

675 *endangered or invasive species). They can also include social dimensions such as*
676 *provision of ecosystem services.*

677 Table 1. A typology of human-made reefs (HMRs) from a conservation perspective, with non-exhaustive examples of the diverse
678 modes of production, purposes and uses, conservation intentions and conservation benefits of HMRs.

MODE OF PRODUCTION	DEFINITION	PURPOSES AND USES	EXAMPLES OF CONSERVATION INTENTION	EXAMPLES OF CONSERVATION BENEFITS	EXAMPLES OF STRUCTURES
Artworks	Artistic structures, often created to convey cultural meaning	Tourism, art, education, spiritual, conservation	"The art of conservation" (MUSA 2016)	Diverse algae and macrofauna identified on underwater sculptures (Solís-Weiss et al. 2015)	Underwater sculpture museum (www.musa.org)
Prefabricated modules	Individual designed structures produced industrially for a modifying purpose, often produced and deployed en masse	Conservation, coastal engineering, tourism, education, fishing	"Our mission is to rehabilitate our world's ocean reef ecosystems" (The Reef Ball Foundation 2017)	Coral growth rates on Reef Balls vary by species (Cummings et al. 2015)	Reef Balls (www.reefball.org); Lobster traps (Headley 2017)
Sunken artefacts	Structures produced for regular human use, subsequently	Accidental, tourism, conservation,	Sinking of ships to create alternative dive sites and reduce pressure on nearby	89 taxa of reef fish observed across two shipwrecks	Shipwrecks (Leeworthy et al. 2006; Simon et al.

	sunk accidentally or on purpose	culture, archaeology	coral reefs (Leeworthy et al. 2006)	(Simon et al. 2013)	2013; Krumholz & Brennan 2015)
Infrastructure	Fixed complex structures built to enable large-scale human activities	Energy extraction and production, trade, tourism, recreation	Unknown	"Oil platforms off California are among the most productive marine fish habitats globally" (Claisse et al. 2014)	Oil & gas platforms (Claisse et al. 2014); Wind farms (Russell et al. 2014); Docks and jetties (Storrie & Morrison 2003)
Traditional structures	Structures created through reconfiguration of locally available natural materials such as rocks or wood	Fishing, coastal engineering, tourism, conservation, water quality	Oyster reefs used to restore hard substrate and oyster populations (Cabral 2014); Rock piles used for coral restoration (Fox et al. 2019)	Community oyster reef restoration programme creates opportunities for education and community building (Cabral 2014)	Hawaiian fish ponds (Costa-Pierce 1987); Mayan fishing structures (Garduño Argueta & Caballero Pinzón 1998); Rock piles (Fox et al. 2019); Oyster reefs (Seaman 2007; Lee et al. 2018)

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680

681 **Biographical narratives**

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