
Supplementary information

Current and projected global extent of marine built structures

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Supplementary Methods: Estimations of physical footprint and seascape modified as of 2018

Data search was done between June 2018 and March 2019. The search was done per structure type (as in subheadings below).

Oil and gas rigs

The location of oil and gas platforms per country in 2007 was obtained from Lujala, Ketil Rod ¹, and updated by this study based on Harvard World Map Project ². For countries with offshore oil fields, a Google search was performed (keywords in Supplementary Table 1) to obtain the number of active and inactive (non-decommissioned) rigs. Due to a lack of information on the type of rigs used for each country, we estimated the physical footprint of rigs using an average between the area of different rig types weighted by global use of rigs. Specifically, the most commonly used type of oil and gas extraction rig is jack-up (61.5%), followed by semi-submersible (26.7%) and drillship (11.8%) ³. Areas for different models of jack-up and semisubmersible rigs (www.infield.com) were averaged to obtain the mean sizes for jack-up (3,753.8 m²) and semisubmersible (32,083.8 m²) drills. Drillship size was estimated at 3 m², as only the drilling equipment is in contact with the substratum. Weighted average size of oil rig estimated was 3,625.021 m².

Previous studies have reported changes to ecological (benthic and pelagic) communities at distances of 755 ± 679 m (mean $\pm$ 95% CI, $n = 7^{4, 5, 6, 7, 8, 9}$) from rigs, and changes in sediment characteristics at distances of 20 m ($n = 1^5$). Hence, the extent of modified seascapes around structures was estimated based on the highest of these numbers, as 755 ± 679 m. ^{4, 5, 6, 7, 8, 9 4, 5, 6, 7, 8, 9} It was assumed that this scale of modification was too small to reach land so the extent of modified seascape was calculated as a circle with radius of 755 ± 679 m (Supplementary Table 2).

Subsea pipelines

The length of subsea pipelines per Exclusive Economic Zone (EEZ) was obtained using a GoogleTM search for those EEZs with offshore oil and gas production, as above. Length of these

pipelines was either reported directly or calculated from scaled maps. Physical footprint of pipelines was estimated by multiplying length by the average diameter of oil and gas pipelines (1 m^{10}).

Previous studies assessing seascape modifications around subsea pipelines were focussed on scouring effects, which modified sediment characteristics to distances of $3.9 \pm 0.87\text{ m}$ ($n = 219^{11, 12, 13}$). From an ecological perspective, subsea pipelines add hard substratum and therefore can have similar effects than artificial reefs, estimated to reach distances of $41 \pm 20\text{ m}$ around structures (see relevant section below). Hence, the extent of modified seascape was estimated as a $82 \pm 40\text{ m}$ -wide corridor along pipelines (Supplementary Table 2).

Wind, tidal and wave farms

Information on developed and planned offshore wind, tidal and wave farms was publicly available at 4cOffshore.com and used based on 2018 data. From here, we extracted geographical location, number of turbines, the type of foundation used for turbines and length of cables for each project. The physical footprint was calculated based on (i) the minimum area for each foundation type available in the market as reported in 4cOffshore.com (Supplementary table 3, no weighted average was possible due to lack of information on use); (ii) for test sites where seafloor has been leased for testing prototypes (relevant for United Kingdom), total leased area was considered; or (ii) for planned farms, details of their foundations were usually missing (i.e. they specified if they were grounded or floating, but not the exact type used), so area was calculated based on the most common type of foundation used in existing projects (jacket and spar floater). Projects for which turbines have been attached to existing structures (e.g. bridges) or barrages that used existing breakwaters were excluded from the calculations, as these structures were included in their respective sections. Projects for which no information about foundations was available (eight wind and tidal projects) were not considered for the projections. For wind farms, physical footprint also included the area of submarine cables, calculated assuming a diameter of 0.08 m^{10} .

Wind turbines have been previously shown to produce changes in sediment characteristics at distances of 0.55 km (range 0.014 – 0.1, $n = 3^{14, 15, 16}$) around turbines, as well as in water quality (0.04 km, $n = 1^{17}$) and ecological (benthic) communities (0.04 – 0.05 km, $n = 2^{14, 17}$). But their most extensive effect is underwater noise pollution, which has been reported to reach 5.5 km (1–10, $n = 2^{18, 19}$) around turbines. The extent of modified seascapes by wind farms was therefore estimated as a circle of radius of 5.5 (1–10) km, and we accounted for overlap with land by using EEZ maps R 3.6.2 (maps by Flanders Marine Institute²⁰, Supplementary Table 2).

The area of seascape affected around tidal farms depends on the MW of energy produced, with impacts to currents extending $0.71 \pm 0.66 \text{ km}^2$ per MW of energy produced ($n = 5^{21, 22, 23, 24, 25}$), and seafloor levels extending $0.86 \pm 0.79 \text{ km}^2/\text{MW}$ ($n = 4^{24, 26, 27, 28}$). Wave farms were modelled to affect wave heights at 1.2 (0.29–3) km^2 per MW ($n = 3^{29, 30, 31}$). Hence, the extent of modified seascape around tidal and wave farms was calculated by multiplying the area of change in seafloor level or wave action (respectively) by MW of energy produced by the capacity of each farm (in MW, obtained from 4coffshore.com, Supplementary Table 2).

Telecommunication cables

The length of submarine cables was obtained from TeleGeography (www.telegeography.com) in 2018. The area of seafloor occupied by cable was estimated based on a reported common diameter of 0.08 m³². Cables were reported to erode substrates at 0.258 (0.066–0.45) m around cables ($n = 2^{33}$) as well as produce thermal radiation up to 0.2 m from cables ($n = 1^{34}$). They also produced changes in the magnetic field at 10 (8–12) m from the cable ($n = 3^{35, 36}$). Hence, the extent of modified seascapes around them was estimated as a 10 (8–12) m corridor at each side of the cable (Supplementary Table 2).

Aquaculture

Information on marine aquaculture farms were obtained through Google™ searches per EEZ (see keywords in Supplementary Table 1). For each web search, each result (website) was explored for information on farms location, number and size. As Google works on algorithms based on ‘relevance’

(match to keywords, [google.com/search/howsearchworks/algorithms](https://www.google.com/search/howsearchworks/algorithms)), websites were explored one by one until 10 consecutive results were found to be unrelated to the search topic. Our search found that the physical footprint of aquaculture farms per EEZ (not georeferenced) was mainly reported by international agencies, such as the Food and Agriculture Organization of the United Nations (FAO), Organisation for Economic Cooperation and Development (OECD) and the European Union, national government agencies or scientific articles and books (see raw data for further details). The date of data collection varied from 1991 to 2018 (see raw data). Earlier data may underestimate the physical footprint of aquaculture, but in the absence of updated data, it was used in preference to assumption-laden extrapolations, resulting in conservative estimates. As ponds (e.g. prawn farms) are often constructed on land, ponds were only included if it was explicitly mentioned that they replaced marine habitats (mangroves, tidal flats, etc).

Previous studies have shown aquaculture farms affect ecological (benthic) communities in surrounding seascapes at distances of 71 ± 36 m ($n = 16^{37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47}$) and sediment chemistry at 92 ± 68 m ($n = 17^{38, 39, 40, 42, 43, 44, 46, 48, 49, 50, 51, 52, 53, 54}$). Hence, the extent of modified seascapes was calculated per aquaculture site as a semicircle of radius 92 ± 68 m. This is conservative estimation assuming all farms are coastal, as offshore aquaculture is still in its infancy⁵⁵ (Supplementary Table 2).

Commercial Ports

The physical footprint of ports was estimated for those listed in World Resources Institute⁵⁶ by measuring a subset of ports using Google Earth Pro 7.1. The World Resources Institute dataset categorises ports by size based on physical area (on land and on water) and traffic. Twelve ports were randomly chosen for each size category (very large, large, medium, small and very small) and their area was measured using Google Earth Pro 7.1. results showed that sizes for categories “very large”, “large” and “medium” had similar physical footprint on-water (mean = 5.927 km^2 , t-test, $p > 0.05$), so an

combined average port size was used for these categories. Average sizes for “small” and “very small” ports were 0.85 and 0.083 km², respectively.

Previous studies detected sediment and ecological effects of contamination of ports at 13.2 ± 7.52 km ($n = 5^{57, 58, 59, 60}$) and noise pollution from shipping activity at distances of 19.8 ± 6.5 km ($n = 5^{18, 61, 62, 63, 64}$). The extent of modified seascapes around ports was therefore estimated as the area of water in a radius of 19.8 ± 6.5 km around each port, and filtering out land area using EEZ maps in R 3.6.2 (maps by Flanders Marine Institute²⁰, Supplementary Table 2).

Bridges and tunnels

We tabulated a list of bridges and submerged tunnels that were excavated or layered over the seabed from records collated by the general public (Wikipedia). We recorded the EEZ, length and geographical location of each. As the number and sizes of pilings supporting bridges was not readily available, the physical footprint of bridges could not be accurately estimated. However, we did consider the effect of bridges on surrounding seascapes, as they can scour sediments at 0.61 m, ($n = 1^{65}$) and act as artificial reefs, affecting benthic communities at distances of 41 ± 20 m (see below). The physical footprint of submerged tunnels was estimated using the default assumption of a width equivalent to two lanes of traffic (8 m wide). No information on the extent of seascapes modified by tunnels was found, but their ecological impacts are also likely to be similar to those of artificial reefs. Hence, for both tunnels and bridges, the extent of modified seascapes was estimated as a 82 ± 20 m-wide corridor (Supplementary Table 2).

Breakwaters

Inventories of breakwaters were obtained from DELOS⁶⁶ (EEZ, length and width per structure) and www.kennisbank-waterbouw.nl⁶⁷ (geographical coordinates, length and width). DELOS targeted structures for coastal erosion prevention and does not include structures protecting ports and marinas. To avoid counting the structures considered as part of ports and marinas, for the inventory obtained from www.kennisbank-waterbouw.nl, breakwaters in ports and marinas were filtered out by examining them one by one using (282 out of 522 were retained) and missing length or widths were measured using

Google Earth Pro 7.1. The total length of breakwaters used for coastal defence in Italy was obtained from the Italian Government⁶⁸. Width data missing for structures from DELOS and Italian Government were estimated as the average width of reported for other breakwaters (14.32m). The physical footprint of breakwaters therefore estimated as length $\times$ width.

Breakwaters have been reported to affect surrounding sediments up to 0.29 (0.23–0.35) km² ($n = 3^{69, 70, 71}$), and currents and waves over areas of 0.14 km² ⁷¹ for every 100 m of breakwater built. The extent of modified seascapes was therefore calculated as a 0.29 (0.23–0.35) km² /100 m of breakwater (Supplementary Table 2).

Recreational marinas

Number of marinas per EEZ was obtained from a variety of government agencies and online travel guides found using GoogleTM searches per EEZ as explained for aquaculture (keywords in Supplementary Table 1). Physical footprint of all marinas was estimated using an the average on-water area of a random sample of marinas across all EEZ (a total of 440) measured using Google Earth Pro 7.1 (average area = 0.081 km²).

Marinas have been shown to affect surrounding sediment communities at 20 (1–50) m ($n = 3^{72, 73}$) and release contaminants affecting sediments at 1,100 (300–2000) m ($n = 3^{74, 75, 76}$). Hence, the extent of modified seascapes was estimated per marina as a semicircle (to account for the overlap with land) of radius 1,100 (300–2000) m (Supplementary Table 2).

Artificial reefs

Information on artificial reef projects were obtained through GoogleTM searches per EEZ as explained for aquaculture (see keywords in Supplementary Table 1). Further searches were made to find for missing information for specific projects found in the first search. The sources of information found were a mix of government agencies, NGOs, media articles and enthusiasts. Navigational charts were also screened for information on artificial reefs. However, these did not yield useful information as the terms ‘obstructions’ and ‘fish havens’, which may be human-made or natural, are generally used on these.

Most sources of information included number of structures and/or area. When number of structures was not reported, a minimum number was assigned based on the wording (e.g. “reef” = 1, “reefs” = 2, “several/numerous reefs” = 3). When area of seabed occupied by artificial reefs was not reported, it was estimated based on photographs, videos or similar projects developed in the same area, at the same time and by the same organisation. In particular, where the size of Reef BallsTM was not reported, these were conservatively assigned the minimum size available (Oyster Reefball, 0.3 m in diameter)⁷⁷. Ship wrecks were assumed to be a minimum of 10 m long (minimum size of scuttled ship found) and military tanks were assumed to be 5 × 3 m. After this, any projects still lacking an estimation of area were excluded from our results.

Artificial reefs were found to modify infaunal communities in surrounding sediments at distances of 41 ± 20 m ($n = 8^{4, 78, 79, 80, 81, 82, 83, 84}$), as well as the characteristics of surrounding sediments at distances of 2–10 m ($n = 2^{4, 78}$). Hence, the extent of modified seascapes around artificial reefs was estimated as a radius or corridor of 41 ± 20 m (depending on the shape of structure), with calculations adjusted for areas of overlap among adjacent, closely-spaced structures. At sites with multiple structures where the geometric placement of units or distance between units was not reported, then structures were assumed to be deployed in a circle of area equivalent to the total area occupied by the structures in the site, hence the area of seascape modified was estimated as a buffer of 41 ± 20 m around the units. If the area of the artificial reefs was not reported, a halo of modified area was still calculated as a circle of 41 ± 20 m radius per site (Supplementary Table 2).

Artificial islands

To date, there are no studies reporting the extent of artificial islands, so we have produced an inventory of artificial islands, their location and size, and included it within our land reclamation discussion in Panel 1. A list of artificial islands and their geographical location was obtained using a GoogleTM search using the keyword “artificial island” and the same criteria used of aquaculture. Physical footprint of each artificial island was measured area using Google Earth Pro 7.1.

Supplementary Tables

Supplementary Table 1. Keywords used in several languages to collect information about ocean infrastructure around the world.

Infrastructure	Keywords in English	Keywords in other languages
Oil and gas rigs	offshore rig + <i>country name</i> ; offshore well+ <i>country name</i> ; offshore field+ <i>country name</i>	Spanish = Plataformas petroleras costa afuera + <i>country name</i>
Subsea pipelines	offshore pipelines+ <i>EEZ name</i>	Spanish = tuberias coastal afuera + <i>EEZ name</i> ; oleductos costa afuera + <i>EEZ name</i> Portuguese = oleodutos + <i>EEZ name</i>
Marinas	marina+ <i>EEZ name</i> ; boating club+ <i>EEZ name</i> ; mooring+ <i>EEZ name</i>	Spanish = puerto+ <i>EEZ name</i>
Tunnels and bridges	tunnel+ <i>EEZ name</i> ; bridge+ <i>EEZ name</i>	Spanish = tunel+ <i>EEZ name</i> ; puente+ <i>EEZ name</i>
Artificial reefs	artificial reef + <i>EEZ name</i> ; reef ball + <i>EEZ name</i>	Spanish = arrecife artificial+ <i>EEZ name</i> ; Chinese = 人造礁, 人工鱼礁; Romanian = recife artificiale; Portuguese = recife artificiai + <i>EEZ name</i> ; Bulgarian = изкуствен риф; Estonian = kunstlik reef; Catalan = escull artificial; Italian = barriera artificiale; Greek= τεχνητό ύφαλο; Persian = صخره مصنوعی; Arabic = الشعاب الاصطناعية+ <i>EEZ name</i> ; Urdu=مصنوعی ریف; Sinhala=කෘතීම ඊළුව; Bengali = কৃত্রিম রিফ; Malay = terumbu buatan; Philippino = artipisyal na bahura; Japanese = 魚礁; French = recif artificiel+ <i>EEZ name</i>
Aquaculture	<i>EEZ name</i> +mariculture OR aquaculture OR fish farming OR shellfish OR marine farming+hectare OR area OR km2	Spanish = <i>EEZ name</i> +aquaculture
Artificial islands	artificial islands	

Supplementary Table 2. Mean $\pm$ 95% CI (n), or data ranges for those with less than 3 data points, on the extent of seascape modified by the different types of structures. *Denotes the type chosen to calculate the extent of seascape modified for Figure 1b.

Structure type	Ecological	Sediment chemistry	Water quality	Current speed	Wave height	Noise	Scour	Magnetic field
Gas and oil rigs (km)	0.75 $\pm$ 0.68 (7)*	0.02 (1)						
Subsea pipelines (km)	same as artificial reefs*						0.0039 $\pm$ 0.0009 (219)	
Wind farms (km)	0.04-0.05 (2)	0.014-0.1(3)	0.4 (1)			1-10 (2)*		
Tidal farms (km ² /MW)		0.86 $\pm$ 0.79 (4)*		0.71 $\pm$ 0.66 (5)				
Wave farms (km ² /MW)					0.29-3 (3)*			
Telecommunication cables (km)	0 (1)		0.0002 (1)				0.000066-0.00045 (2)	0.008-0.012 (3)*
Aquaculture (km)	0.0709 $\pm$ 0.0363 (16)	0.0924 $\pm$ 0.0681 (17)*						
Commercial ports (km)		13.2 $\pm$ 7.52 (5)				19.8 $\pm$ 6.5 (5)*		
Tunnels (km)	same as artificial reefs*							
Bridges (km)	same as artificial reefs*						0.00061 (1)	
Breakwaters (km ² /100m length)	same as artificial reefs	0.23-0.35 (3) *		0.14 (1)	0.14 (1)			
Recreational marinas (km)	0.001-0.05 (3)	0.3-2 (3)				11.5 (1)*		
Artificial reefs (km)	0.041 $\pm$ 0.020 (8)*	0.002-0.01 (2)					0.015 (1)	

Supplementary Table 3. Minimum area for each foundation type available in the market as reported in 4coffshore.com in 2018. These were used to estimate area of wind, wave and tidal farms for projects for which data on area of foundation were missing.

Foundation type	Area (m2)
Floating	81.00
Floating semi-submersible	162.00
Floating tension leg platform	21.21
Gravity Base	254.47
Grounded (unknown type)	3.80
Monopile	12.57
Mobile jack up	18.47
Tripod	706.86
High rise pile cap	18.47
Jacket	3.80
Multipile	3.80
Suction Bucket	7.07
Tripile	21.21
Various (unknown type)	3.80

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