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Artificial reef footprint in the United States ocean

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Marine ecosystem declines have spurred global efforts to restore degraded habitats, manage marine life and enhance recreation opportunities by installing built structures called artificial reefs in seascapes. Evidence suggests that artificial reefs generate ecosystem services and risks, yet a fundamental ecological characteristic—the area of seafloor occupied by these constructed reefs—remains poorly quantified. Here we calculate the physical footprint (seafloor extent) of artificial reefs in the US ocean using spatial data from all 17 US coastal states with ocean reefing programmes. Our synthesis revealed that purposely sunk reef structures such as ships and concrete pipes occupy 19.23 km^2 of the ocean through 2020. Over the past five decades (1970–2020), the intentional reef footprint increased 20.85-fold (~1,980%), but this rate of increase slowed in the past decade (2010–2020) to 1.12-fold (~12%). These baseline findings will inform sustainable use of built marine infrastructure and generation of ecological functions.

Increased human uses of the ocean and effects from climate change have contributed to declines in coastal ecosystems[1]. These declines often manifest through reduced ecosystem extent and losses in ecosystem services[2] of structured systems such as coral reefs[3] and oyster reefs[4], as well as vegetated systems such as kelp forests[5] and seagrass meadows[6]. Approaches for managing coastal ecosystems strive to overcome these losses through restoring habitats and managing marine life, thus increasing not only habitat and biodiversity benefits but also capacities for food production and opportunities for recreation[7,8]. These approaches have traditionally been implemented by restoring natural habitat types such as vegetation or reef[9], but another popular avenue for generating multiple ecosystem

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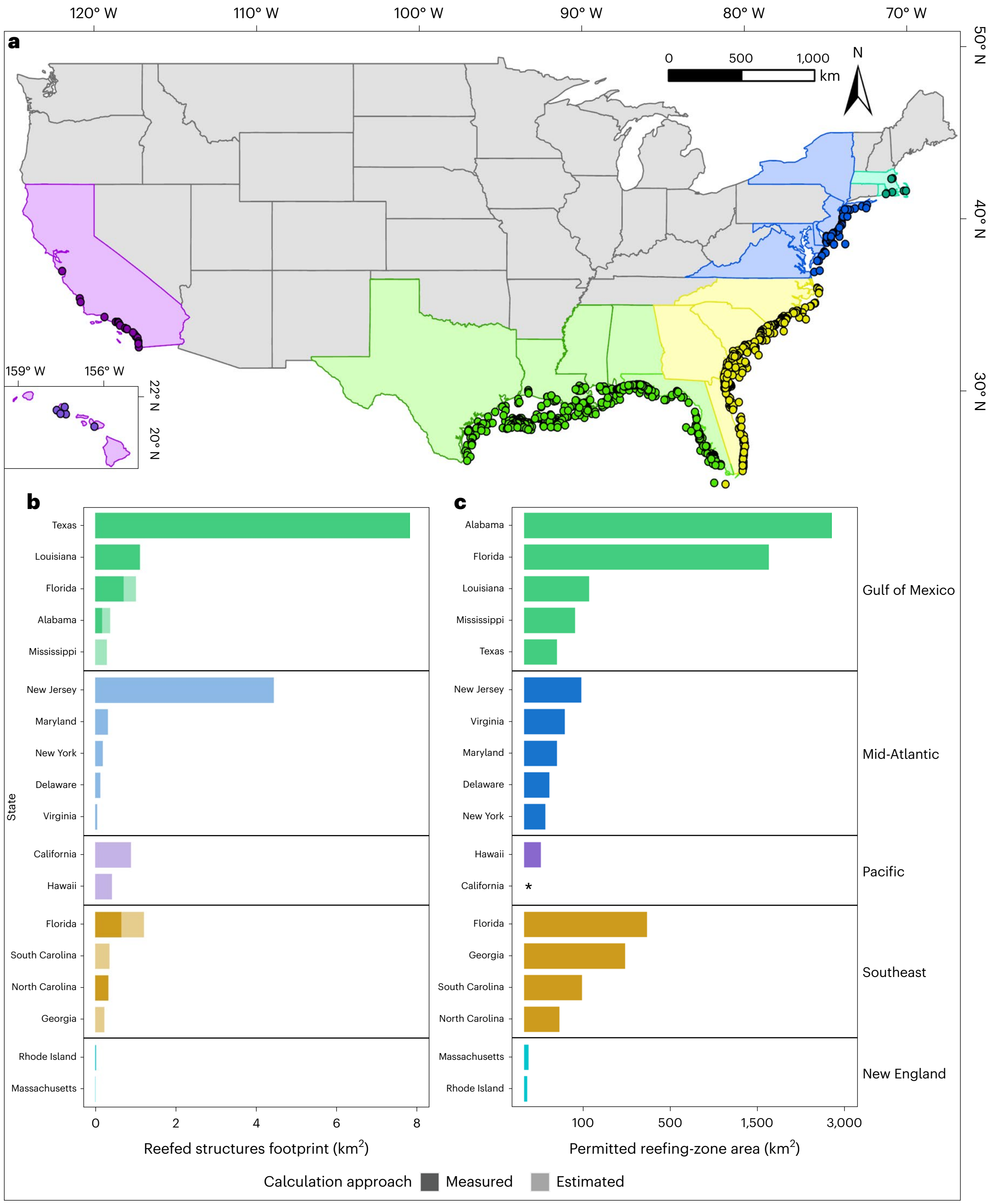

Fig. 1 | Physical footprint of artificial reefs in the US ocean (2020). a, Locations of ocean zones permitted for intentional reefing. Points correspond to reef-zone centroids. **b**, Footprint (km^2) of intentionally reefed structures by state. **c**, Permitted area (km^2) of reef zones within which structures can be reefed by state; *x* axis is square root scale, and * indicates states without designated reef-zone areas. Colour grouping indicates geographic region: New England, Mid-Atlantic, Southeast, Gulf of Mexico and Pacific. Bar shading indicates calculation approach: measured (dark shading) or estimated (light shading). States are listed in order of decreasing footprint (B) and reef-zone (C) areas.

services exists—installing artificial, built structures in the seascape to act as reefs[10,11].

Evidence suggests that intentionally sinking artificial materials such as ships, concrete pipes, bridge structures and designed modules to build reefs can generate provisioning and supporting services ranging from food production[12] to habitat enhancement[13] and recreation benefits[14]. Built reefs may also provide regulating services such as primary and secondary production[15,16] and possibly carbon sequestration[17]. Intentional reefing of built structures, however, can also lead to ecological risks through mechanisms such as enhancing habitat connectivity[18], which can facilitate the spread of invasive species[19,20] and potentially attract mobile species away from nearby natural habitats[21]. Other risks associated with artificial reefs include contamination, depending on the material used[22,23], as well as the movement of improperly secured reef structures[24]. Artificial reefs have also been linked to overexploitation of marine resources

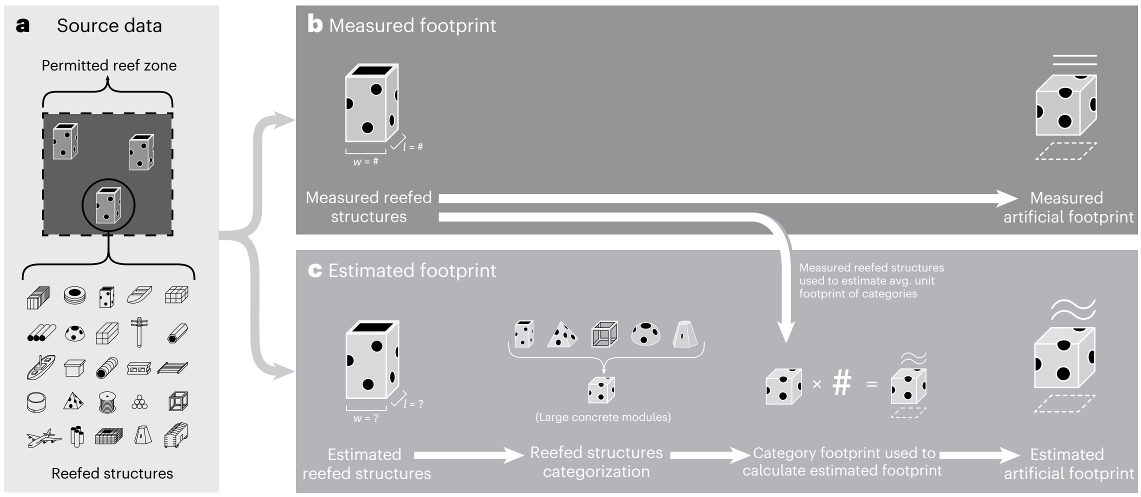

Fig. 2 | Approach for calculating footprint of reefed structures. a, Source data were obtained from 17 US states that included ocean areas zoned or permitted as locations where reefed structures are allowed. Reefed structures come in a variety of types and sizes, including ships, planes, train boxcars, bridge pieces, concrete pipes and concrete modules. **b**, Measured footprints were calculated for structures with known dimensions either from pre-deployment measurements or from seafloor mapping data collected following deployment. **c**, Estimated footprints were calculated for reefed structures that lacked dimensions. Estimated footprints were conducted for categories of reefed structures, such as large concrete modules, to find a per-unit footprint. The per-unit footprint was then multiplied by the number of reefed structures to generate the estimated artificial reef footprint at a particular location. Credit: Alex Boersma.

(for example, ecological traps) and can have unintended socioeconomic consequences, especially in developing countries if reefs are not protected[25,26].

Despite growing evidence of ecological benefits and risks linked to built reefs, a fundamental ecological characteristic of these structures—the amount of seafloor they cover—remains poorly quantified. Previous global calculations probably underestimated artificial reef extent because of data gaps—no data were available for 33% of exclusive economic zones[27]. For the United States, which hosts one of the top ten most extensive reefing systems in the world, reef data were not included (data were unpublished) for 7 states and partially included for 9 of 17 states with ocean reefing programmes[27]. Rectifying these data gaps is warranted because numbers of deployed artificial reefs are on the rise[28,29].

In this Article, we calculate the 'physical footprint' of artificial reefs in the US ocean using fine-scale spatial data from all 17 US states with ocean reefing programmes. We define an artificial reef following the US National Fishing Enhancement Act of 1984 (33 U.S.C. §2101 et seq.) as "a structure which is constructed or placed in waters (navigable US waters or those adjacent to the outer continental shelf) for the purpose of enhancing fishery resources and commercial and recreational fishing opportunities." We define physical footprint as the seafloor area covered by artificial reefs, following ref. 27. Our effort represents a collaboration among US reefing programmes to collate and synthesize the best available data (including previously unpublished data) on artificial reef extent. Because this synthesis focuses on artificial reefs, it excludes oil and gas infrastructure and historic shipwrecks, except for those managed by state artificial reef programmes. We ask the following questions. (1) How much seafloor area is covered by reefed structures (artificial reef footprint)? (2) Which types of reefed structures occupy the largest footprint? (3) How has artificial reef footprint changed over time? (4) What proportion of the seafloor permitted as reefing zones is covered by reefed structures? Answers to these questions will provide baseline data to help improve spatial planning, management and sustainable use of artificial reefs.

Results

Calculations of artificial reef physical footprint revealed that intentionally reefed structures such as ships, concrete pipes and bridges occupied 19.23 km^2 of the US ocean in 2020 (Fig. 1a,b). These footprint calculations stem from the reefing records of 17 US states, which are maintained independently by each state-managed artificial reef programme (Fig. 2a, Extended Data Table 1 and Supplementary Methods). The majority of reefing records contained measured footprints of sunken structures derived from either dimensions or tonnage recorded before sinking or delineated from habitat mapping following deployment (Fig. 2b). In cases where reefed structures lacked measured footprints, footprints were estimated using a data-driven approach informed by similar structures with known measurements (Fig. 2c). Combined measured and estimated footprints exhibited regional variability, where reefed structures in the Gulf of Mexico covered the most seafloor (10.62 km^2), followed by the Mid-Atlantic (5.13 km^2), Southeast (2.13 km^2), Pacific (1.31 km^2) and New England (0.03 km^2) (Fig. 1b). At the state level, reefed structures in Texas (7.82 km^2), New Jersey (4.44 km^2), Florida (1.22 km^2 southeast + 1.01 km^2 Gulf = 2.23 km^2 total) and Louisiana (1.14 km^2) covered the most seafloor, and Virginia (0.05 km^2), Rhode Island (0.03 km^2) and Massachusetts (<0.01 km^2) covered the least (Fig. 1b and Extended Data Table 3).

Reefed structures encompassed a diversity of materials such as concrete, metal, rock and miscellaneous materials, including materials that are now prohibited, such as rubber, fibreglass, wood and plastic (Fig. 3). Across the 17 states, there was a diversity of reefed structure types, including decommissioned ships (for example, tugboats, barges, fishing vessels, ferries, military vessels), train boxcars, aircraft, vehicles (for example, military vehicles, cars), tyres, concrete pipes, cables, lobster shelters, missile platforms, limestone pyramids, rock, manhole covers, concrete rubble, purpose-built modules, radio and power transmission towers, light poles, dry docks, bridge pieces, chicken transport cages and structures without any description (Fig. 2a). Structures also include oil and gas infrastructure such as jacket tops and bases that have been reefed and are now managed by artificial reef programmes and several historic shipwrecks that are also managed by reefing programmes (Fig. 2a). To standardize data among states for footprint calculations, the wide variety of structures were grouped into categories of similar material, size and shape (Extended Data Table 2). Of the 27 groupings, unspecified structures for which there were no structure descriptions (for example, material, size, shape missing; 5.30 km^2) had the largest footprint

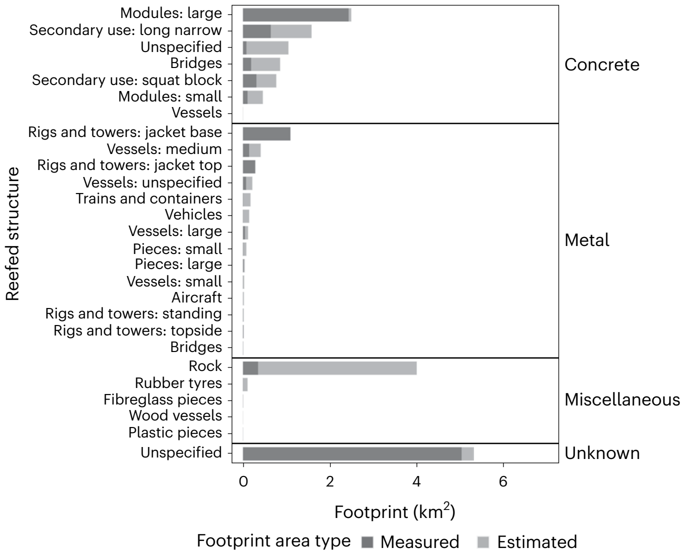

Fig. 3 | Footprint (km^2) of reefed structures in the US ocean (2020). Facets indicate reef structure material (concrete, metal, miscellaneous, unknown). Shading indicates the method used to calculate reefed structure footprint: measured (dark shading) or estimated (light shading). See Extended Data Table 2 and 4 for information on each type of reefed structure.

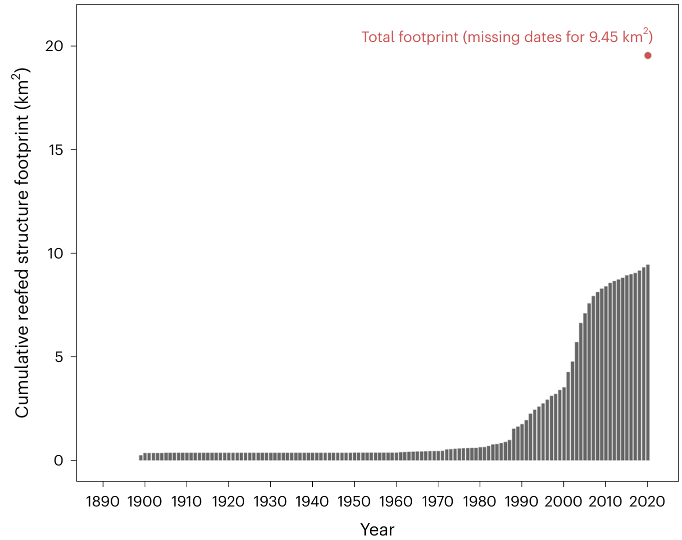

Fig. 4 | Cumulative footprint (km^2) of reefed structures in the US ocean with known reefing dates from 1899 to 2020. Date records for reefing were missing for 9.45 km^2 of structure footprints. Red point represents total footprint of structures with and without known dates.

(Extended Data Tables 4 and 5). Within reefs composed of concrete (7.19 km^2), large concrete modules extending >2 m off the seafloor that were designed specifically for reefing occupied the largest area (2.49 km^2), trailed by long, narrow concrete structures that have been repurposed for reefing (1.58 km^2), unspecified concrete materials such as rubble (1.05 km^2) and secondary-use structures with squat or block shapes (0.77 km^2). For metal reefs (2.63 km^2), portions of rigs and towers (for example, oil jacket base) covered the most seafloor (1.09 km^2), followed by medium-sized vessels (0.40 km^2). Of the miscellaneous materials, reefs composed of rocks (4.00 km^2) and rubber tyres (0.11 km^2) had the largest footprints.

The footprint of reefed structures in the US ocean has increased since the first recorded reefing event in 1899, the introduction of oil and gas infrastructure off Louisiana, which was later incorporated into the state-managed artificial reef programme (Fig. 4). This was followed closely by deployment of concrete rubble and concrete pipes in Mississippi in 1900. There were several deployments through 1950, and then reefing became more prolific starting in the 1970s. For nearly half of reefed structures (9.45 km^2), there is no recorded deployment date. The areal extent of structures for which deployment dates are known, however, increased by a factor of 20.82 (~1,980%) over the past five decades (1970–2020). The rate of change slowed in the past two decades (2000–2020), as the footprint has only increased by a factor of 2.67 (~168%) and then slowed further in the past decade (2010–2020) to a factor of 1.12 (~12%).

Whereas 19.23 km^2 of the US seafloor is occupied by reefed structures, 729 discrete seafloor areas totalling 5,811.33 km^2 have been officially designated through the permitting process as areas, which we refer to as 'zones', where intentional reefing can occur (Fig. 1c and Extended Data Table 3). Thus, as of 2020, 99.67% of the space zoned for artificial reefs is not covered by reefed structures; this reflects strategic, intentional decisions to keep portions of the permitted zones devoid of reefed structure. Alabama had the most extensive reef zones (2,751.09 km^2) and Rhode Island the least extensive (0.31 km^2). One state, California, did not have formally designated reef zones as all of California state waters are candidates for reefing, so we did not include California waters in our calculation of reef-zone area.

Discussion

This study presents a nationally coordinated calculation of a fundamental ecological characteristic of artificial reefs in the United States—their physical footprint on the seafloor. The finding that built reefs cover 19.23 km^2 of the US seafloor hinged on collating and standardizing the best available published and unpublished reefing data from all 17 US states with ocean reefing programmes. The resulting calculated footprint updates a previous US estimate (1.1 km^2; calculated by ref. 27), paints a portrait of intentional reefing in the United States and helps place US artificial reefs into the context of other built and natural habitats in the seascape.

A national portrait of artificial reef footprints

The artificial reef footprint in the United States is on the rise, as demonstrated by a 20.82-fold increase in reef extent from 1970 to 2020; however, the rate of increase has slowed substantially over the past decade (1.12-fold increase). The tapering rate of footprint increase may reflect a combination of limited funding, challenging deployment logistics and lack of available materials for reef deployments. For example, historically deployed artificial reef structures included materials of opportunity, such as rejected concrete culverts from US Department of Transportation projects, materials from demolition projects and older, decommissioned ships. Now there is a push to use intentionally designed concrete modules instead of materials of opportunity. These concrete modules often cost more per ton compared with materials of opportunity. We also hypothesize that this slowed rate of increase may relate to growing global and national emphasis on restoration of natural habitats[30], often without incorporating built structures, to help achieve targets associated with the United Nations 'Decade on Ecosystem Restoration'[8]. Other potential drivers may include the popularity of hybrid solutions (for example, structures that combine some 'grey' and some 'green' elements, such as living shorelines) sometimes in lieu of purely artificial structures[31,32]. While US artificial reefs are often established to restore or enhance habitats, many are constructed to provide sites for recreational fishing and diving. Most US artificial reefs are open to fishing and are not managed as protected areas. This is the case, for example, in Alabama, where artificial reefs are intended to help displace fishing effort from natural reefs towards artificial reefs. Recently, however, some artificial reefs in the southeastern United States have been designated as special management zones, where high-efficiency gear is now restricted to help prevent inequitable fishing and overexploitation. Careful consideration of artificial reef seascape effects and their interplay with management strategies will be a key area for future socio-ecosystem research[26,33], especially given the increasing emphasis on restoration amidst the increasing artificial reef footprint.

The reef footprint is composed of a staggering assortment of structures that have been intentionally reefed, including (especially in recent years) materials designed for reefing, as well as those reefed opportunistically. Among the designed concrete modules are commercially engineered structures, such as dome-shaped and tetrahedron-shaped modules, that can be used to create custom reefs based on recommendations from managers and stakeholders to achieve goals such as ease of stacking and offshore transport, as well as maximizing habitat enhancement or supporting target species. Engineered modules often incorporate nature-inspired designs such as holes for fish to seek refuge from predation[34] and eco-friendly construction materials suitable for rapid invertebrate colonization[35,36]. Other reefed structures have been repurposed from original functions in infrastructure (for example, concrete pipes, bridge spans), transportation (for example, vessels, trains) or energy extraction (oil rigs)[28,37]. The range of materials, shapes, sizes and vertical extents can influence services afforded by built reefs such as habitat provisioning, food production, recreation support and economic value[11,13,38]. The type of reef material can also affect the potential for pollution[22,23].

Reefed structures are typically deployed within permitted reefing zones. Our finding that the portion of the ocean zoned for reefing is several orders of magnitude greater than the footprint of reefed structures highlights that permitted reef zones are, by design, not completely covered with built reefs. This is often an intentional, strategic decision by reefing programmes to space out reefed structures for stakeholder use (for example, diffuse fishing and diving), optimize ecological connectivity[18] or create structure-free ecological buffer zones among reefed structures and around the perimeter of reefing zones[39]. For example, small and widely spaced reef structures have been demonstrated to enhance gag *Mycteroperca microlepis* abundance compared with large, clustered reef structures[40], suggesting ecological benefits from spacing out reef structures. Indeed, most permitted reef zones are established with the intent that they will (and should) take decades or more to reach a planned maximum capacity; the planned maximum capacity is not for 100% reef-zone coverage by reefed structures. For example, Florida and Georgia spread out reef structures to ensure enough space between new and existing structures to limit the risk of damaging existing reefs during deployment, as well as to allow enough foraging area for biota surrounding the reef structures. Similarly, Alabama constructs numerous reefs that are relatively small and spread out, rather than fewer larger reefs within a small area of the seafloor. There may be room for additional reefing within the already established zones if available materials and deployment events align with reefing priorities and management strategies. Ultimately, these types of ocean planning decisions should be dictated not only by logistical considerations, but also by ecological principles to minimize risks (for example, spread of invasive species, different community structure than on nearby natural habitats) and maximize benefits (for example, enhance habitat, provide connectivity corridors)[41]. For example, decisions on how much material to reef should consider seascape effects associated with reef structures and how they may alter connectivity[42] with potential benefits such as facilitating fish at their climate range edges[43] but also unintended consequences such as assisting the spread of invasive species[20].

The level of detail contained in reefing records varied by state, requiring a reproducible approach for footprint calculations using measured footprints when available and using a data-driven approach to estimate missing footprints. Missing footprints were estimated on the basis of the best available data, that is, measured footprints of similar reef structures. While this approach garnered the comprehensive reef footprint calculation in the United States, it makes several assumptions. First, it assumes that measured dimensions of structures either pre-sinking or post-sinking are static and not subject to changes from deterioration, physical disturbances or intentional removal. Deterioration, especially of metal structures from corrosion in saltwater[44], can reduce footprints to near zero. Physical disturbances can cause scour and alternatingly bury or expose built reefs with sediment[45,46], and in more extreme cases can break artificial reefs into multiple pieces or relocate reefed structures[47], altering footprints. Concerted efforts (for example, Osborne Reef waste tyre removal project, Florida) have been made to remove reefed structures such as tyres that, due to their mobility combined with physical disturbances from storms and currents, often moved from their deployment locations, notoriously washing up on beaches[24]. Such removal efforts can also affect footprint calculations. Second, our estimation approach assumes that reefed structures of similar shapes and sizes have similar footprints. If for a given class of structures, those with known footprint substantially differ in footprint from those for which we estimated the footprint, then our approach may lead to biased or otherwise inaccurate figures. For example, we assume that concrete pipes, concrete culverts and other long and narrowly shaped secondary-use concrete have similar footprints, but they may differ slightly, especially if these materials are intentionally spread out across the seafloor versus piled atop one another.

Pronounced data gaps existed in reefing records. Most notably, there were many reefed structures of unspecified material type, quantity and deployment date. In these cases, we substituted an average of other materials' footprints for these unspecified structures, which may have over- or underestimated the footprint. This approach, however, was necessary to estimate the US artificial reef footprint from the differing levels of information recorded by ocean reefing programmes. Our artificial reef footprint calculation highlights the need to fill such gaps through efforts such as censusing reef structures to update and validate footprint calculations. These updated footprint calculations could be collected using seafloor mapping techniques and associated sensors (for example, multibeam echosounder, side-scan sonar, LIDAR). To ensure that the footprint calculated here can serve as a baseline that can be updated as reefing continues, states may consider developing a collaborative, standardized reefing database. Such a nationwide database could not only help track changes in footprint and patterns in artificial reef deployments (for example, structure type, depth, vertical relief), but also inform interstate spatial planning decisions related to multiple ocean uses.

Placing built-reef footprints into a broader seascape context

The national reef footprint calculation can be applied to quantify seascape effects associated with intentional reefing that extend beyond the physical structure footprint. These modified seascape effects can be pronounced and have been estimated to extend in a semi-circle with radius 92 ± 68 m around artificial reefs[27]. Specifically, the national footprint of artificial reefs provides spatial data needed to help scale up calculations of seascape benefits such as primary and secondary production[15,16,48] and seascape risks such as the spread of invasive species[49] often quantified on subsets of built reefs. This could pave the way for regional calculations of reef productivity, as has been conducted for oil and gas infrastructure in California[50] and artificial reefs in Australia[48], as well as natural habitats, such as seagrass, salt marsh and oyster reefs[51]. The footprint also provides baseline spatial data necessary for improved ecological connectivity modelling of artificial reef arrangements in the seascape that would help determine optimal locations for new built reefs. Such models could forecast invertebrate larval dispersal, invasive species spread and fish population dynamics. For example, fish movement patterns such as residence time and home range relative to artificial reefs[52–54] could inform reef placement for particular species or assemblages to best meet enhancement goals.

Similarly, models could help estimate spatial and temporal patterns in stakeholder use, including fishing effort and vessel traffic, experienced on constructed reefs, as well as socioeconomic outcomes associated with artificial reefs.

Knowing the footprint of artificial reefs provides baseline data that help place their seascape presence within the context of other habitat types of natural and anthropogenic origins. Our estimates of artificial reef footprint indicate that their seafloor cover represents a 'drop in the bucket' compared with seafloor cover of natural systems such as coral and rocky reefs[29,55] or sand shoals[56] in the US ocean. Indeed, in a companion analysis to this study, our team compared artificial and natural reef extents in the southeast United States and found that artificial reefs are several orders of magnitude less extensive than natural reefs (artificial reefs <0.01% versus natural reefs 2.57% of the southeast US continental shelf and upper slope between 10 m and 200 m)[29]. Other built structures in the United States not included in our estimated artificial reef footprint include active oil rigs and pipelines (71,194 linear km (ref. 27); only oil infrastructure reefed and now managed by artificial reef programmes is included in our national artificial reef footprint), maricultural infrastructure (337 km^2 (ref. 27)), marinas (179 km^2 (ref. 27)) and hardened shorelines (22,842 linear km (ref. 57)). Compared with these other built structures, artificial reefs cover less seafloor but are unique because their intentional deployment aims to meet diverse goals (increase fishing yield, mitigate habitat loss, create scientific experiments, provide stakeholder fishing and diving opportunities and restore habitats[10]) and either are or have the capacity to be adaptively managed[41]. Other types of human-made structures in the seascape include historic shipwrecks, for which no US footprint is available, so it is unclear how the footprint of artificial reefs compares with that of historic shipwrecks. Wind turbines and other renewable energy infrastructure are also being introduced to the seascape; as of 2020, there were five wind turbines offshore of Rhode Island (Block Island Wind Farm) and two offshore of Virginia (Coastal Virginia Offshore Wind). However, the footprint of structured habitat created by offshore wind farms in the United States is expected to grow substantially in the next decade.

Despite their small national footprint, built reefs have been documented to have high rates of biological productivity[48,50] (but see aggregation versus production debate[16,21]). We hypothesize that, in some settings, constructed reefs may have an outsized effect on seascape ecology even with their relatively small footprint compared with other seascape habitats (see recent confirmation from ref. 58). There are several possible mechanisms that could explain this, including the vertically extensive nature of some introduced reefs, nature-inspired designs and strategic placement in habitat limited areas or in locations close to stakeholder access. Artificial reefs should continue to be evaluated to understand how they function ecologically within the context of other built and natural systems in the seascape and to ensure their sustainable use and ability to generate ecological services.

Methods

Data acquisition and collation

All 17 US states with ocean reefing programmes contributed their best available data on permitted reef zones and the reefed structures within, dating from the start of their reefing records through 2020 (Fig. 1a and Extended Data Table 1). Most states maintained detailed records of zones, which we define as ocean areas officially designated through permitting processes as locations where artificial reef structures such as metal vessels and concrete modules (for example, specially designed concrete reef structures) can be legally deployed, including their spatial extent (coordinates, polygons), depths and seafloor area covered. Records of the extensive array of structures (for example, concrete pipes, metal vessels, rubber tyres, chicken transport cages, train boxcars, voting machines, reefed oil and gas infrastructure) of different shapes, sizes and materials intentionally deployed within reef zones varied considerably among states. Some states maintained detailed records of structure types, materials, quantities and measured physical footprints (seafloor extent of reefed structures), whereas several states' records of reefed structures were sparser and lacked detailed descriptions, quantities and footprints (Extended Data Table 1). We collated and standardized state data using R version 4.2[59] and ArcGIS Pro version 2.9[60] to enable calculations of reefed seafloor area using measured footprints when available and—when unavailable—by estimating footprints (Fig. 1b,c, Extended Data Table 1 and Supplementary Methods). Only reef structures deployed by or now managed by state-managed artificial reef programmes are included in this analysis. Active oil and gas infrastructure are excluded from the analysis because they are not part of state artificial reef programmes. Select oil and gas infrastructure and historic shipwrecks that are now managed by artificial reef programmes are included in the synthesis.

Calculating artificial reef footprints

Measured physical footprints, which represent the most accurate values of seafloor area covered by reefed structures, were fully available for five states and partially available for two states. These measured footprints stemmed from either detailed structure dimensions recorded before deployment (Fig. 1b) or delineation of structure footprints from habitat mapping post-deployment. One state, Florida, modelled footprints for some structures on the basis of validated relationships between structure tonnage and footprint; we consider these model-based footprints to be accurate so include them as a type of measured footprint.

Reefed structures in most states did not have measured footprints, so in these cases, we developed a data-driven approach to estimate the amount of seafloor covered by particular types of structures, such as concrete pipes or large metal vessels (Fig. 1c). We categorized the wide variety of unique reefed structures into 27 broader categories accounting for structure material, size, shape, vertical relief and degradation rate (Extended Data Table 2), as done by ref. 29 and similar to ref. 55. For each category, we calculated the average unit footprint (measured area per count, measured area per ton) from structures for which we had empirical footprint measurements. We then applied these average unit footprints to structures that required footprint estimations. Specifically, we multiplied the average unit footprint by structure quantity (count, ton) for reef structures lacking measured footprints. In cases where we needed to estimate footprint structure but lacked quantity information (for example, unspecified number of concrete pipes deployed), we applied the average footprint area from measured structures across all quantities within an entire category (for example, average footprint of concrete modules).

Determining patterns in reef footprints

For each state, our calculations resulted in measured, estimated or a combination of measured and estimated footprints for reefed structures. Using aggregated footprint estimates by state, region and the nation, we determined spatial and temporal patterns in artificial reef footprints. Specifically, we compared the seafloor area zoned for artificial reefs (sum of reef-zone areas) with the seafloor area occupied by reefed structures (sum of reefed structure footprints). We also examined the footprint of different types of reefed structures, as well as changes in seafloor area covered by reef structures over time.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The US artificial reef inventory produced by the authors is available at https://doi.org/10.5281/zenodo.10235600. The archive includes compiled data on permitted reef zones (Data S1) and reefed structures (Data S2).

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Author contributions

A.B.P., D.N.S., G.T.K., J.C.T., N.M.B. and K.L.R. conceptualized this research. Data on artificial reefs were provided by artificial reef coordinators for each state: K.J.M., J.R., Z.H.H., J.S.B., C.B., A.N., E.S., P.J.C., C.L., P.D.B., M.R., D.C.N., R.B.R., D.T.W., J.B.S. and P.W. Some state artificial reef coordinators converted their states' data into the standard project format, and in other cases D.N.S. and A.B.P. converted data into the project format. A.B.P. and D.N.S. developed the footprint calculation approach with support from G.T.K., J.C.T., N.M.B. and K.L.R. A.B.P., D.N.S., K.J.M. and J.R. led development of structure categorization. M.R., D.T.W., Z.H.H., J.S.B., D.C.N., R.B.R., P.J.C. and C.B. assisted in developing structure categorizations and categorizing their states' structures. J.R. wrote code required for Florida data wrangling and footprint estimations. R.B.R. and D.C.N. conducted spatial analyses for Alabama reef structures. A.B.P. and D.N.S. cleaned, processed and analysed the overall dataset. A.B.P., D.N.S. and B.J.R. developed synthesis code and produced figures and tables. A.B.P. and D.N.S. drafted the manuscript. All authors reviewed and edited the manuscript and approved submission.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Table 1 | Approach used to calculate artificial reef structure per US state

state	footprint method	reef zone data	reefed structures data
Alabama	measured; estimated	manager provided shapefile	manager provided shapefile
California	estimated	reef guide document from 2001	reef guide document from 2001
Delaware	estimated	reef guide document	reef guide document
Florida	measured; modeled; estimated	manager provided in project template	manager provided in project template
Georgia	estimated	manager provided shapefiles	manager provided shapefiles
Hawaii	estimated	manager provided documents	manager provided documents
Louisiana	measured	manager provided shapefile	manager provided shapefile
Maryland	estimated	reef guide document; charter captain interview	charter captain interview
Massachusetts	measured	manager provided in project template	manager provided in project template
Mississippi	estimated	manager provided shapefile	manager provided shapefile
New Jersey	estimated	manager provided spreadsheet	reef guide document
New York	estimated	reef guide document	reef guide document
North Carolina	measured	manager provided shapefiles	manager provided shapefiles
Rhode Island	measured	manager provided in project template	manager provided in project template
South Carolina	estimated	manager provided spreadsheets	manager provided spreadsheets
Texas	measured	manager provided feature layers	manager provided shapefile
Virginia	estimated	manager provided .KMZ	manager provided shapefiles supplemented by website text and reef guides

Details on the format of data provided for permitted artificial reef zones and the reefed structures within.

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Extended Data Table 2 | Standardized categories of reefed structures in the United States

structureID	material	type	sub_type	relief	degradation	description
concrete_secondary-use_long-narrow	concrete	secondary-use	long-narrow	< 2 m	low	concrete structures of secondary use with long or narrow shape, such as pipes, pilings, utility poles, railroad ties, culverts
concrete_secondary-use_squat-block	concrete	secondary-use	squat-block	< 2 m	low	concrete structures of secondary use with squat or block shape, such as junction boxes, ballast blocks, boxes, catch basins
concrete_modules_small	concrete	modules	small	< 2 m	low	low-relief concrete modules specifically for reef formation, such as Reef Balls™
concrete_modules_large	concrete	modules	large	> 2 m	low	high-relief concrete modules specifically for reef formation, such as tetrahedrons
concrete_bridges	concrete	bridges	NA	> 2 m	low	concrete bridge material, including spans, dividers, and pilings
concrete_vessels	concrete	vessels	NA	> 2 m	low	concrete vessels, of any size
concrete_unspecified	concrete	unspecified	NA	< 2 m	low	concrete rubble or other concrete structures with unspecified type or shape
metal_pieces_small	metal	pieces	small	< 2 m	high	small, low relief (<2m tall) metal pieces, such as chicken transport cages and cables
metal_pieces_large	metal	pieces	large	> 2 m	medium	large, high relief (>2m tall) metal pieces, such as cable reels, missile sleeves, oil tanks, and yarn racks
metal_rigs-towers_tower-standing	metal	rigs-towers	tower-standing	> 2 m	medium	metal towers or oil rigs that are standing
metal_rigs-towers_jacket-base	metal	rigs-towers	jacket-base-toppled	> 2 m	medium	metal towers or oil rig jacket bases that have been toppled, partially removed, or towed
metal_rigs-towers_jacket-top	metal	rigs-towers	jacket-top	> 2 m	medium	metal towers or oil rig jacket tops
metal_rigs-towers_topside	metal	rigs-towers	topside	>2 m	medium	metal topside component of oil rig, such as deck
metal_aircraft	metal	aircraft	NA	> 2 m	medium	metal aircraft
metal_vehicles	metal	vehicles	NA	> 2 m	medium	metal vehicles, such as army tanks and automobiles
metal_trains-containers	metal	trains-containers	NA	> 2 m	high	metal train boxcars or shipping containers
metal_vessels_small<60ft	metal	vessels	small<60ft	> 2 m	medium	small metal vessels (often recreational) and barges, less than 60 ft long
metal_vessels_medium60-400ft	metal	vessels	medium60-400ft	> 2 m	medium	medium metal vessels and barges, between 60 ft and 400 ft long
metal_vessels_large>400ft	metal	vessels	large>400ft	> 2 m	medium	large metal vessels and barges, greater than 400 ft
metal_vessels_unknown	metal	vessels	NA	>2 m	medium	unknown metal vessels of any length
metal_bridges	metal	bridges	NA	> 2 m	medium	metal bridge pieces, such as spans
rubber_tires	rubber	tires	NA	< 2 m	high	rubber tires
fiberglass_pieces	fiberglass	pieces	NA	> 2 m	high	fiberglass pieces of any size, such as boat molds and vessels
wood_vessels	wood	vessels	NA	> 2 m	high	wooden vessel, of any size
plastic_unspecified	plastic	unspecified	NA	< 2 m	medium	plastic structures, such as plastic modules, plastic containers, plastic pipes
rock_unspecified	rock	unspecified	NA	< 2 m	low	rock structures, such as boulders and quarry rock
unknown_unspecified	unknown	unspecified	NA	NA	unknown	structures of unknown material and unspecified type

Each category includes the information on the material and finer classifications like the type and – as warranted – a sub-type. Vertical relief or height on the seafloor is also provided as either low relief (<2 m) or high relief (>2 m). Degradation is classified as low, medium, and high, as determined through conversations with state managers.

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Extended Data Table 3 | Artificial reef extent by US state and region

		reef zones		reefed structures		
region	state	n	extent (km^2)	measured footprint (km^2)	estimated footprint (km^2)	total footprint (km^2)
Gulf of Mexico	AL	14	2751.09	0.17	0.20	0.38
Gulf of Mexico	MS	23	75.47	NA	0.29	0.29
Gulf of Mexico	LA	126	123.11	1.11	NA	1.11
Gulf of Mexico	TX	92	31.47	7.82	NA	7.82
Gulf of Mexico	FL	158	1742.59	0.71	0.31	1.01
Mid-Atlantic	NY	8	13.16	NA	0.19	0.19
Mid-Atlantic	NJ	18	95.24	NA	4.44	4.44
Mid-Atlantic	DE	5	18.61	NA	0.13	0.13
Mid-Atlantic	MD	10	31.66	NA	0.32	0.32
Mid-Atlantic	VA	5	48.07	NA	0.05	0.05
Pacific	CA	NA	NA	NA	0.89	0.89
Pacific	HI	5	8.19	NA	0.42	0.42
Southeast	NC	43	36.26	0.33	NA	0.33
Southeast	SC	47	97.85	NA	0.36	0.36
Southeast	GA	31	297.62	NA	0.23	0.23
Southeast	FL	113	440.02	0.65	0.56	1.22
New England	MA	5	0.60	0.01	NA	0.01
New England	RI	2	0.32	0.03	NA	0.03
TOTAL		**734**	**5811.33**	**10.83**	**8.40**	**19.23**

For each state and geographic region, the number of permited reef zones (n) and their summed area (extent, km^2) are provided. The reefed structure footprint (measured, estimated, total; km^2) is also provided.

Extended Data Table 4 | Artificial reef footprints by structure type

structureID	material	measured footprint (km^2)	estimated footprint (km^2)	total footprint (km^2)	unit area (m^2) per count	average area (m^2) across counts	unit area (m^2) per ton	average area (m^2) across tons
concrete_bridges	concrete	0.19	0.67	0.85	89.33	564.21	2.72	716.79
concrete_modules_large	concrete	2.43	0.06	2.49	15.00	1205.33	3.77	33.11
concrete_modules_small	concrete	0.11	0.35	0.45	7.66	109.07	2.97	51.16
concrete_secondary-use_long-narrow	concrete	0.64	0.94	1.58	60.17	657.58	3.67	377.85
concrete_secondary-use_squat-block	concrete	0.31	0.46	0.77	18.49	455.81	2.68	1659.07
concrete_unspecified	concrete	0.08	0.97	1.05	36.49	2045.71	1.81	2409.96
concrete_vessels	concrete	<0.01	<0.01	<0.01	51.98	51.98	5.64	10.53
fiberglass_pieces	fiberglass	<0.01	<0.01	0.01	62.93	247.50	NA	NA
metal_aircraft	metal	<0.01	0.02	0.02	469.19	473.87	NA	NA
metal_bridges	metal	<0.01	0.01	0.01	425.75	425.75	NA	NA
metal_pieces_large	metal	0.02	0.02	0.04	24.98	99.60	5.56	99.03
metal_pieces_small	metal	0.01	0.07	0.08	8.27	8.33	6.39	75.04
metal_rigs-towers_jacket-base	metal	1.09	NA	1.09	1904.13	1904.13	NA	NA
metal_rigs-towers_jacket-top	metal	0.28	NA	0.28	NA	NA	NA	NA
metal_rigs-towers_topside	metal	0.02	NA	0.02	624.10	624.10	NA	NA
metal_rigs-towers_tower-standing	metal	0.01	0.01	0.02	261.12	261.12	20.19	112.5
metal_trains-containers	metal	0.01	0.16	0.17	41.71	243.83	5.25	152.62
metal_vehicles	metal	0.01	0.13	0.14	34.63	35.22	0.81	50.62
metal_vessels_large>400ft	metal	0.04	0.07	0.12	2775.54	2775.54	0.34	15545
metal_vessels_medium60-400ft	metal	0.14	0.27	0.41	521.69	521.69	2.06	646.52
metal_vessels_small<60ft	metal	0.01	0.02	0.03	162.35	162.35	7.71	45.42
metal_vessels_unknown	metal	0.07	0.14	0.21	620.97	620.97	2.55	100
plastic_unspecified	plastic	<0.01	<0.01	<0.01	1.39	4.18	NA	NA
rock_unspecified	rock	0.35	3.65	4.00	775.33	1478.76	1.88	2342.07
rubber_tires	rubber	<0.01	0.10	0.11	1.52	168.49	0.20	201.67
unknown_unspecified	unknown	5.03	0.27	5.3	50.69	7670.41	1.07	600
wood_vessels	wood	<0.01	<0.01	<0.01	185.81	185.81	NA	NA
TOTAL		**10.83**	**8.40**	**19.23**	**9231.22**	**23001.34**	**77.27**	**25228.96**

For each structure type, the reefed structure footprint (measured, estimated, total; km^2) is provided. The unit area (m^2) per count and per ton are included, as are the average (m^2) area across counts and tons.

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Extended Data Table 5 | Artificial reef footprints by structure material

material	measured footprint (km^2)	estimated footprint (km^2)	total footprint (km^2)
concrete	3.75	3.44	7.19
metal	1.70	0.93	2.63
fiberglass	<0.01	<0.01	0.01
plastic	<0.01	<0.01	<0.01
rock	0.35	3.65	4.00
rubber	<0.01	0.10	0.11
wood	<0.01	<0.01	<0.01
unknown	5.03	0.27	5.30
TOT AL	**10.83**	**8.40**	**19.23**

For each structure material, the reefed structure footprint (measured, estimated, total; km^2) is provided.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	All 17 U.S. states with ocean reefing programs contributed their best available data on permitted reef zones and the reefed structures within, dating from the start of their reefing records through 2020.
Data analysis	Data were collated, standardized, and synthesized in R (version 4.2).

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Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The U.S. artificial reef inventory produced by the authors is available at: http://doi.org/10.5281/zenodo.10235600. The archive includes compiled data on permitted reef zones (Data S1) and reefed structures (Data S2).

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study presents findings from the first nationally coordinated calculation of a fundamental ecological characteristic of built reefs in the U.S. – their physical footprint on the seafloor. Drawing upon the best available published and unpublished data from all 17 U.S. states with ocean reefing programs, we calculated the area of reef zones and the area of reefed structures in the U.S.
Research sample	Samples correspond to artificial reef zones and reefed structures.
Sampling strategy	N/A
Data collection	All 17 U.S. states with ocean reefing programs contributed their best available data on permitted reef zones and the reefed structures within, dating from the start of their reefing records through 2020.
Timing and spatial scale	Through 2020
Data exclusions	N/A
Reproducibility	N/A
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging