nature sustainability

ARTICLES

https://doi.org/10.1038/s41893-020-00595-1

Check for updates

Current and projected global extent of marine built structures

A. B. Bugnot[1,2,3] ✉, M. Mayer-Pinto[2,3], L. Airoldi[4,5], E. C. Heery[6], E. L. Johnston[3], L. P. Critchley[7], E. M. A. Strain[8], R. L. Morris[9], L. H. L. Loke[10], M. J. Bishop[7], E. V. Sheehan[11], R. A. Coleman[1] and K. A. Dafforn[2,10]

The sprawl of marine construction is one of the most extreme human modifications to global seascapes. Nevertheless, its global extent remains largely unquantified compared to that on land. We synthesized disparate information from a diversity of sources to provide a global assessment of the extent of existing and projected marine construction and its effects on the seascape. Here we estimated that the physical footprint of built structures was at least 32,000 km^2 worldwide as of 2018, and is expected to cover 39,400 km^2 by 2028. The area of seascape modified around structures was 1.0–3.4 × 10^6 km^2 in 2018 and was projected to increase by 50–70% for power and aquaculture infrastructure, cables and tunnels by 2028. In 2018, marine construction affected 1.5% (0.7–2.4%) of global Exclusive Economic Zones, comparable to the global extent of urban land estimated at 0.02–1.7%. This study provides a critical baseline for tracking future marine human development.

The expansion of urban areas has been posited as one of the main contributors to biodiversity loss in terrestrial ecosystems[1]. The global extent and projected expansion of urban areas is an issue broadly recognized[2], with new developments limited by planning acts and, in many jurisdictions, requiring offsets for impacts. Urbanization is, however, not only a land-based problem, as growth of coastal cities and sea level rise are driving a marine construction boom. Marine built structures include those built in the marine environment for a wide range of purposes, such as coastal and foreshore defence (for example, breakwaters, groynes), residential and commercial developments (for example, bridges, tunnels), transport and tourism/recreational infrastructure (marinas), as well as resource extraction (for example, wave, tidal and wind farms, oil and gas rigs) and fisheries (for example, aquaculture installations, artificial reefs)[3].

In the United States, for example, >50% of natural shorelines have been replaced by seawalls, breakwaters and other hard structures, impacting marine diversity and ecosystem functioning and services[4]. Beyond urban areas and increasingly further offshore, growth in marine construction has been driven by hydrocarbon extraction and transport (gas and oil) and the rise of the renewable energy industry, among others[5]. This construction may, in some instances, produce notable environmental benefits—for example, the exclusion by new obstacles of damaging trawl-fishing from offshore seabeds[6], the provision of habitat and refuges for invertebrates and fish[7] and the transition of economies from fossil fuels to renewable energy. Additionally, artificial reefs have been used as 'sacrificial habitat' to drive tourism and fishing effort out of natural habitats[6]. When poorly regulated, however, this construction may lead to habitat degradation and destruction[4,8] and contribute to losses in ocean wilderness[9]. In coastal areas, marine built structures can also reduce the adaptive capacity of shoreline ecological communities to sea level rise[10].

Marine construction obliterates and fragments habitats and introduces 'novel habitats'—for example, where aquaculture farms replace mudflats[11]. These built structures differ in physico-chemical, ecological and socio-economic characteristics compared to the natural habitats they replace[12]. In addition, in modifying flows of energy and materials, built structures can change habitat quality at scales of centimetres to hundreds of kilometres[13]. They do so by changing the physico-chemical (water quality, hydrodynamics, noise, electromagnetic fields, substrate scouring and sediment characteristics) and ecological (movement of organisms, food webs)[14,15] characteristics of the environment. While some marine built structures may enhance ecological connectivity by serving as a conduit for the dispersal of native species at range edges, facilitating their spread in response to climate change[16], others can inhibit the movement of organisms and propagules or matter and energy. Particularly where these structures act as stepping stones for the spread of non-indigenous species, they may result in significant ecosystem changes[17,18]. To truly gauge the status of ocean health, a qualitative understanding of the physical footprint of marine construction—that is, the area of seafloor directly occupied by marine construction—is required, as well as the potential extent of seascape modifications associated with particular structures, which includes any direct or indirect change to the surrounding marine environment produced by marine constructions at adjacent (<100 m), local (<10 km) and regional (>10 to hundreds of kilometres)

[1]School of Life and Environmental Sciences, The University of Sydney, Sydney, New South Wales, Australia. [2]Sydney Institute of Marine Science, Mosman, New South Wales, Australia. [3]School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales, Australia. [4]Department of Biology, Chioggia Hydrobiological Station Umberto D'Ancona, University of Padova, UO CoNISMa, Chioggia, Italy. [5]Dipartimento di Scienze Biologiche, Geologiche ed Ambientali & Centro Interdipartimentale di Ricerca per le Scienze Ambientali, University of Bologna, Ravenna, Italy. [6]MarineGEO, Smithsonian Institute, Friday Harbor Laboratories, Friday Harbor, WA, USA. [7]Department of Biological Sciences, Macquarie University, North Ryde, New South Wales, Australia. [8]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia. [9]National Centre for Coasts and Climate, School of BioSciences, University of Melbourne, Melbourne, Victoria, Australia. [10]Department of Earth and Environmental Sciences, Macquarie University, North Ryde, New South Wales, Australia. [11]School of Biological and Marine Sciences, Marine Institute, University of Plymouth, Plymouth, UK. ✉e-mail: ana.bugnot@sydney.edu.au

scales. These include both ecological changes and changes to the physico-chemical characteristics of the environment.

While the local extent and effects of individual marine construction projects are increasingly reported[14,17,18] and global assessments have been performed for certain structure types[19], there have been no attempts to derive a global estimate of the extent of physical footprint and potential seascape modification by marine construction. Mapping of many of these structures using remote sensing is difficult because satellite images cannot capture benthic structures in optically deep waters. Hence, the most complete assessments of anthropogenic impacts on the oceans[20] and ocean health[21] have relied upon proxies for marine construction, such as human population density, mariculture production and night light intensity from oil and gas platforms[21]. Here, we present synthesis and estimation of the global extent and distribution of existing and projected future marine construction. We quantify both the physical footprint of different structures, as well as the extent of seascape potentially modified around structures, identify data gaps and recommend future steps to continue collating and refining these important data.

Physical footprint and modified seascapes as of 2018

Marine construction has claimed a minimum of 32,000 km² of seafloor, while the estimated total area of seascapes modified around ports, wind farms, breakwaters, tunnels and bridges is 1.0–3.4 × 10^6 km². Most of these artificial habitats were built for the purposes of aquaculture (71%, 2.3 × 10^4 km²), commercial ports (14%, 4,500 km²) and artificial reefs (11%, 3,600 km², Fig. 1).

The scales of seascape modifications were dependent on infrastructure type (Table 1 and Fig. 1). Noise pollution caused by shipping activity in ports and marinas showed the greatest extent of modification, affecting seascapes at regional scales (>10 km). Commercial ports, therefore, contributed to >99% of seascape modification (2.1 ± 1.1 × 10^6 km²; Fig. 1) due to their extensive physical footprint, combined with widespread noise pollution at distances of 19.8 ± 6.5 km per port[22] (Table 1). Tidal farms affected tidal elevation at regional scales while wind farms, oil and gas rigs and breakwaters affected seascapes at local scales (100 m–10 km). The remainder of the structures affected only adjacent seascapes (<100 m).

Most construction (99%) has occurred in EEZs, except for submarine cables. Georeferenced data showed that 47% of wind farms were located within 10 km of the shoreline (range 0.6–210 km) and 50% of oil and gas fields were located at distances within 40 km (range 0.1–350 km) of the shore. Tidal farms were located closer to the shoreline, with 41% closer than 2 km (ranging from 0 to 30 km offshore), and no wave farms were in operation in 2018. This concentration of structures close to the shore means that many coastal habitats are affected by multiple structures. We found that 3,500 km² (range 485–11,700 km²) of global coastal areas were potentially modified by multiple structures in 2018, including commercial ports, wind farms, breakwaters, tunnels and bridges. Moreover, the area affected by multiple structures is likely to be much higher, because aquaculture farms, marinas and artificial reefs are typically built on the coast[6,23,24] but their overlap could not be estimated because georeferenced data for these structures were not available.

The EEZ with the greatest amount of marine construction was China (40% of global ocean construction, 13,000 km² occupying >1% of its EEZ), mainly driven by ~12,600 km² of aquaculture farms including offshore farms and farms built on mudflats[11] (Extended Data Fig. 1). This was followed by South Korea's EEZ (10% of global ocean constructions, 3,300 km² occupying >7.5% of its EEZ) and the Philippines' (8% of global ocean constructions, 2,600 km² occupying ~0.1% of its EEZ; Fig. 2). These structures are probably affecting zones of high macrofaunal species richness[25] and functional diversity[26] commonly found in these EEZs. Marinas were concentrated in the United States and Canada (34% of all marinas;

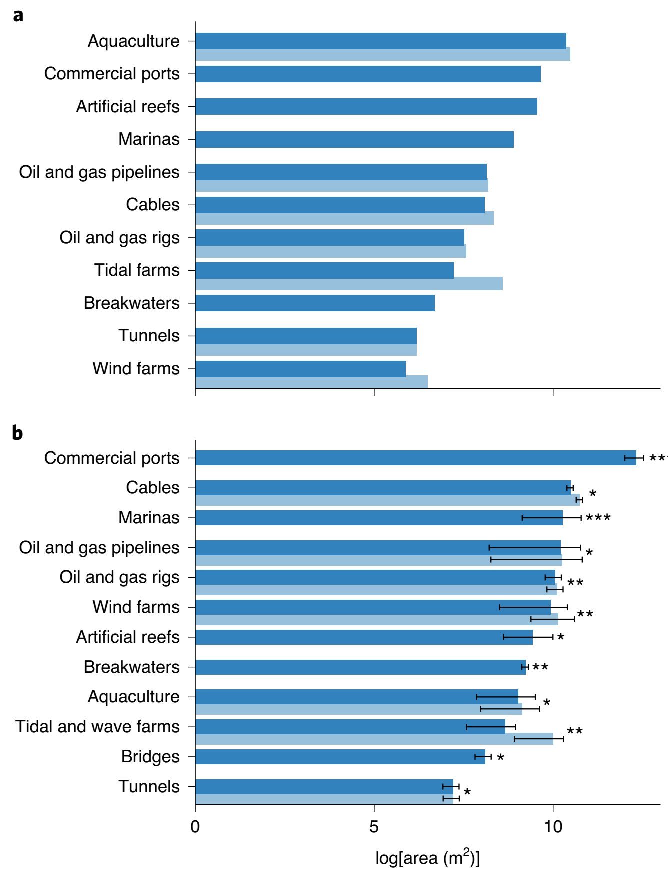


Fig. 1 | Global extent of marine construction. a,b, Present (2018, dark blue bars) and predicted (for 2028, light blue bars) area (m², log scale) of physical footprint (**a**) and modification of surrounding seascapes (mean and 95% confidence intervals) (**b**) by different types of marine built structure. Future projections were available only for aquaculture, submarine cables, wave, tidal and wind farms and oil and gas pipelines and rigs. Note: no wave farms were operational up to 2018, hence data on wave farms are presented only for future projections. Asterisks denote the scale of seascape modifications: * adjacent (<100 m), ** local (<10 km) and *** regional (>10 to hundreds of km).

Extended Data Fig. 1), with oil and gas extraction rigs being primarily located in the US Gulf of Mexico (49% of global offshore rig area, 15.72 km²; Extended Data Fig. 1). Over 1.36 × 10^5 km of pipelines were installed as of 2018, predominantly concentrated in the United States and the North Sea (Extended Data Fig. 1). Most of the physical footprint of wind and tidal farms was located on the coast of the United Kingdom (16 km² (99.5%) of tidal farms and 0.25 km² (30%) of wind farms; Fig. 3), with the remaining wind and tidal farms spread along the coasts of North America, India, Germany and in the Asian North Pacific. Tunnels and bridges were mainly located in the Northern Hemisphere, and breakwaters for coastal defence claimed the greatest amount of area in Italy (3.3 km²). However, the physical footprint of breakwaters for regions with substantial coastal modification (for example, China) was not available (Extended Data Fig. 1; see 'Data quality and gaps' section below for further discussion).

Projections for future increase

Construction will continue to sprawl into the ocean for the foreseeable future, with the global physical footprint projected to increase by at least 23% (7,300 km²). The extent of modification of seascapes

Table 1 | Summary of data gathered and calculations made to estimate the physical footprint and area of seascape modification around marine construction as of 2018, including future trends

Infrastructure	Data available	Estimation of physical footprint	Estimation of extent of seascapes modified	Estimation of future extent based on:
Gas and oil rigs	Geographical location of existing oil and gas fields in 2018 and number of rigs per offshore field in 2010–2018	(Number of rigs) × (mean rig area, 3,625.021 m^2)	Ecological effects within a 755 ± 679-m radius around each rig	Average growth for oil and gas production to 2040 (mean between oil and gas weighted on 2018 production)[5]
Subsea pipelines	Length of existing pipelines per EEZ with offshore fields in 1998–2018	(Length of pipelines) × (mean diameter of pipelines, 1 m)	Ecological effects within a 82 ± 40-m corridor along pipelines	Average growth for oil and gas production to 2028 (mean between oil and gas weighted on 2018 production)
Wind farms	Number and type of turbines and their foundation, length of cables and geographical location for existing and planned farms in 2018	Area of turbine estimated based on foundation type reported. Area of existing cables calculated as: (length of cables) × (diameter of cables, 0.08 m)	Noise pollution within 5.5-km radius (range 1–10) around each farm	Number and location of planned projects. Area of planned project estimated based on existing projects
Wave and tidal farms	Number and type of turbines and their foundation, length of cables and geographical location for existing tidal farms and planned wave and tidal farms in 2018	Area of turbine estimated based on foundation type reported	Tidal farms: sediment characteristics modified in an area of 0.86 ± 0.79 $km^2\,MW^{-1}$ Wave farms: wave height modified in an area of 1.27 (0.28–3.0) $km^2\,MW^{-1}$	Number and location of planned projects. Area of planned projects estimated based on existing projects
Telecommunication cables	Length of existing and planned submarine cables in 2018	(Length of cables) × (diameter of cables, 0.08 m)	Magnetic field affected in a 20-m corridor (range 16–24) along cables	(Length of planned cables) × (diameter of cables, 0.09 m)
Aquaculture	Area of existing aquaculture facilities per EEZ. Date of data source varied from 1991 to 2018	As obtained from literature	Sediment characteristics modified in a semi-circle of radius 92 ± 68 m	Average growth for aquaculture production to 2026 (ref. [59])
Commercial ports	Geographical location and size category of all existing ports in 2017	Mean area for each port size estimated measuring a subsample of ports (48) in Google Earth Pro 7.1	Noise pollution within a circle of radius equal to 19.8 ± 6.5 km, accounting for overlapping areas between ports and land	N/A
Tunnels and bridges	Inventories of existing bridges and submerged tunnels in 2018, including length and geographical location	(Length of tunnels) × (width of tunnels, estimated at 8 m assuming all tunnels have two lanes at least). Area covered by the pilings supporting bridges is not reported	Ecological effects within a 82 ± 40-m corridor along bridges and tunnels	List of planned tunnels per country including length, as generated by the general public
Breakwaters	Inventories of existing breakwaters in 2018, including length, width and geographical location	(Length of breakwaters) × (width of breakwaters). Missing widths were estimated by averaging known widths (9.03 m)	Sediment characteristics modified in an area of 0.29 $km^2\,100\,m^{-1}$ (range 0.23–0.35) around breakwaters	N/A
Recreational marinas	Inventories of existing marinas per EEZ in 2018	Mean area for marinas (0.081 km^2) estimated by measurement of a subsample (n = 440) in Google Earth Pro 7.1	Noise pollution within a semi-circle of radius 1.1 km (range 0.3–2.0)	N/A
Artificial reefs	Number and area for existing reefs per EEZ in 2018	As obtained in the literature or estimated based on similar projects. Structures where area was not reported were excluded	Ecological effects within 1 ± 20 m from reefs, calculated per site depending on geometric shape	N/A

The total area of seascape modified per individual structure accounted for the presence of land (that is, coastal structures abutting the land) by exclusion of land areas using Economic Exclusive Zone (EEZ) maps (for georeferenced structures) or assuming a semi-circle of area modified (for non-georeferenced shoreline structures). Extended explanations and data sources can be found in Supplementary Methods. N/A, not available.

around power and aquaculture infrastructure, cables and tunnels will probably increase by at least 50–70% (from 30,000–139,000 to 54,000–212,000 km^2) by 2028. Traditional energy sources, the most widespread in 2018, had a predicted annual growth of 0.46 and 2.26% for oil and gas, respectively, which was projected to drive an increase in the physical footprint of rigs and pipelines of 3.8 and 16.2 km^2, respectivly, by 2028 (Fig. 1). Offshore gas infrastructure was predicted to expand in both deep-sea areas and those closer to the coast, while oil extraction growth will mainly occur in offshore areas[5]. Telecommunication cables had a projected annual

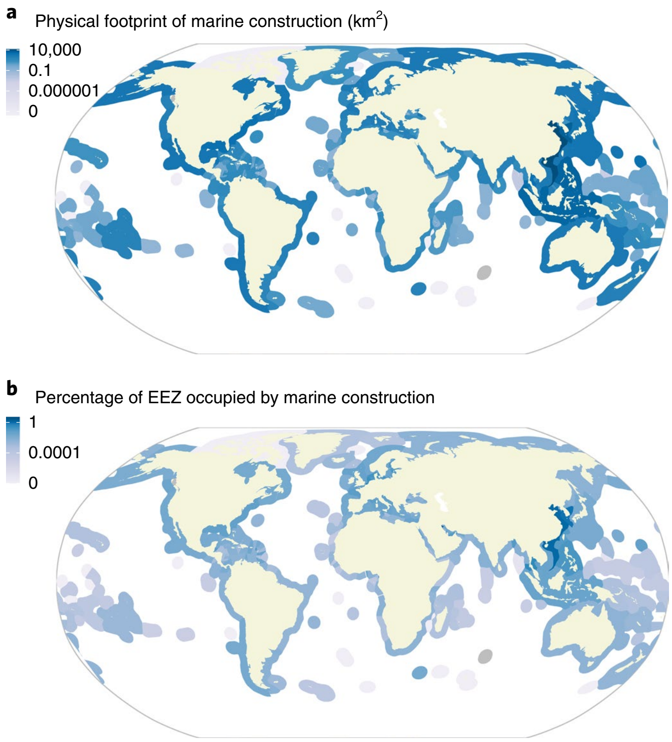


Fig. 2 | Global distribution of the physical footprint of marine construction (2018). **a**, Total physical footprint (km^2) per EEZ. **b**, Percentage of EEZ area occupied by marine construction. Map colours are scaled to allow visual comparisons among countries with footprints that span many orders of magnitude. Grey indicates missing data. This figure does not include submarine cables, because they extend beyond the EEZ.

global growth rate of 8.2%, which would translate as an increase in their physical footprint to a total of 98 km^2 by 2028 (Fig. 1; maps can be found at www.submarinecablemap.com). Although the extent of alternative sources of energy such as wave, tidal and wind farms was smaller in scale than oil or gas in 2018 (Fig. 1), these are projected to have the greatest growth, expanding at a yearly rate of ~208% (growth of 358 km^2) for tidal farms and 30% (growth of 2.3 km^2) for wind farms based on projects planned in 2018. Most wind (39%) and wave and tidal farms (97.5%) will expand along the coast of the United Kingdom (Fig. 3). Particularly for tidal farms, their expansion is likely to replace large areas of natural habitats due to their sheer size (up to 3.86×10^5 m^2 per farm for planned tidal energy projects in the United States). Underwater tunnels are also estimated to increase 0.15% by 2028, which represents a growth in physical footprint of 0.02 km^2 based on eight projects planned as of 2018 in the North Sea, Brazil, India and Malaysia.

Even though there are clear indications that the extent of other structure types will increase in the next decade, calculations of their future extent were not possible. For example, population density in low-elevation coastal areas is expected to increase by 40–50% from 2000 to 2030 (ref. [27]), but its effect on the rate of construction of coastal defences cannot be directly predicted. Commercial port capacity is predicted to double by 2030 (ref. [28]), and regional reports predict a 0.6–2.5% growth in berth demand in Australia and the United States[29,30]. China is the third largest shipping country in the world and experienced 41% growth in vessel throughput between 1949 and 2010, with substantial growth still occurring[31]. It is uncertain, however, how this growth will translate into increases in the physical footprint of on-water infrastructure of ports and marinas in the future. In the state of New South Wales (Australia) alone, two new artificial reefs were deployed in 2019 and two more are planned to be built by the end of 2020[32]. In addition, the Rigs-to-Reefs programme in the United States estimated that 400 existing rigs are eligible for decommissioning and may become artificial reefs[33]. Over 220 offshore installations will also need to be decommissioned in the North Sea by 2025, yet the future of these structures is uncertain while policy in regard to the North Sea prevents a Rigs-to-Reef programme[34]. Finally, new extraction activities, such as deep-sea mining, are expected to grow exponentially, creating the opportunity for habitat modification in previously undeveloped locations[5].

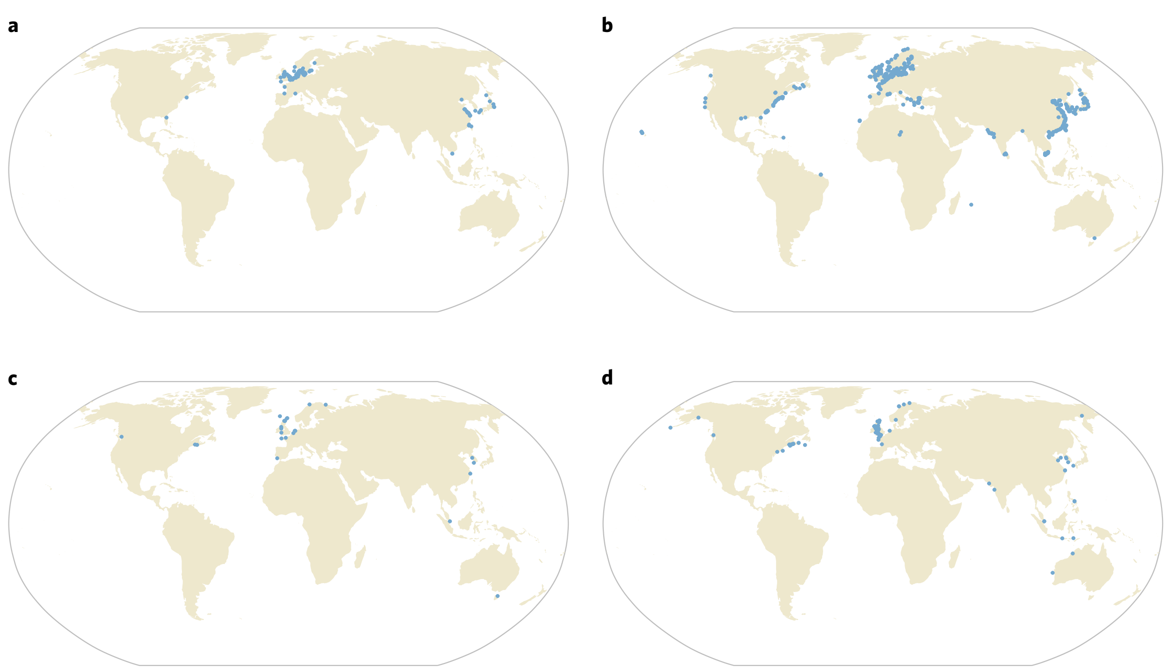


Fig. 3 | Global distribution of wind, wave and tidal farms. **a**, Locations of built wind farms as of 2018. **b**, Locations of planned wind farms predicted to be built before 2028. **c**, Locations of built tidal farms as of 2018. **d**, Locations of planned tidal and wave farms predicted to be built before 2028. Data gathered from 4COffshore[54].

Data quality and gaps

The pervasive extent of marine construction reported here is a conservative estimate, due to data limitations and gaps. Ocean data management has been traditionally based on a 'sector-by-sector' approach, resulting in some international industries regularly publishing up-to-date data with global coverage (for example, power infrastructure), while the availability and quality of data for regional industries (for example, marinas, aquaculture and artificial reefs) vary between different parts of the world (Extended Data Fig. 1). In addition, a comprehensive assessment of marine built structures can be achieved only with the inclusion of historical data to incorporate structures built before the beginning of records (see Boxes 1 and 2).

In general, up-to-date data about the size and location of nearshore built structures (for example, aquaculture, marinas, artificial reefs and coastal armouring), which represent most of the estimated global physical footprint of marine construction, were often not publicly available or were provided only by local jurisdictions due to regulation and management actions occurring at local and regional levels. In particular, data on the physical footprint of aquaculture farms were not available for 37% of EEZs, including some known areas with important aquaculture production such as Japan (Extended Data Fig. 1). Even when information on the area of aquaculture infrastructure was available, it was often outdated (information on the Food and Agriculture Organization of the United Nations website was dated any time between 1991 and 2018). This study found no data on artificial reef infrastructure for 33% of EEZs (Extended Data Fig. 1). In parts of the Caribbean, for example, local fisherman and communities can build small reefs with no control or regulation from the local authorities, meaning that, when data became available, sources of information were anecdotal, outdated and not comprehensive.

The lack of information on coastal armouring was a notable information gap highlighted by this study. While information on the length of coastal armouring was available for some regions, such as European EEZs[35] and the United States[36], most EEZs (86%) had missing data. Another big gap in knowledge was related to recreational infrastructure. The most extensive publicly available lists of recreational marinas were owned/managed by private companies/individuals, and the accuracy of this material is uncertain. This issue also applied to inventories of tunnels and bridges per EEZ produced by the public (Table 1 and Supplementary Methods).

Finally, estimations of the extent of seascape modified around each construction type were based on a review of data from 74 peer-reviewed articles that provided extensive data, but could not account for the size, age and intensity of activity associated with individual structures in most cases. While size of each structure was incorporated in estimations for seascape modified around breakwaters, wave and tidal farms, the effects of size on spatial extent of seascape modification were not documented for other structures. In addition, potential ecological impacts of marine construction can depend on the recipient ecosystems (that is, the ecological habitats present where construction is taking place and surrounding areas). Since the majority of structures were not georeferenced and information on the current and historical extent of different marine habitats is largely non-existent[19], we could not directly relate the modifications mapped here to specific marine habitats. As georeferencing of spatial information improves and more data on the locations and extent of different structures become available, we expect that assessments of the full suite of impacts, including their ecological relevance and extent, from different structures can be further refined.

Discussion

This study found that most marine construction was located in EEZs and that it affected at least 1.5% (0.7–2.4%) of global EEZs, comparable to previous estimates of global urban land extent that range between 0.02 and 1.7% (refs. [2,37]). Moreover, the extent of the seascape modified around marine built structures (1.0–3.4×10^6 km^2) was greater than the global extent of some vegetated natural habitats, including mangrove forests (0.14×10^6 km^2)[38] and seagrass beds (0.34×10^6 km^2)[39]. Our results highlight the concentration of structures occurring in coastal areas, directly affecting the most productive environments in the ocean[40,41] and resulting in considerable overlap in the area affected by individual structures, adding to the multitude of other human pressures associated with urbanization[14,17,42].

The proliferation of marine built structures shown here provides a suite of ecological, social and economic benefits[5]—for example, the expansion of renewable sources of energy in the oceans can minimize greenhouse gas emissions. In addition, energy extraction infrastructure may sometimes serve to benefit sensitive habitats due to the fishing exclusion zones set up around them and even act as focal points for restoration activities[43]. Nevertheless, all marine construction replaces natural habitats and can modify environmental conditions critical to habitat persistence at regional scales. For example, a tidal turbine array in the Pentland Firth (Scotland, UK) has been modelled to force changes in tidal levels up to 700 km down the east coast of the UK[44]. Their coastal nature means they are likely to affect sensitive environments, such as seagrasses, saltmarsh and coral reefs. Hence, they can have unintended and sometimes hidden ecological and economic costs, as the natural habitats they replace or modify provide valuable ecosystem services that are not always explicitly documented or valued (for example, coastal

Box 1 | Land reclamation

Land reclamation is the infill or draining of submerged substrate for agricultural, urban, tourist or industrial developments. In expanding the foreshore or creating artificial islands, land reclamation produces direct loss of marine habitat. Records of this practice date back to historical times (see Box 2), and mapping efforts using remote sensing are now revealing the extent of this issue. For example, 13,380 km^2 of land was reclaimed along the coast of China between 1950 and 2008 (ref. [60]), while in the Netherlands and India reclaimed land is estimated at 7,000 and 1,500 km^2, respectively[61]. As a direct consequence of this practice, tidal mudflats in the Yellow Sea have shrunk by 28% (1,560 km^2) in 20 years[62]. This has reduced the habitat available for many migratory birds, weakened coastal defences and resulted in lower rates of sediment retention[63].

The creation of artificial islands, a form of land reclamation that is separated from land by marine waters, has captured special public interest, so informal records (news articles, inventories generated by the general public) are available online. Artificial islands have been built in coastal areas since at least the time of the Egyptians, and benchmarked by the construction of Kansai International Airport, Japan (1994). Currently, artificial islands have also extended into deeper waters, up to ~500 km offshore (for example, the Spratly Islands (Chinese name, Nansha Qundao), China). We found 479 human-made islands in marine environments worldwide, adding to a total area of 282 km^2 (Extended Data Fig. 1i). This includes islands that have been built in groups, such as The World (United Arab Emirates, 300 islands) and the Fortress Islands (Russia, 19 islands). Ongoing demands for space to accommodate an increasing coastal population[64] and the need for 'designer islands' to host climate refugees[65] means that land reclamation will continue to spread and occupy a substantial extension of the marine environment, with many associated impacts.

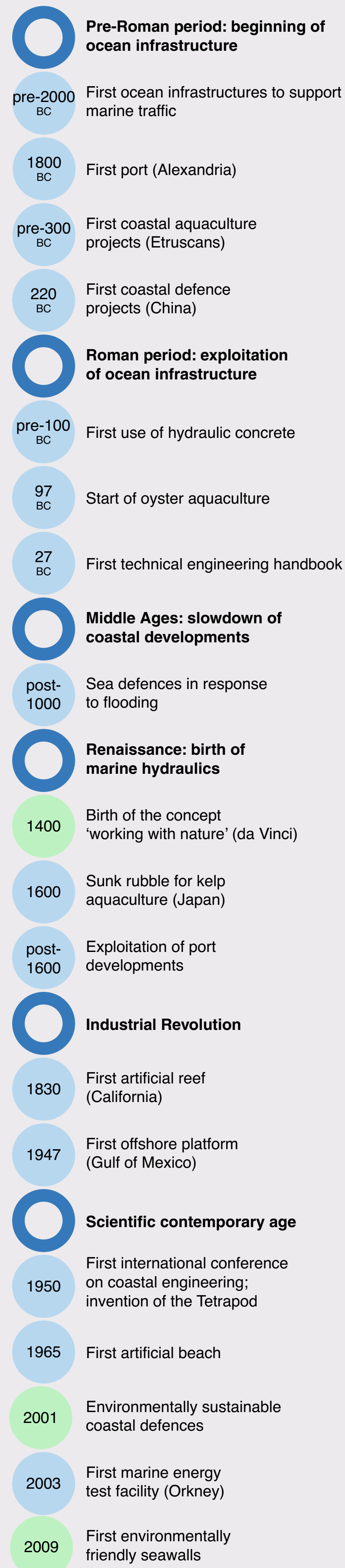
Box 2 | History of marine construction

Marine construction was first introduced well before 2000 BC (see the figure in this Box), to support maritime traffic and protect low-lying coasts. The oldest known seaport was built by the Minoans around 1800 BC in Alexandria (Egypt) to accommodate ~400 ships[66]. The Romans introduced many innovations, including the discovery of pozzolanic ash hydraulic cement that enabled construction underwater and along exposed coasts, and developed techniques to control silting and dredge sediments, which were used for centuries[67]. The fifteenth to the eighteenth century saw the development of the first dry dock in intertidal flats, port defence structures (breakwaters) and enclosed docks in England[68]. However, it was not until the nineteenth century, with the advent of the steam engine and the search for new lands and trade routes, that modern port works started[69].

Coastal armouring is also a practice that dates back millennia. In China, large coastal defences initiated between about 220 and 25 BC (ref. [66]). In northern Europe, the Frisians developed coastal defences by using earth mounds or dams as early as 175 BC[70]. A contraction of coastal developments was observed in the Middle Ages, when sea defences were constructed in Europe only in response to severe flooding events[71]. The Renaissance saw the birth of the science of maritime hydraulics, with Leonardo da Vinci as a precursor of coastal engineering science anticipating ideas and solutions by over three centuries. He also championed the credo of 'working with Nature', rather than against it, warning against fundamental errors in land and water engineering management[70].

Aquaculture construction started in Europe, with the Etruscans managing coastal lagoons for aquaculture in the fourth and fifth centuries BC[72]. In Japan, in the 1600s, building rubble and rocks were sunk for growing kelp[73]. In the 1830s log reefs started to be built to improve fishing off the coast of South Carolina (USA)[73]. The offshore petroleum industry began in the late nineteenth century with the drilling of piers at Summerland, California[74]. By the 1940s, wells had been developed far into the Gulf of Mexico and, in 1947, the Kerr–McGee Corporation drilled the first well from a fixed platform out of sight of land, marking the beginning of the modern offshore industry[75]. The world's first offshore renewable energy field was established in 1991 in Germany, and kick-started the marine renewable energy industry[76].

The first International Conference on Coastal Engineering (Long Beach, California, 1950) marked the start of the scientific contemporary age in marine construction. In that year the invention of the Tetrapod—very stable under wave attack and easier to obtain than quarried rock—revolutionized the design of maritime structures and hydraulic works[77]. By the 1980s it was clear that certain coastal defence works were failing to fulfil their aims and that erosion problems had shifted further along the coast or, in some cases, were even aggravated[78]. The Centre for Research on Ecological Impacts of Coastal Cities (The University of Sydney, 1997–2009) led the development of environmentally beneficial seawalls[79], and the EU project DELOS (2001–2004) made important advances in the search for more sustainable approaches to marine and coastal engineering[80]. Numerous projects are continuing to build on these scientific foundations, including The World Harbour Project and Living Seawalls (www.sims.org.au). See the figure in this Box.



History of marine construction worldwide. Events coloured green show advances in the use of environmental approaches.

defence, carbon sequestration). To reduce this conflict, marine spatial planning and nature-based solutions (sensu ref. [45]), such as the use of mangroves, saltmarshes, shellfish or coral reefs as coastal defence structures, or the use of ecological principles in the design of built structures (eco-engineering), can be used to minimize impacts of marine construction and maximize benefits[46,47]. By applying nature-based solutions, marine development can serve not only their primary economic or social function, but also support a diversity of secondary functions including carbon sequestration, fisheries productivity, habitat provision, maintenance of clean air and water and resilience to climate change[10]. In any case, caution should be taken in avoiding 'greenwashing' through using 'greened' structures, which will always impact natural habitats, to facilitate and justify the growth of future developments[48].

The conservative estimates of marine construction presented here are substantial and serve to highlight the urgent concern and need for the management of marine environments. We hope these estimates will trigger national and international initiatives, such as the EU Marine Strategy Framework Directive, and boost global efforts for integrated marine spatial planning. We have highlighted that the way forward to quantifying global ecological impact associated with the extent of seafloor modification will be through mapping of historical and existing marine habitats, and by targeted impact assessments that link the magnitude of impact to the physical characteristics of different structures and habitats. We hope that this study will drive improved data collection efforts that will allow detailed estimations of the magnitude of impacts of marine construction to inform environmental solutions. The datasets provided by this study offer a starting point for a working database that can be updated over time, enabling improved estimates of the current physical footprint of marine construction and extent of seascape modified around these structures, and provide important tracking for future developments.

Methods

Because data-gathering practices have primarily been managed by individual sectors of marine industries, our search was organized by structure type. The categories were: energy infrastructure (wave, tidal and wind farms, oil and gas rigs and pipelines and cables), telecommunication cables, commercial ports, recreational marinas (as listed on the relevant websites), service infrastructure (tunnels, bridges), coastal armouring (groynes and breakwaters) and artificial reefs and marine aquaculture facilities. We have summarized the information on the extent of coastal land reclamation (that is, the infill of submerged substrate for agricultural, urban or industrial developments) in Box 1 because it has been widely reported before. We have also included an estimation of the extent of artificial islands as a form of land reclamation in Box 1. This study aimed to consider all structures in these categories built up to 2018; however, marine structures have been built for centuries (Box 2) and there are incomplete records of ancient structures. In addition, public information recording modern structures is also incomplete (see Data quality and gaps). Dumping grounds, accidentally sunk shipwrecks and other unintentional or pelagic debris deposits were not considered in this study.

Physical footprint. Information about the location, abundance and area of existing marine built structures and their spatial distribution in estuaries, coasts and open oceans was collated between June 2018 and March 2019. Data on geographical position and number and/or size (length or area) of structures supporting highly regulated industries, such as oil and gas extraction infrastructure, wind and tidal farms, telecommunication cables and commercial ports, were available in scientific articles and from international organizations and private companies, dated from 2017 to 2018, except for oil and gas infrastructure which were dated 1998–2018 (Table 1). The number of rigs per country with offshore oils and gas production (Lujala, Ketil Rod[49]) and length of subsea pipelines per EEZ were obtained through a Google search (keywords listed in Supplementary Methods and Table 1). When the area was not available for rigs, wind and tidal turbines, it was estimated based on the mean size of foundations commercially available (Table 1 and Supplementary Methods). The physical footprint of pipelines was estimated using a 1-m buffer corresponding to the average diameter of oil and gas pipelines (Table 1 and Supplementary Methods). The physical footprint of ports was calculated by measuring the area of 12 randomly chosen ports for each size category created based on area and traffic (as specified by the World Resources Institute[50]) using Google Earth Pro 7.1. We then multiplied the average area by the number of ports in each size category. The length of submarine cables was obtained through the website Submarinecablemap.com[51]. We then assumed an average of 0.08 m for the width of cables to calculate the total area of these structures (Table 1 and Supplementary Methods).

For aquaculture, marinas and artificial reefs, however, data were available only at local to national levels and came from a wide range of sources, including government reports, digital news and inventories gathered by private companies and the general public. To gather these data and create the most comprehensive dataset on marine construction, searches were conducted in Google, which can access these multiple forms of data. Keywords used for searches can be found in Supplementary Table 1. This resulted in a total of ~696 searches (232 EEZs × 3 structure types). We evaluated results in each search until either (1) an estimation of area was obtained for each EEZ from a primary source (that is, direct measurements), (2) all search outputs were checked for relevant information or (3) the tenth consecutive search output showed information irrelevant to the search topic. For recreational marinas, searches resulted in a list per EEZ of 9,628 existing marinas in 2018, compiled from a variety of government agencies and online travel guides. The physical footprint of marinas was estimated by averaging the areas of a random sample of marinas across all EEZs ($n = 440$, ~5% of the total number of marinas), measured using Google Earth Pro 7.1 (average area = 0.081 km^2), and multiplying this for the total number of reported marinas. For aquaculture, their physical footprint was mainly reported by international agencies including FAO, AQUAFIMA and the Organisation for Economic Cooperation and Development (OECD), national government agencies or scientific articles and books. These publications were dated between the years 1991 and 2018. Information on artificial reefs comprised a mix of whole-EEZ and project-by-project reports. The sources of information found were a mix of government agencies, non-governmental organizations, media articles and inventories developed by enthusiasts. For all structures missing number of reefs and/or area, estimates were made assuming that the same structure sizes and numbers as similar projects were possible, as described in Table 1 and Supplementary Methods. An additional Google search was done to create a list of artificial islands using the keyword 'artificial island'. Unreported areas of islands were measured in Google Earth Pro 7.1 (see Supplementary Methods).

Seawalls, groynes and breakwaters built to support other infrastructure were included in the calculations of physical footprint for their respective marinas, ports and land reclamation. Information on coastal armouring structures not associated with marinas, ports or land reclamation was mostly missing, except for a few efforts to list these structures by the European community (DELOS project, www.delos.unibo.it; Virtual Knowledge Centre of the Delft University of Technology, www.kennisbank-waterbouw.nl). These datasets contain the geographical location of most breakwaters listed, but incomplete information on their length and width. We have combined the data from these initiatives, plus data available from the Italian Government[52], to obtain a unified inventory of breakwaters around the world. We identified and filtered out all georeferenced breakwaters in ports and marinas using Google Earth Pro 7.1. For those georeferenced breakwaters for which no information on length or width was reported, these were measured using Google Earth Pro 7.1. For breakwaters for which a georeferenced location was not reported but information on length was available, we estimated width as the average of the reported width.

As with coastal armouring, the approval and construction of tunnels and bridges occurs locally and compilations of data were generally not available from primary sources. A Google search using the keywords 'tunnel' or 'bridge' did not produce useable information, because these words are in common usage. Hence, the only sources of information were inventories of bridges and tunnels created by the general public (including length and geographical position). Only immersed tunnels, which are excavated or layered over the seabed and covered, were included. The area of tunnels was calculated assuming that all structures had two lanes that fit a truck or bus (8 m). Because bridges are sustained by pilings and either their number or size was not reported, their physical footprint was not estimated.

Extent of modified seascape. The total extent of seascape modified by built structures extends beyond their direct physical footprint. Marine construction can modify surrounding environments by changing ecological and sediment characteristics, water quality and hydrodynamics, as well as noise and electromagnetic fields (see Supplementary Methods). To estimate the extent of such modifications, we extracted data that explicitly reported the extent of these modifications by marine construction from published studies. Because there is no consistent language to identify the extent of seascape modifications around built structures, a systematic review was not possible. Therefore, we gathered relevant studies from our databases and searched their cited and citing articles.

From this search we obtained a total of 74 articles assessing the scale of seascape modifications due to the presence of marine construction and associated operations (Supplementary Table 2). Effects during the construction or decommissioning phase, although recorded[14], were not considered here because they are often temporary. For each of the 74 studies, the reported distance of effects or area of seascape modified around each structure type was extracted for all available modification types (for example, ecological, sediment quality, noise pollution and so on; see Supplementary Table 2). For ecological modifications in particular, we assumed that effects by subsea pipelines, tunnels, bridges and breakwaters on surrounding habitats are similar to those of artificial reefs, as this study revealed that they are often built using the same materials and are even of similar shape (artificial reefs are made in a diverse range of designs). If studies included information from several locations, these were all extracted to account for spatial variability. For breakwaters, tidal farms and planned wave farms, the reported extent of the seascape modified was greatly dependent on the size of the structure or the energy extraction capacity, respectively, and highly asymmetrical. Hence, for these types of structures, we extracted data for total area (km^2) affected per 100 m of breakwater or megavolts (MV) of energy production (Supplementary Table 2). For all other structures, their effect on surrounding seascapes was reported as a measure of distance from structure. For each type of structure and modification, we calculated the mean and 95% confidence intervals of the distance or area modified whenever possible (that is, $n > 3$). Otherwise, we used the mean as well as the maximum and minimum values. We then chose the modification type with the largest extent for further calculations (estimates marked with an asterisk in Supplementary Table 2).

For those structure types for which seascape modification was expressed as a distance, the area of seascape modified per structure was calculated assuming that this effect was symmetrical around the structure and taking into consideration its position relative to the shoreline. Whereas structures in the open ocean may produce halos of seascape modification, many coastal structures abut land on one or more sides. For georeferenced data such as commercial ports and wind farms, we did this by drawing a circle of radius equal to the extent of effect around each port and farm, and excluded the abutting land area using EEZ maps (Flanders Marine Institute[53]) in R 3.6.2. As georeferenced locations were missing for marinas and aquaculture farms, we assumed that all structures were coastal for conservative estimations (marinas are coastal by definition and aquaculture farms are mostly coastal[23]). Hence, calculations of the extent of seascape modified around these two types of structures were done assuming that the effect had the shape of a semi-circle (Table 1 and Supplementary Methods). For rigs, pipelines, cables, tunnels and bridges, it was assumed that the scale of modification was sufficiently small not to reach land (around tens of metres) and, hence, modified area was calculated as a circle or corridor around each individual structure, depending on its shape (Table 1 and Supplementary Methods). For georeferenced structures (commercial ports, wind and tidal farms, bridges, tunnels and breakwaters), we also accounted for areas simultaneously affected by more than one structure by calculating the overlap of modified areas. We did this by mapping the extent of seascape modification for each commercial port, wind, wave and tidal farm, using the 'buffer' function in the *raster* package in R 3.6.2, which deletes all overlaps between structures.

To estimate the global extent of seascape modification for all structure types, we added all areas of seascape modified by commercial ports and wind farms, as calculated above, per structure type and then subtracted overlaps estimated using the function 'intersect' in the *raster* package in R 3.6.2. The shape of the area modified around tidal and wave farms, tunnels, bridges and breakwaters, however, depends on the orientation of the structure and the shape of the shoreline and bathymetry. Therefore, we avoided overlaps by removing all structures that fell within the spatial extent of modifications by wind and commercial ports from the calculations. Also, we did not include structures that did not have georeferenced data in this calculation but, given that commercial ports accounted for >96% of the global area modified (see section 'Physical footprint and modified seascapes as of 2018'), the influence of excluded structures on final estimates is negligible.

Projections for increase. To estimate the physical footprint of marine construction in 2028 we used information on planned projects or projected production growths, depending on the data available. A business-as-usual scenario was applied, assuming construction is at constant production capacity over time, there are no technological advances and that current infrastructure is working at full capacity. Under these conditions, production growth predictions are linearly related to construction growth.

For wind, tidal and wave farms, spatial extent for projects in 'early planning' to 'construction phase' (as listed in 4COffshore[54] in 2018) was calculated based on the type of foundation, as for current extent (Table 1 and Supplementary Methods). For telecommunication cables and tunnels, the area for each project in the planning or construction phase in 2018 was estimated based on the reported length, as for current extent (Table 1 and Supplementary Methods). Projected production growths of marine aquaculture and oil and gas by 2026 and 2028, respectively, as reported by the OECD[5], was used to estimate future extent. Even though projected growth in port capacity (maximum volume that can be handled at a given terminal facility in a given time period) has been reported, no estimation of seaward expansion of ports was possible because this growth will be achieved by the addition of onshore facilities (for example, roads, rails, storage capacity)[28]. Data on global growth or planned construction were not found for bridges, breakwaters, artificial reefs or artificial islands.

Because completion of wind, tidal and wave farms can take up to 10 years[55] after planning, this procedure estimated the projected extent of these structure types by 2028. Yearly growth rates were calculated for aquaculture and oil and gas considering the different time periods for market projections (2028 for oil and gas production and 2026 for aquaculture; Table 1), and their estimated extent was calculated for 2028 for consistency. Unfortunately, none of these market predictions on production reported an estimation of error. Oil and gas industries have different production projections, but their combined data were often reported in our search results. Hence, growth of oil and gas infrastructure was calculated by averaging their growth weighted on the present production.

Data analysis and visualization. Results were mapped using the packages rgdal[56], rworldmap[57] and ggplot[58] in R 3.4.1. For structure types that did not have georeferenced data (aquaculture, artificial reefs, marinas and breakwaters), the total area constructed was mapped by EEZ[53].

Data availability

The marine construction inventory produced by the authors and original data sources that support the findings of this study are available at http://doi.org/10.5281/zenodo.3898027. An inventory of offshore wind, tidal and wave farms can be found at 4Coffshore.com. Source data are provided with this paper.

Code availability

No custom computer code or algorithm was used to generate results.

Received: 2 August 2019; Accepted: 22 July 2020;
Published online: 31 August 2020

References

1. McKinney, M. L. Effects of urbanization on species richness: a review of plants and animals. *Urban Ecosyst.* **11**, 161–176 (2008).
2. Elvidge, C. D. et al. Global distribution and density of constructed impervious surfaces. *Sensors* **7**, 1962–1979 (2007).
3. Firth, L. B. et al. Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. *Oceanogr. Mar. Biol. Annu. Rev.* **54**, 189–262 (2016).
4. Gittman, R. K., Scyphers, S. B., Smith, C. S., Neylan, I. P. & Grabowski, J. H. Ecological consequences of shoreline hardening: a meta-analysis. *BioScience* **66**, 763–773 (2016).
5. *The Ocean Economy in 2030* (OECD Publishing, 2016).
6. Ali, A., Hassan, R., Bidin, R. & Theparoonrat, Y. *Enhancing Management of Fishery Resources through Intensified Efforts in Habitat Conservation and Rehabilitation* (Secretariat, Southeast Asian Fisheries Development Center, 2011).
7. Santos, M. N. & Monteiro, C. C. The Olhão artificial reef system (south Portugal): fish assemblages and fishing yield. *Fish. Res.* **30**, 33–41 (1997).
8. Murray, N. J. et al. The global distribution and trajectory of tidal flats. *Nature* **565**, 222–225 (2019).
9. Jones, K. R. et al. The location and protection status of earth's diminishing marine wilderness. *Curr. Biol.* **28**, 2506–2512. (2018).
10. Mayer-Pinto, M., Dafforn, K. A. & Johnston, E. L. A decision framework for coastal infrastructure to optimize biotic resistance and resilience in a changing climate. *BioScience* **69**, 833–843 (2019).
11. Cao, L. et al. Environmental impact of aquaculture and countermeasures to aquaculture pollution in China. *Environ. Sci. Pollut. Res. Int.* **14**, 452–462 (2007).
12. Hobbs, R. J. et al. Novel ecosystems: theoretical and management aspects of the new ecological world order. *Glob. Ecol. Biogeogr.* **15**, 1–7 (2006).
13. Merchant, N. D., Pirotta, E., Barton, T. R. & Thompson, P. M. Monitoring ship noise to assess the impact of coastal developments on marine mammals. *Mar. Pollut. Bull.* **78**, 85–95 (2014).
14. Heery, E. et al. Identifying the consequences of ocean sprawl for sedimentary habitats. *J. Exp. Mar. Biol. Ecol.* **492**, 31–48 (2017).
15. Davis, N., VanBlaricom, G. R. & Dayton, P. K. Man-made structures on marine sediments: effects on adjacent benthic communities. *Mar. Biol.* **70**, 295–303 (1982).
16. Hawkins, S. J. et al. Consequences of climate-driven biodiversity changes for ecosystem functioning of North European rocky shores. *Mar. Ecol. Prog. Ser.* **396**, 245–259 (2009).
17. Bishop, M. J. et al. Effects of ocean sprawl on ecological connectivity: impacts and solutions. *J. Exp. Mar. Biol. Ecol.* **492**, 7–30 (2017).
18. Airoldi, L., Turon, X., Perkol-Finkel, S. & Rius, M. Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. *Divers. Distrib.* **21**, 755–768 (2015).
19. Halpern, B. S. et al. A global map of human impact on marine ecosystems. *Science* **319**, 948–952 (2008).
20. Halpern, B. S. et al. Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* **6**, 7615 (2015).
21. Halpern, B. S. et al. An index to assess the health and benefits of the global ocean. *Nature* **488**, 615–620 (2012).
22. Ban, N. C., Alidina, H. M. & Ardron, J. A. Cumulative impact mapping: advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. *Mar. Policy* **34**, 876–886 (2010).
23. Kapetsky, J. M., Aguilar-Manjarrez, J. & Jenness, J. A. *FAO Fisheries and Aquaculture Technical Paper No. 549* (FAO, 2013).

24. Trujillo, P., Piroddi, C. & Jacquet, J. Fish farms at sea: the ground truth from google earth. *PLoS ONE* **7**, e30546 (2012).
25. Kaschner, K. et al. *AquaMaps: Predicted Range Maps for Aquatic Species* (Secretariat of the Pacific Regional Environment Programme, 2018); https://go.nature.com/2FhXpzU
26. Stuart-Smith, R. D. et al. Integrating abundance and functional traits reveals new global hotspots of fish diversity. *Nature* **501**, 539–542 (2013).
27. Neumann, B., Vafeidis, A. T., Zimmermann, J. & Nicholls, R. J. Future coastal population growth and exposure to sea-level rise and coastal flooding—a global assessment. *PLoS ONE* **10**, e0118571 (2015).
28. Corporate Partnership Board *Capacity to Grow: Transport Infrastructure Needs for Future Trade Growth* (International Transport Forum, OECD, 2016).
29. *NSW Boat Ownership and Storage: Growth Forecasts to 2026* (New South Wales Government, 2010).
30. Gibson, J. A., Pratt, W. B. & Holcomb, J. C. in *Report to the California Department of Boating and Waterways* 6-1–6-17 (Department of Boating and Waterways, 2002).
31. Yang, D., Liu, Q., Jiang, L., Zhang, W. & Chu, W. in *Maritime Business and Economics: Asian Perspectives* (ed. Duru, O.) 99–117 (Routledge, 2019).
32. *Artificial Reefs* (NSW Department of Primary Industries, accessed May 2020); https://go.nature.com/2DErppg
33. *Rigs to Reefs* (Bureau of Safety and Environmental Enforcement, accessed June 2019); https://go.nature.com/3fKYxsg
34. Jørgensen, D. OSPAR's exclusion of rigs-to-reefs in the North Sea. *Ocean Coast. Manag.* **58**, 57–61 (2012).
35. Eurosion *Living with Coastal Erosion in Europe: Sediment and Space for Sustainability: PART II – Maps and Statistics* (Directorate General Environment, European Commission, 2004).
36. Gittman, R. K. et al. Engineering away our natural defenses: an analysis of shoreline hardening in the US. *Front. Ecol. Environ.* **13**, 301–307 (2015).
37. Schneider, A., Friedl, M. A. & Potere, D. Mapping global urban areas using MODIS 500-m data: new methods and datasets based on 'urban ecoregions'. *Remote Sens. Environ.* **114**, 1733–1746 (2010).
38. Bunting, P. et al. The global mangrove watch—a new 2010 global baseline of mangrove extent. *Remote Sens.* **10**, 1669 (2018).
39. UNEP-WCMC & Short, F. T. *Global Distribution of Seagrasses (version 6.0)* (UN EWC Monitoring Centre, 2018);https://data.unep-wcmc.org/datasets/7
40. Kennish, M. J. Environmental threats and environmental future of estuaries. *Environ. Conserv.* **29**, 78–107 (2002).
41. Duggins, D., Simenstad, C. & Estes, J. Magnification of secondary production by kelp detritus in coastal marine ecosystems. *Science* **245**, 170–173 (1989).
42. Sheehan, E. V. et al. Development of epibenthic assemblages on artificial habitat associated with marine renewable infrastructure. *ICES J. Mar. Sci.* **77**, 1178–1189 (2018).
43. Kamermans, P. et al. Offshore wind farms as potential locations for flat oyster (*Ostrea edulis*) restoration in the Dutch North Sea. *Sustainability* **10**, 3942 (2018).
44. De Dominicis, M., O'Hara Murray, R. & Wolf, J. Multi-scale ocean response to a large tidal stream turbine array. *Renew. Energy* **114**, 1160–1179 (2017).
45. Cohen-Shacham, E., Walters, G., Janzen, C. & Maginnis, S. *Nature-based Solutions to Address Global Societal Challenges* (IUCN, 2016).
46. Dafforn, K. A. et al. Marine urban sprawl: how can ecology inform the design of multifunctional artificial structures? *Front. Ecol. Environ.* **13**, 82–90 (2015).
47. Morris, R. L. et al. *Design Options, Implementation Issues and Evaluating Success of Ecologically Engineered Shorelines* (Taylor & Francis, 2019).
48. Firth, L. B. et al. Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. *J. Appl. Ecol.* https://doi.org/10.1111/1365-2664.13683 (2020).
49. Lujala, P., Ketil Rod, J. & Thieme, N. Fighting over oil: introducing a new dataset. *Confl. Manag. Peace Sci.* **24**, 239–256 (2007).
50. *Reefs at Risk Revisited* (World Resources Institute, 2011).
51. Inventory of Submarine Telecommunication Cables (www.submarinecablemap.com). *TeleGeography* www2.telegeography.com (2018).
52. *State of the Environment 2018* (Italian Institute for Environmental Protection and Research, 2018).
53. *The Intersect of the Exclusive Economic Zones and IHO Sea Areas, Version 3* (Flanders Marine Institute, 2008).
54. Offshore wind, wave and tide farms. *4C Offshore Ltd.* www.4coffshore.com (2018).
55. Wyatt, S. et al. *Detailed Appraisal of the Offshore Wind Industry in China* (Carbon Trust, 2014).
56. Bivand, R., Keitt, T. & Rowlingson, B. *rgdal: Bindings for the 'Geospatial' Data Abstraction Library* (CRAN.R-project, 2019); https://CRAN.R-project.org/package=rgdal
57. South, A. rworldmap: a new R package for mapping global data. *R Journal* **3**, 35–43 (2011).
58. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis* (Springer, 2016).
59. *OECD-FAO Agricultural Outlook 2017–2026* (OECD Publishing, 2017).
60. Wang, W., Liu, H., Li, Y. & Su, J. Development and management of land reclamation in China. *Ocean Coast. Manag.* **102**, 415–425 (2014).
61. Reyna, J. et al. in *The First Global Integrated Marine Assessment. World Ocean Assessment* (eds Inniss, L. et al.) Ch. 26 (United Nations, 2016).
62. Murray, N. J., Clemens, R. S., Phinn, S. R., Possingham, H. P. & Fuller, R. A. Tracking the rapid loss of tidal wetlands in the Yellow Sea. *Front. Ecol. Environ.* **12**, 267–272 (2014).
63. MacKinnon, J., Verkuil, Y. I. & Murray, N. *Situation Analysis on East and Southeast Asian Intertidal Habitats, with Particular Reference to the Yellow Sea (including the Bohai Sea)* (IUCN, 2012).
64. Hugo, G. Future demographic change and its interactions with migration and climate change. *Glob. Environ. Change* **21**, S21–S33 (2011).
65. Sovacool, B. K. Hard and soft paths for climate change adaptation. *Clim. Policy* **11**, 1177–1183 (2011).
66. Loke, L. H. L., Heery, E. C. & Todd, P. A. in *World Seas: An Environmental Evaluation* 2nd edn (ed. Sheppard, C.) Ch. 26 (Academic Press, 2019).
67. Jackson, M. D. et al. Phillipsite and Al-tobermorite mineral cements produced through low-temperature water-rock reactions in Roman marine concrete. *Am. Mineral.* **102**, 1435–1450 (2017).
68. Dietz, B. Dikes, dockheads and gates: English docks and sea power in the sixteenth and seventeenth centuries. *Mar. Mirror* **88**, 144–154 (2002).
69. Palmer, S. Current port trends in an historical perspective. *J. Marit. Res.* **1**, 99–111 (1999).
70. Charlier, R. H., Chaineux, M. C. P. & Morcos, S. Panorama of the history of coastal protection. *J. Coast. Res.* **21**, 79–111 (2005).
71. Galloway, J. A. Storm flooding, coastal defence and land use around the Thames estuary and tidal river c.1250–1450. *J. Medieval Hist.* **35**, 171–188 (2009).
72. Beveridge, M. C. & Little, D. C. in *Ecological Aquaculture. The Evolution of the Blue Revolution* (ed. Costa-Pierce, B. A.) 3–29 (Blackwells, 2002).
73. D'itri, F. M. *Artificial Reefs: Marine and Freshwater Applications* (CRC Press, 2018).
74. Grosbard, A. Treadwell warf in the Summerland, California oil field: the firmest sea wells in petroleum exploration. *Oil Ind. Hist.* **3**, 1–18 (2002).
75. Priest, T. Extraction not creation: the history of offshore petroleum in the gulf of Mexico. *Enterp. Soc.* **8**, 227–267 (2007).
76. Breton, S.-P. & Moe, G. Status, plans and technologies for offshore wind turbines in Europe and North America. *Renew. Energ.* **34**, 646–654 (2009).
77. Danel, P. Tetrapods. *Coast. Eng. Proc.* **1**, 28 (1953).
78. Phillips, M. R. & Jones, A. L. Erosion and tourism infrastructure in the coastal zone: problems, consequences and management. *Tour. Manag.* **27**, 517–524 (2006).
79. Chapman, M. G. & Blockley, D. J. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. *Oecologia* **161**, 625–635 (2009).
80. Burcharth, H. F., Hawkins, S. J., Zanuttigh, B. & Lamberti, A. *Environmental Design Guidelines for Low Crested Coastal Structures* (Elsevier, 2007).

Acknowledgements
This research was supported by the Australian Research Council through a Linkage Grant (no. LP140100753) awarded to K.A.D., L.A. and E.L.J. A.B.B. was funded by a Maple Brown Foundation grant awarded to K.A.D. and R.A.C. and an Ian Potter Foundation grant to K.A.D. E.M.A.S. received funding from the World Harbour Project, The Ian Potter Foundation and The New South Wales Government Office of Science and Research. L.A. received funding through the Macquarie University FSE Visiting Researcher Fellowship Scheme. This is Sydney Institute of Marine Science (SIMS) publication no. 259.

Author contributions
All authors contributed to the original concept of this manuscript, helped in the data-gathering effort and commented on the manuscript. A.B.B., K.A.D., M.M.-P., L.A. and E.L.J. led the implementation of the initial concept and manuscript preparation. A.B.B. led the data-gathering effort, analysed data and prepared the manuscript.

Competing interests
The authors declare no competing interests.

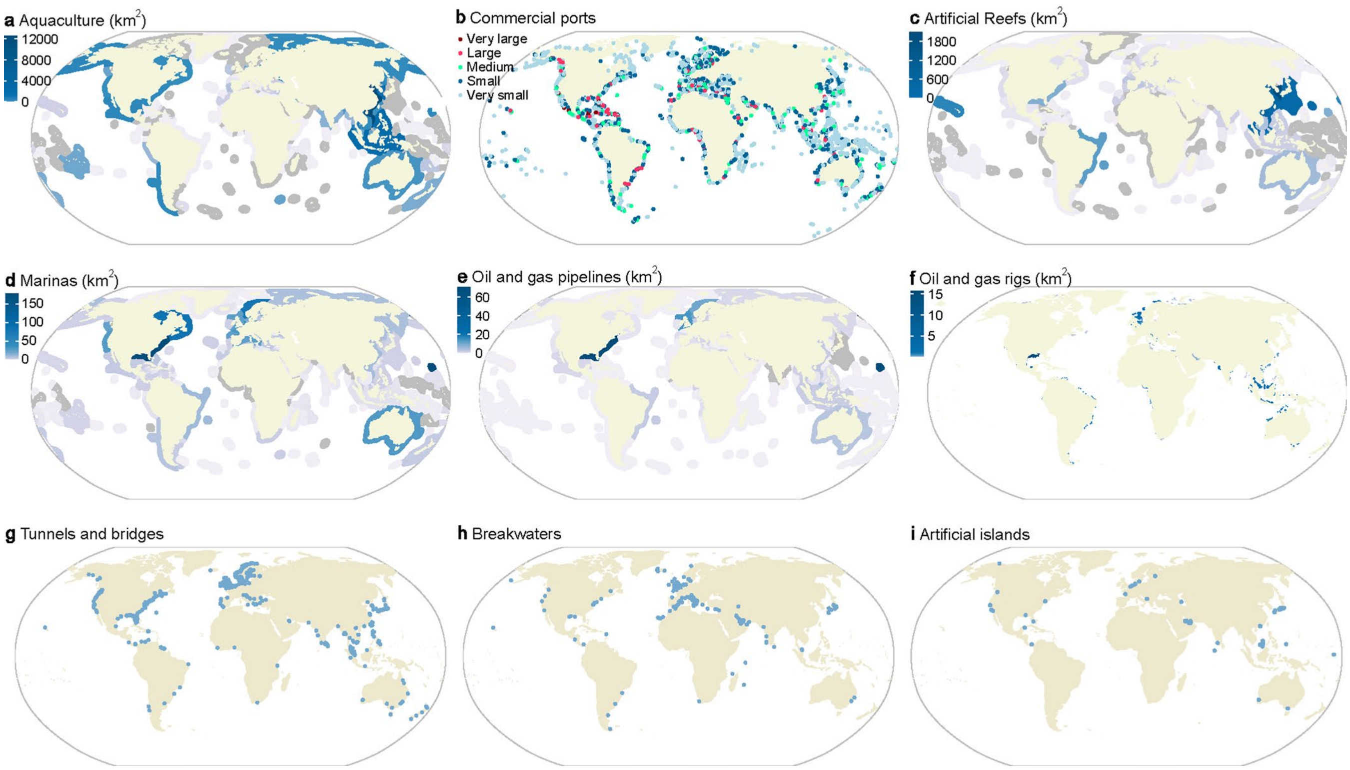
Additional information
Extended data is available for this paper at https://doi.org/10.1038/s41893-020-00595-1.

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-00595-1.

Correspondence and requests for materials should be addressed to A.B.B.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Extended Data Fig. 1 | Global distribution of physical footprint of marine construction as of 2018. Data for aquaculture **a**, artificial reefs **c**, marinas **d**, and oil and gas pipelines **e**, are expressed per km^2 within each Exclusive Economic Zone (grey: missing data). The location of commercial ports and their size (estimated considering physical size and traffic) were sourced from the World Resources Institute **b**. Oil and gas rigs **f**, are expressed per km^2 within each offshore field. Location of each structure (blue dots) is shown for tunnels and bridges **g**, breakwaters **h**, and artificial islands **i**.