A global meta-analysis of ecological effects from offshore marine artificial structures

Lemasson, AJ

https://pearl.plymouth.ac.uk/handle/10026.1/22266

10.1038/s41893-024-01311-z
Nature Sustainability
Springer Science and Business Media LLC

nature sustainability

Analysis

https://doi.org/10.1038/s41893-024-01311-z

A global meta-analysis of ecological effects from offshore marine artificial structures

Received: 13 April 2023

Accepted: 14 February 2024

Anaëlle J. Lemasson[1], Paul J. Somerfield[2,5], Michaela Schratzberger[3], Murray S. A. Thompson[3], Louise B. Firth[1,4], Elena Couce[3], C. Louise McNeill[2], Joana Nunes[2], Christine Pascoe[2], Stephen C. L. Watson[2] & Antony M. Knights[1,4]

Marine artificial structures (MAS), including oil and gas installations (O&G) and offshore wind farms (OWFs), have a finite operational period. Selecting the most suitable decommissioning options when reaching end-of-life remains a challenge, in part because their effects are still largely undetermined. Whether decommissioned structures could act (sensu 'function') as artificial reefs (ARs) and provide desired ecological benefits is of particular interest. Here we use a meta-analysis approach of 531 effect sizes from 109 articles to assess the ecological effects of MAS, comparing O&G and OWFs to shipwrecks and ARs, with a view to inform their decommissioning. This synthesis demonstrates that while MAS can bring ecological benefits, important idiosyncrasies exist, with differences emerging between MAS types, habitat types, taxa and ecological metrics. Notably, we find limited conclusive evidence that O&G and OWFs would provide significant ecological benefits if decommissioned as ARs. We conclude that decommissioning options aimed at repurposing MAS into ARs may not provide the intended benefits.

The direct environmental consequences of the Anthropocene include global climate change from emissions, habitat degradation, and loss and homogenization of biodiversity[1,2] resulting in a global redistribution of life[3,4]. The speed and scale of these changes underpin the international recognition that urgent action must be taken to prevent and mitigate further degradation. In response, governments have adopted targets for habitat protection, biodiversity and emissions[5]. For instance, several nations have committed to protect 30% of land and seas, to halt and reverse biodiversity loss by 2030[6], and set targets of net-zero emissions by 2050 as part of their decarbonization agenda[7].

To fulfil their energy transition and achieve their targets, governments are pushing for reduced reliance on fossil fuel[8]. For many coastal nations, an option is to promote green renewable energies such as offshore wind farms (OWFs) and other renewable energy installations, leading to the creation of marine artificial structures (MAS)[9]. MAS also include older well-known structures such as oil and gas (O&G) installations and now represent widespread features of marine ecosystems[9,10]. All MAS will eventually reach their ends of operational life and require decommissioning[11,12]. With many O&G and some OWF installations already at that stage, societies must make choices regarding MAS decommissioning.

How best to tackle the urgent but complex decommissioning problem is an on-going challenge, with several options being proposed[13] and no clear scientific consensus on which option(s) might be preferable. Because studies have suggested that some existing structures might provide valuable habitat for marine organisms[13–15] and thus provide similar function to artificial reefs (ARs), one option that has gained momentum over the past two decades is the repurposing of O&G installations as ARs (for example, 'Rigs-to-Reefs' programme in the USA[14]). Similarly, OWFs have the potential to function as ARs[15,16], with

---

[1]School of Biological and Marine Sciences, University of Plymouth, Plymouth, UK. [2]PML – Plymouth Marine Laboratory, Plymouth, UK. [3]Cefas - Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Suffolk, UK. [4]Present address: School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland. [5]Deceased: Paul J. Somerfield. e-mail: anaelle.lemasson@plymouth.ac.uk

the suggestion of a 'Renewables-to-Reefs' programme[17]. ARs are 'submerged structures deliberately constructed or placed on the seabed to emulate some functions of a natural reef'[18]. Most ARs consist of either purpose-built structures (for example, ReefBalls) or anthropogenic structures and materials repurposed to function as ARs (for example, scuttled vessels or used tyres)[19]. They have a long history of being deployed for societal benefits (for example, fisheries enhancement), to protect sites from harmful or illegal activities (for example, trawling), or to enhance habitats and ecosystems[20,21]. They can also be placed in sedimentary habitats to provide ecological benefits associated with the introduction of hard substrate and/or habitat heterogeneity or be used in degraded natural reefs systems to restore or improve functioning by replicating lost features. As such, they may be an important tool to promote biodiversity—thus helping reach targets—and achieve environmental net gain that includes wider benefits to society (for example, increased/improved ecosystem services and natural capital)[22].

Whether repurposed O&G and OWFs function as ARs is yet to be established with any degree of certainty. A recent systematic synthesis describing the evidence base for the ecological effects of decommissioned MAS demonstrates that it is too disparate and sparse to ascertain whether they behave as ARs[23]. While a plethora of studies on the effects of standing MAS (including ARs) were identified (947 articles), just 51 were directly related to the real-world decommissioning of O&G (which we refer to as 'direct' evidence)[23]. Given the sparsity of 'direct' evidence, quantifying what the effects of various decommissioning options will be, and in particular the effects of turning MAS into ARs, represents a substantial challenge. This is problematic when it comes to supporting and informing decommissioning management and associated policy decisions[24].

An alternative approach is to use 'indirect' evidence, such as comparing the effects of MAS relative to before their installation or relative to natural habitats[24]. Ref. 23 showed that an abundance of these data exists, which can be used to determine the 'cost' of decommissioning. For example, complete removal would lead to the loss of 'presence effects'—effects that are assumed to be retained if the structure is instead decommissioned as a reef.

Here we present a meta-analysis that explores the 'indirect' evidence using a subset of studies collated in ref. 23, aiming to answer the overarching question: (1) What are the ecological effects of MAS? We address several related questions that guide current understanding of the effects of decommissioning: (2) What are the ecological effects of ARs? (3) Do O&G infrastructure and OWF installations act as ARs (otherwise formulated: are all MAS in the sea de facto ARs?)? To finally address (4) can specific decommissioning options be selected to benefit biodiversity and promote positive ecological outcomes?

Results

Bibliographic results

In total, following outlier analysis (Supplementary Results), 109 articles were retained generating 531 effect sizes (Supplementary Fig. 1). The geographic spread of studies (Fig. 1a) indicates that the majority were undertaken in the USA and Europe (North Atlantic and North Pacific Oceans). Articles were published between 1985 and 2020, with a clear increase in the number of studies published annually over time (Fig. 1b). The majority of effect sizes were associated with ARs (65%; 7.5% shipwrecks intentionally deployed as ARs, 57.6% other purpose-built ARs), with the remainder split between O&G (13.3%; 11.5% standing production platforms, 1.8% decommissioned as ARs), accidental shipwrecks (12.3%) and OWFs (7.9%) (Fig. 1c). At the time the studies were undertaken (and effects assessed), structures ranged in ages from under a year since deployment (for example, for purpose-built ARs) to >400 years for accidental shipwrecks. Of the effect sizes, 64.4% originated from studies comparing MAS to natural reefs, while 35.6% compared them to natural sedimentary habitats. The majority of effect sizes (85%) reflected changes in abundance (43.3%) and diversity (41.7%); a lower number looked at changes in biomass (11%), with very few relating to reproduction (2%), behaviour (1.7%) or survivorship (0.4%) (Fig. 1d). Of the 531 effect sizes calculated, 38.5% related to fish, 49.7% to invertebrates and 11.8% to both invertebrates and fish (combined/undifferentiated) (Fig. 1e).

Meta-analysis results

The overall meta-analytic model assessing the overall ecological effect of MAS revealed a significant moderate positive effect (Hedges' $g = 0.47$; $P < 0.001$) of MAS on ecological metrics compared with sites without MAS present (Fig. 2 and Supplementary Table 3). However, large residual heterogeneity both between ($I_{\text{between}}^2 > 58\%$) and within ($I_{\text{within}}^2 > 38\%$) studies was apparent.

Single moderators were sequentially included in the model to identify key sources of variability in ecological responses and assess the effects of different MAS across habitats and ecological metrics.

Testing the effect of MAS presence relative to natural seabed types (that is, natural reef or natural sedimentary habitat) indicated that some heterogeneity identified in the overall model was due to the seabed type comparator. The subgroup model used to partition seabed types indicated large significant positive effects of MAS on ecological metrics in comparison with natural sedimentary habitats, but not compared with natural reefs without MAS present, which showed a non-significant positive effect (Fig. 3a and Supplementary Table 4). The effects were significantly larger compared with natural sedimentary habitats than compared with natural reefs (Omnibus test of moderators: $QM_{1,529} = 8.77, P < 0.001$).

The effects of MAS type on ecological metrics compared to sites without MAS varied largely according to structure type (Fig. 3b and Supplementary Tables 5 and 6). The Omnibus test of moderators detected significant differences between MAS types ($QM_{4,527} = 4.54$, $P < 0.01$) and pairwise contrasts revealed that ARs behaved significantly differently from all other structure types, and that shipwrecks, OWF and O&G had similar effects to one another. While significant very large and moderate positive effects are apparent for shipwrecks and ARs, respectively, no significant effects detected for O&G and OWFs. Running the same model for natural sedimentary habitat and natural reef separately revealed that effects of structure type differed with habitat (Fig. 4 and Supplementary Tables 7 and 8). All structure types, except for OWFs, had significant moderate to very large positive effects on ecological metrics compared with natural sedimentary sites without MAS (only marginally for O&G). In contrast, when comparing with natural reef sites without structures, only shipwrecks had (very large) significant positive effects, whereas the effects of all other structure types were not statistically different from that of natural reefs (note the limited number of data points for OWFs and O&G).

The effects of MAS on ecological metrics varied between fish and invertebrates ($QM_{2,465} = 14.85, P < 0.001$) (Fig. 3c and Supplementary Table 9), with significant large positive effects on fish but no significant effects on invertebrates.

The effects of MAS depended on the ecological response measured ($QM_{6,525} = 4.21, P < 0.001$; Fig. 3d and Supplementary Table 10). Pairwise contrasts revealed significant differences in effects among all three responses measured (Supplementary Table 11). Specifically, significant large positive effects of MAS were apparent on abundance, significant moderate positive effects on biomass, but no significant effect on diversity. The evidence base for the metrics survivorship, reproduction and behaviour provided low to extremely low numbers of effect sizes; thus any estimates may not reflect true mean effect sizes. These metrics were therefore not subject to pairwise comparisons and are not discussed further.

The effects of different MAS across ecological metrics, taxon and seabed type were assessed using multiple moderator analysis. An additive model including seabed type, MAS type, taxon and outcome

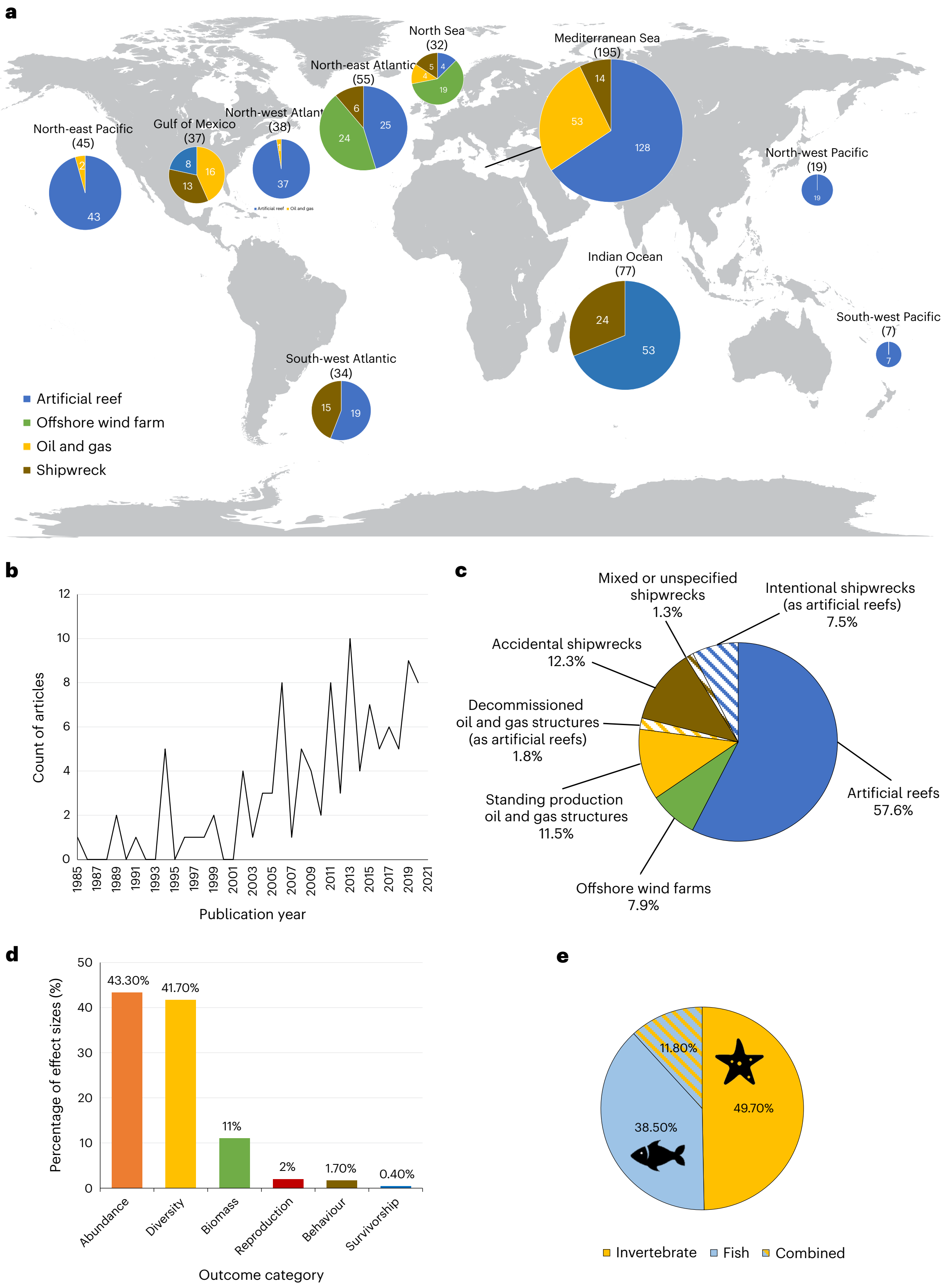

Fig. 1 | Nature and distribution of evidence included in the meta-analysis. **a**, Geographical distribution of effect sizes included in the meta-analyses (data shown for each oceanic basin by MAS type). **b**, Temporal trend in article publication. **c**, Distribution of effect sizes by MAS type. **d**, Distribution of effect sizes by outcome (ecological metric) category. **e**, Distribution of effect sizes by taxa category. The fish and starfish icons in **e** were made by DinosoftLabs from www.flaticon.com and obtained from pngwing.com, respectively.

type as moderators resulted in the best fit. This maximal model showed that the effects of MAS on ecological metrics vary significantly with all the moderators considered (test of moderators (coefficients 1:11): $QM_{11,449} = 5.09$, $P < 0.0001$).

Compared with natural sedimentary sites without MAS (Fig. 5a, top), sites with either MAS type supported significantly greater abundances of fish but similar abundances of invertebrates. O&G and OWFs supported similar abundances of fish and invertebrates to natural reefs

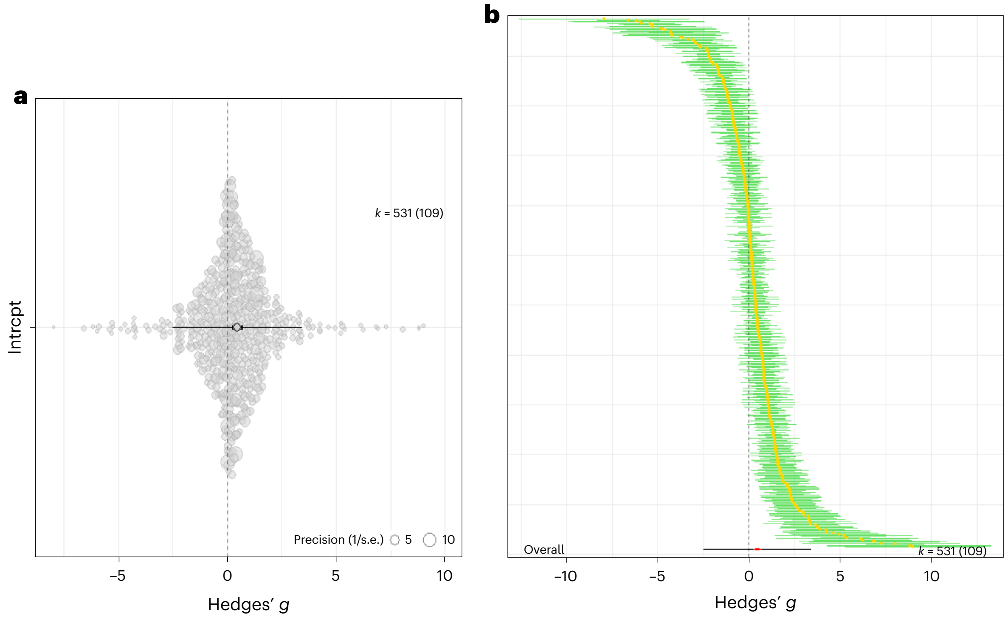

Fig. 2 | Overall ecological effect of MAS. The overall meta-analytic model shows significant moderate positive effects of MAS on marine ecosystems compared with sites without structures present ($t_{108} = 3.7249, P = 0.0003$). **a**, Visualized using an orchaRd plot. Individual effect sizes from studies are represented as grey bubbles. The dot represents the estimated mean Hedges' *g* value 0.47. The bold error bars represent the 95% confidence interval (95% CI 0.22, 0.73). The thin error bars represent the 95% prediction interval. Please note that the CI around the mean is very small in this instance. **b**, Visualized using a caterpillar plot. The estimated mean Hedges' *g* value is depicted at the bottom in red. Individual effect sizes are ordered by magnitude and each individual effect size is depicted by a yellow dot with green 95% CI bars. Based on 531 effect sizes from 109 articles.

(note the limited number of data points); ARs, however, supported significantly more fish but similar numbers of invertebrates, while shipwrecks supported significantly greater abundances of both fish and invertebrates (Fig. 5a, bottom). Details of effect size estimates are provided in Supplementary Table 12.

No data on the effects of shipwrecks on the biomass of fish or invertebrates compared to natural sedimentary habitats were found (Fig. 5b, top). No other MAS types had significant effects on the biomass of fish or invertebrates, compared to either natural sedimentary habitats or natural reefs, except for O&G which supported significantly greater biomasses of fish compared with natural sedimentary habitats (note the limited number of data points) and shipwrecks which supported greater biomasses of fish compared with natural reefs (Fig. 5b). Details of effect size estimates are provided in Supplementary Table 13.

Compared with natural sedimentary habitats (Fig. 5c, top), only ARs showed more diverse fish and invertebrates, but not O&G, OWFs or shipwrecks where diversities were similar (but note the limited number of data points available for shipwrecks). Compared to natural reefs (Fig. 4, bottom), fish diversity was similar at ARs and shipwrecks. Invertebrate diversities were higher at ARs and shipwrecks than in natural reefs. No data on the effects of O&G on the diversity of fish or invertebrates compared to natural reefs were found and only very limited data for OWFs. Details of effect size estimates are provided in Supplementary Table 14.

Discussion

Our meta-analysis provides a global quantitative assessment of the ecological effects of MAS in the sea, compared to natural habitats. Below, we use our findings to address our initial set of questions and then discuss the limitations and implications of our work.

The ecological effects of MAS

Our results show that MAS can have positive ecological effects. Yet, this general picture becomes intricate when adding context-based complexity, with critical differences emerging between MAS type, habitat type, taxon and ecological metric.

Unsurprisingly, the ecological effects of MAS differed between the types of natural habitat they were compared to. When considering all data grouped only by natural habitat type (but undifferentiated by structure type, taxon or metric), MAS have overall statistically positive ecological effects across natural sedimentary habitats but not when compared to natural reefs. Ergo, they offer additional ecological benefits over natural sedimentary habitats but can also replicate the ecological benefits of natural reefs. Previously, ref. 25 argued that MAS could represent 'oases in the desert', with sedimentary habitats considered a 'sea of sand' of low diversity and ecological value compared with reef habitats. It is unsurprising that introducing MAS leads to different ecological outcomes compared with unmodified natural sedimentary habitats, given that these structures are a fundamentally different substrate. The complexity introduced to natural sedimentary systems by MAS has long been known to affect diversity[26] and the potential effects have been reinforced here. MAS can also provide similar ecological benefits to natural reefs, which is surprising given previous well-documented concerns over MAS's ability to replicate natural features[27]. This finding might be reassuring if we wish to consider MAS (and not solely ARs) as potential restoration and/or biodiversity enhancement tools in heavily degraded environments.

The ecological effects of ARs

ARs are deployed for multiple purposes; although the exact objectives of individual ARs are not always clearly articulated[28], they include protecting living resources and enhancing/restoring biodiversity. For those ARs deployed to enhance/restore ecosystems and boost biodiversity, what should the aim be: (1) habitat creation; (2) ecological enhancement compared with natural sedimentary habitats; (3) similar levels of ecological functioning as natural reefs; or (4) for ARs to outperform all types of natural habitat? Here we consider that to 'act as an AR', a structure must provide similar levels of ecological functioning

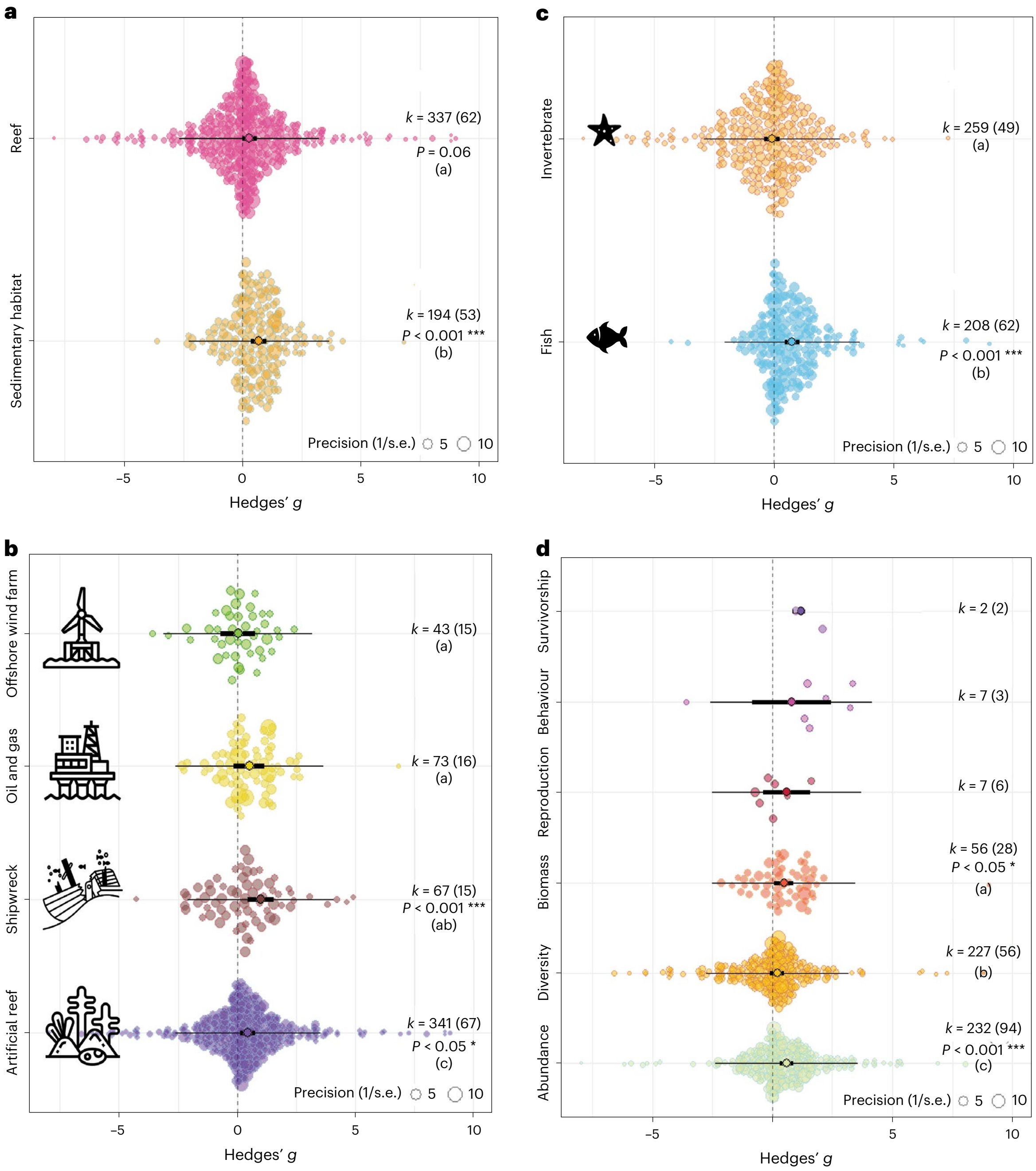

Fig. 3 | Effects of MAS across habitats and ecological metrics – results of subgroup analyses. Orchard plots for each single-moderator meta-analytic model. **a**, Seabed type as moderator. The model shows significant positive effects of MAS when compared with natural sedimentary habitats without structures ($t_{529} = 4.0798$, $P < 0.0001$), but not when compared with natural reefs without structures ($t_{529} = 1.8431$, $P = 0.0659$). Natural sedimentary habitat: $g = 0.69$ (95% CI 0.36, 1.03). Natural reef: $g = 0.29$ (95% CI −0.02, 0.60). **b**, MAS as moderator. The model shows significant very large and large positive effects of shipwrecks ($g = 1.0$; 95% CI 0.45, 1.56; $t_{520} = 3.5549$, $P = 0.0004$) and of artificial reefs ($g = 0.45$; 95% CI 0.13, 0.77; $t_{520} = 2.7903$, $P = 0.0055$) on ecological metrics compared with sites without structures present, but no significant effects of oil and gas infrastructure ($g = 0.52$; 95% CI −0.12, 1.16; $t_{520} = 1.5914$, $P = 0.1121$) or offshore wind farms $g = 0.04$; (95% CI −0.68, 0.76; $t_{520} = 0.1113$, $P = 0.9114$). **c**, Taxon type as moderator. The model shows significant large positive effects of MAS on fish ($g = 0.77$; 95% CI 0.47, 1.06; $t_{465} = 5.1397$, $P < 0.0001$), but no significant effect on invertebrates ($g = -0.08$; 95% CI −0.39, 0.24; $t_{465} = -0.4713$, $P = 0.6377$). **d**, Outcome (ecological response type) as moderator. The model shows significant large positive effects of MAS on abundance ($g = 0.60$; 95% CI 0.33, 0.87; $t_{525} = 4.3376$, $P < 0.0001$), significant moderate positive effects on biomass ($g = 0.48$; 95% CI 0.09, 0.87; $t_{525} = 2.4034$, $P = 0.0166$), but no significant effect on diversity ($g = 0.21$; 95% CI −0.09, 0.50; $t_{525} = 1.3754$, $P = 0.1696$). Note that survivorship, reproduction and behaviour had low to extremely low sample sizes; hence estimates may not reflect true effect sizes. For each plot, the coloured bubbles represent individual effect sizes from studies, the circled dots represent the estimated mean Hedges' *g* values, the bold error bars represent the 95% CIs, and the thin error bars represent the 95% prediction interval. *k* represents the number of effect sizes included for each group; in brackets is the number of studies they originated from. Asterisk denotes groups for which significant effects were detected. For each plot, groups that do not share a letter (for example, (a)) are significantly different from each other. The starfish icon was obtained from pngwing.com. The fish, oil rig, offshore wind, shipwreck and artificial reef icons were made by DinosoftLabs, Freepik, Ultimatearm, Amethyst prime and Eucalyp, respectively, all from www.flaticon.com.

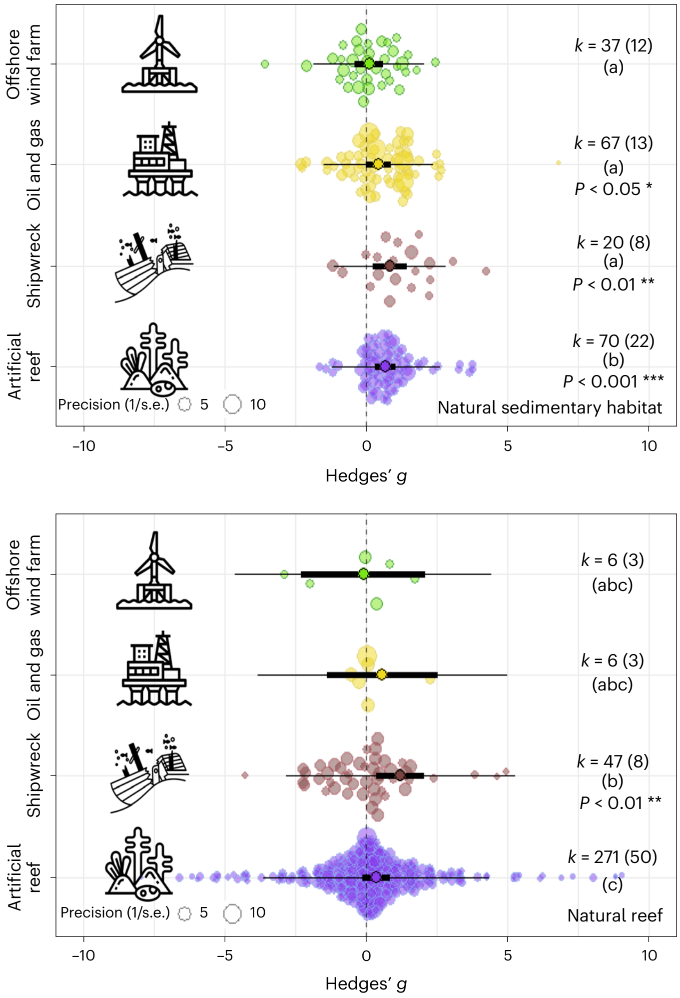

Fig. 4 | Ecological effects of MAS type by structure and seabed type. Orchard plots for the single-moderator meta-analytic models using 'structure type' as moderator applied to the data split by seabed type. The natural sedimentary habitat model (top) shows significant moderate to large positive effects of all MAS (artificial reefs: $g = 0.69$; 95% CI 0.33, 1.06; $t_{49} = 3.8391$, $P = 0.0004$; shipwrecks: $g = 0.85$; 95% CI 0.23, 1.46; $t_{190} = 2.7652$, $P = 0.0062$), except for offshore wind farms ($g = 0.10$; 95% CI −0.10, 0.60; $t_{190} = 0.3886$, $P = 0.6980$), but only marginally for oil and gas ($g = 0.44$; 95% CI 0, 0.89; $t_{190} = 1.9999$, $P = 0.0469$). The natural reef model (bottom) shows significant positive effects only for shipwrecks ($g = 1.21$; 95% CI 0.38, 2.05; $t_{3260} = 2.8503$, $P = 0.0046$). All other MAS types had no significant effects (statistically similar to natural reefs; artificial reefs: $g = 0.35$; 95% CI −0.13, 0.84; $t_{326} = 1.4426$, $P = 0.1501$; oil and gas: $g = 0.58$; 95% CI −1.35, 2.50; $t_{326} = 0.5911$, $P = 0.5549$; offshore wind farms: $g = -0.10$; 95% CI −2.25, 2.06; $t_{55} = -0.0888$, $P = 0.9296$). Note the low number of effect sizes found for offshore wind farms and oil and gas. For each plot, the coloured bubbles represent individual effect sizes from studies, the circled dots represent the estimated mean Hedges' g values, the bold error bars represent the 95% CIs, and the thin error bars represent the 95% prediction interval. k represents the number of effect sizes included for each group; in brackets is the number of studies they originated from. Asterisk denotes groups for which significant effects were detected. For each plot, groups that do not share a letter are significantly different from each other. The oil rig, offshore wind farm, shipwreck and artificial reef icons were made by Freepik, Ultimatearm, Amethyst prime and Eucalyp, respectively, all from www.flaticon.com.

to natural reefs. Our meta-analyses showed that ARs support similar invertebrate abundances but a greater abundance of fish, and similar biomass of both fish and invertebrates compared to natural sedimentary habitats and natural reefs. ARs support greater diversities of fishes and invertebrates than natural sedimentary habitats, but similar fish diversity and lower invertebrate diversity than natural reefs. This suggests that ARs mostly do indeed 'act as ARs', except that they host lower invertebrate diversity than natural reefs. This, in turn, suggests that ARs can serve as enhancement tools but that their effects might be limited. Other MAS might provide benefits of greater magnitude, such as accidental shipwrecks which appear to at times outperform natural reefs (enhancing fish and invertebrate abundances).

Our findings for the effects of ARs on fish compared to natural reefs are mostly in agreement with a previous meta-analysis[29], which also found that ARs exhibited similar fish biomass and diversity to natural reefs. However, it is worth noting that while we separated O&G and ARs into two distinct categories, they included O&G in their AR category, which might have confounded the effects. Although not accounted for in our analyses, some of the variability in the results stemming from individual studies is probably linked with location and local environmental conditions[30,31].

The ecological effects of offshore energy structures

O&G infrastructures and OWF installations: between oases in the desert and de facto artificial reefs? On face value, our results suggest that different types of MAS can provide similar enhanced ecological functions over natural sedimentary habitats and replicate or even exceed the benefits of natural reefs. However, when considering each structure, metric and taxon separately (thereby adding complexity), there are some clear structure-specific positive and negative effects of different types of MAS for fish and invertebrates with respect to local abundance, biomass and diversity.

Compared with natural sedimentary habitats, O&G and OWFs increase fish abundance but not invertebrate abundance in the area. Locally, O&G also support higher fish biomass than natural sedimentary habitats but OWFs do not and neither support higher invertebrate biomass. Surprisingly, diversity was not greater at O&G, OWFs or shipwrecks than at natural sedimentary sites (unlike what was apparent for ARs). These results suggest that only ARs (which in addition to supporting greater fish abundance also supported greater fish and invertebrate diversities), but not O&G and OWFs, may represent 'oases in the desert'[25]. This was surprising given recent studies showing that O&G and OWFs can benefit the surrounding animal communities[32–34]. Several reasons could explain the differences between structure types and their ability to provide ecological benefits compared with natural sedimentary habitats. Among others, the material used[35], the complexity of the structure[36], the depth of deployment[37] and the distance to the coast or to the nearest natural reef (that is, source of supply)[38] can affect ecological outcomes. As ARs tend to be deployed in very different environmental conditions from those of O&G and OWFs (and accidental shipwrecks, which also tend to be a lot older and at a more mature successional stage) and designed differently, it is perhaps unsurprising that their efficacy would differ. For example, ARs are often placed in shallower waters and closer to shore, where environmental conditions were probably appraised during their site selection process[39,40], and can be purpose-built to enhance ecological benefits through increased complexity and selection of specific material[41].

A lack of studies limited our assessment of the effects of O&G and OWFs on abundance, biomass or diversity compared to natural reefs. This in turn prevented us from drawing robust conclusions about whether these structures act as de facto ARs (sensu function as natural reefs), as is often argued[42].

Implications for decommissioning MAS

This analysis was designed to shed light on the ecological effects of different MAS with a view to inform the management and decommissioning of O&G and OWFs. Given the notable paucity of direct evidence of decommissioning effects[23,24], our objective was to determine whether indirect evidence might be a valuable source of information to identify potential decommissioning options that promote positive ecological

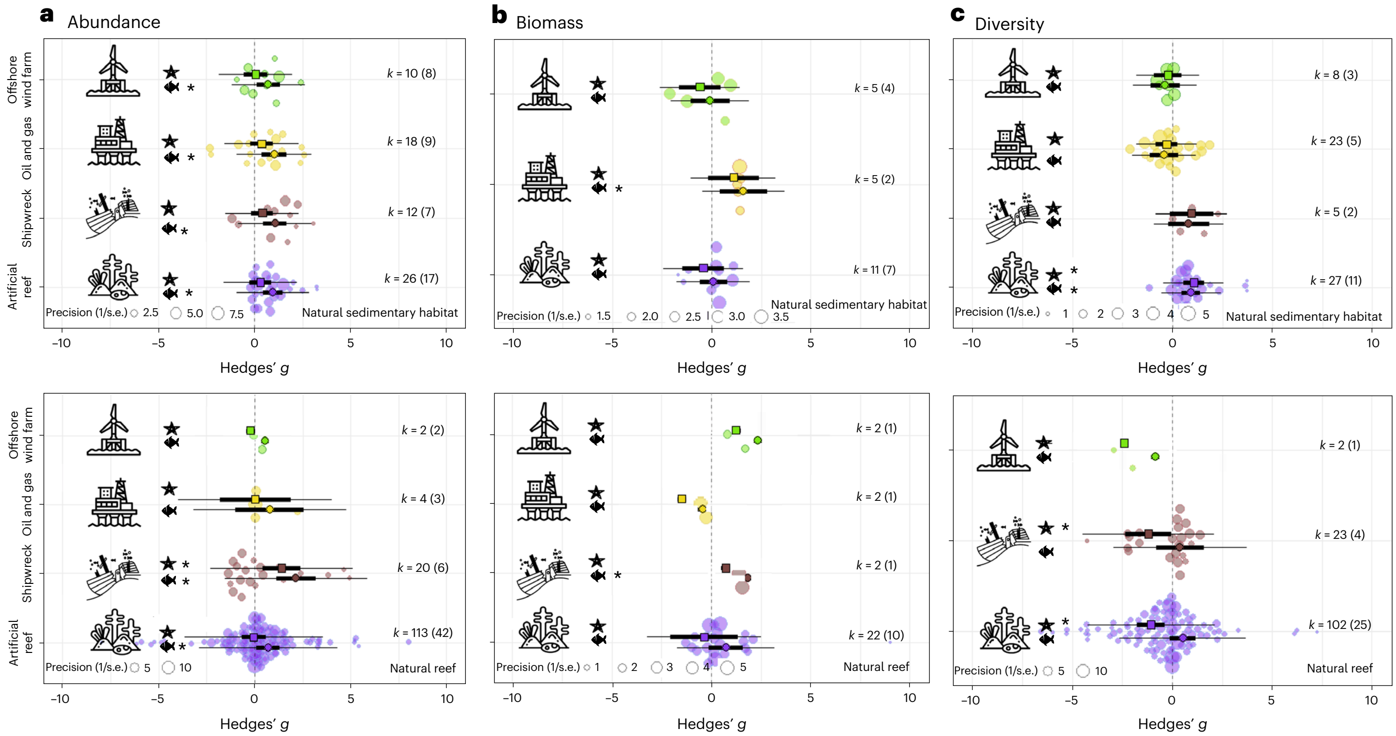

Fig. 5 | Orchard plots for the full complex model showing the effects of MAS on ecological metrics. a–c, Effects on the abundance (**a**), biomass (**b**) and diversity (**c**) of fish and invertebrates, compared to natural sedimentary habitat (top) and to natural reef (bottom). For each plot, the coloured bubbles represent individual effect sizes from studies, the circled dots represent the estimated mean Hedges' *g* values, the bold error bars represent the 95% CIs, and the thin error bars represent the 95% prediction interval. *k* represents the number of effect sizes included for each group; in brackets is the number of studies they originated from. Asterisk denotes groups for which significant effects were detected. Note that some groups had low to extremely low sample sizes; hence estimates may not reflect true effect sizes. The starfish icon was obtained from pngwing.com. The fish, oil rig, offshore wind farm, shipwreck and artificial reef icons were made by DinosoftLabs, Freepik, Ultimatearm, Amethyst prime and Eucalyp, respectively, all from www.flaticon.com.

outcomes. In theory, if O&G and OWFs 'acted as ARs' (sensu function as natural reefs), decommissioning them by toppling, topping or reefing them in situ or after relocation[13] could assist nations in reaching their environmental targets and achieve environmental net gain[22]. However, we found no evidence to support or rebut the common assumption that these structures function as ARs. Beyond simply assessing their ability to replicate the functions of natural reefs, our meta-analysis also assessed the environmental value of O&G and OWFs compared to natural sedimentary habitats, highlighting only limited ecological benefits (if reefed) or loss (if removed)—elevated local abundance of fish at both O&G and OWFs, and elevated local biomass of fish at O&G.

Overall, we found limited evidence to support the argument that alternative decommissioning options to complete removal of O&G and OWFs might be used to promote healthy productive ecosystems, and no evidence that they might benefit biodiversity. We also show that other MAS, such as intentionally deployed ARs and accidental shipwrecks, may be more effective at providing ecological benefits. Hence, decommissioning options aimed at repurposing O&G and OWFs in the sea to function as ARs (either in situ or after relocation) may not provide the intended levels of benefits, at least not to the same levels as other MAS. With that said, we found no evidence that reefing them would cause 'harm' or be detrimental (for example, by reducing local biodiversity); thus, they may provide a viable option to enhance ecological benefits on natural sedimentary habitats, notwithstanding potential unforeseen consequences such as facilitating the spread of invasive species[43].

From an environmental perspective, decisions regarding decommissioning options must be score-based against pre-defined ecological objectives (such as biodiversity enhancement) that are assessed against specific comparators (natural habitats). In one of the simpler models, we found that unsurprisingly, given that MAS are a fundamentally different substrate, their introduction into natural sedimentary habitats affected (mostly enhanced) ecological outcomes, whereas the comparison of MAS against natural reefs indicated similar ecological outcomes. These findings raise two questions. First, should positive effects of MAS based on comparison with fundamentally different habitats be used in decommissioning decision-making? If so, the costs and benefits should be made explicitly clear. Second, given the limited evidence that supports MAS functioning as ARs, is the evidence base sufficiently strong to justify any potential change in policy/legislation which at present largely stipulates complete removal at decommissioning[44,45]? While not discussed here, we also acknowledge that environmental considerations are only one piece of the decommissioning puzzle and that the involvement of other sectors (economic, social, technical and so on) is critical to the decision-making process. Indeed, even if the ecological benefits of reefing structures may not appear to be high, benefits to humans and societies may be important[46,47] and should be incorporated into a whole-ecosystem approach to managing decommissioning.

Limitations, research gaps and future directions

This meta-analysis is based on the best available evidence as of early 2021, when the searches for the systematic map[23] ended, but several aspects considered clearly lacked sufficient quantified effects. Evidence from studies published since (see refs. 33,34,36 for examples) may, however, shed additional light.

Among the six metrics with sufficient available literature to warrant further investigations as part of this meta-analysis, quantified effects were severely lacking for several of them (reproduction, behaviour, survivorship), limiting our analyses to only three metrics with relatively more data (biomass, abundance, diversity). Even for those, further subgroup analyses were limited. For instance, we found no studies with extractable and/or usable data on the effects of O&G on the diversity of either fish or invertebrates and very limited data on the effects of OWF on the diversity of fish or invertebrates, compared to natural reefs. Furthermore, it is evident from this work that MAS have mainly been compared to natural sedimentary sites and much less often to natural reefs (except for ARs). This limits our understanding and interpretation of how these structures perform compared to natural reefs.

Many lines of evidence identified in the systematic map could not be included here, either because of a lack of evidence or due to inappropriate study designs. For instance, effects on trophic structure or larval dispersal[48], which were identified in the map as knowledge gaps, could shed valuable light on the ecological effects of MAS. In addition, numerous studies collated in ref. 23 were only descriptive of the MAS and contained no appropriate comparison to natural habitats. While experimental designs using set comparators (such as control–impact, before–after, or before–after–control–impact) are becoming more standard practice, studies describing solely the structures (no comparator) are still being produced, limiting the interpretation of structure effects.

There are clear research gaps that restrict the interpretation of presence effects of MAS, in particular O&G and OWFs. Even when considering 'indirect' evidence, as we do here, our understanding of decommissioning effects is patchy at best, requiring substantial investment and robust environmental policy to ensure future studies have appropriate experimental designs to provide the necessary data to evaluate the impacts of decommissioning options. Ideally, this would be by producing 'direct' evidence via undertaking case studies of structures being decommissioned on the basis of a before–after–control–impact monitoring design. Additional indirect evidence for the presence effects of O&G and OWFs could also be produced, such as quantifying the effects on metrics other than abundance, biomass and diversity, and comparing them to natural sedimentary and reef habitats.

If reefing of obsolete structures becomes an increasingly popular decommissioning option in the future, eco-engineering concepts, such as those already tested for coastal artificial structures[49] and for a very limited number of active offshore renewable energy installations[50–52], could be applied either prospectively or retrospectively to maximize ecological benefits and contribute to environmental net gain. While this practice is gaining traction in coastal environments, it is unknown how such techniques would function when scaled up geographically and over longer timescales[49]. Applying them to decommissioned structures would therefore require careful considerations to avoid the risk of being promoted as appropriate mitigation to environmental damage and used to enable easier access to alternative decommissioning options to complete removal or facilitate easing of decommissioning policy[49]. Future research should address this avenue.

Importantly, through shifting baseline syndrome[53], human perceptions of what is the normal state of the environment are becoming skewed towards the degraded and the artificial[49]. With urbanization of the global ocean, humans are accustomed to extremely heavily modified coastal environments[50], and they are on the brink of doing the same in offshore environments. As explained in ref. 49, perhaps one of the most insidious environmental threats is that the artificial legacy humans will leave behind—here with the decommissioning of offshore MAS using alternative options to complete removal—might in the long term re-position baseline perceptions and standards of the state in which the planet should be left for future generations.

Methods

We used a systematic approach to our meta-analysis, following as closely as possible the guidelines set by the Collaboration for Environmental Evidence Guidelines and Standards for Evidence Synthesis[54]. We built on the output of recent systematic evidence synthesis work, using the published systematic map of ref. 23 as the evidentiary basis for this meta-analysis (full methodological details available[23,55]) and briefly describe our process here (full details can be found in Supplementary Methods).

We further defined our research questions from the one asked in ref. 23 ("What published evidence exists for the effects of marine [artificial] structures, while in place and after decommissioning, on the marine ecosystem?") by focusing on the research clusters identified in their map (that is, based on the number of articles retrieved for each category examined). Our meta-analysis was thus centred around the following primary question and four secondary questions: (1) What are the ecological effects of MAS? (2) How do their effects differ between the types of natural site they are compared to (natural sedimentary habitat, natural reef)? (3) How do their effects differ between the types of structure (O&G, OWF, AR and shipwrecks, as well as decommissioned O&G structures used as AR)? (4) How do their effects differ between taxonomic groups (fish, invertebrates)? Finally (5) how do their effects differ between ecological metrics (diversity, abundance, biomass, behaviour, reproduction, survivorship)?

Peer-reviewed published literature was searched systematically as part of the systematic map work undertaken in refs. 23,55 up to February 2021. The list of studies catalogued in this map is freely available online as part of their supplementary files. No additional literature search was undertaken specifically for this work. Details of the literature search and study selection steps behind the systematic map are available in their published protocol[55] and map report[23], and a brief summary provided in Supplementary Methods. From the pool of 979 articles collated in the systematic map, we identified 377 as being relevant to our research questions (that is, relevant comparators, MAS types, taxonomic groups, ecological metrics assessed and intervention types) and retained 110 that provided the necessary information (an estimate of means, a measure of variance (standard deviation, standard error, confidence intervals) and the sample size for the different levels considered) to calculate one or multiple effect sizes. From the initial 979 articles to the 377 relevant articles identified, many were excluded due to inappropriate study designs, whereby the study did not use an appropriate comparator, if at all (Supplementary Methods). The full list of 377 articles is presented in Supplementary File 1, along with the reason for exclusion from the remaining 110 retained articles.

For these 110 articles retained, effect sizes for each comparison between a MAS and a natural site were calculated separately for each outcome metric and for each taxon, using Hedges' g as the effect size (Cohen's d corrected for small sample sizes using the bias correction element J). Details of calculations of g are available in the Supplementary Methods and Supplementary File 2. g is generally interpreted as follows: $|g| < 0.2$ (small); $0.2 \le |g| < 0.5$ (moderate); $0.5 \le |g| < 0.8$ (large); $|g| \ge 0.8$ (very large). Data were visualized using orchard plots created in R with the 'orchard' package[56]. Effect sizes were considered significant when their 95% confidence intervals did not overlap with zero. A positive value of g means that the effect is larger at the MAS site than the natural site (and vice versa), while a g of zero indicates no difference in response between the MAS site(s) and the natural site(s). The dataset used for calculating effect sizes and the one used for statistical analyses are presented in Supplementary Files 2 and 3, respectively.

We employed state-of-the-art meta-analytical techniques to interpret our data. As part of the systematic map, meta-data were coded for a range of study qualifiers, such as MAS type, geographic location, taxonomic groups, ecological metric assessed, MAS age and MAS depth. These potential modifiers were used in meta-analyses to account for differences between studies, and thus effect data were extracted and coded in a manner that allowed ease of analyses. In addition, we incorporated the following moderator: type of natural site the MAS is compared to (categorized as either natural sedimentary site or natural reef). We initially ran an overall meta-analytic model using all the effect sizes obtained to estimate the overall ecological effect of MAS on their surrounding environment (without any moderators; that is, all MAS types combined, all taxa combined, all ecological metrics combined, both types of natural sites combined). We then ran separate single-moderator models to investigate the effects of potential a priori modifiers. More complex models with multiple moderators were also built to explain the remaining heterogeneity. The following were considered a priori modifiers: MAS type, taxon, ecological metric, type of natural site. Due to the nature of our data, effect sizes were not all independent (multiple effect sizes arising from a single study, for instance, due to multiple MAS assessed, multiple outcomes being reported or multiple sites studied). Thus, all meta-analyses were performed using multilevel mixed-effects models that included the following random components: effect size unique identifier, nested within the study unique identifier. The random effect structure was chosen by comparing the fit of different models using the Akaike Information Criterion (AIC). All statistical analyses were run in the R environment (R v.4.2.1)[57] using the rma.mv() function in the 'metafor' package (v.3.8.1)[58]. Test statistics and confidence intervals for the fixed effects were computed using *t* distributions. Statistical significance was assumed when 95% confidence intervals around the meta-analytic means did not overlap with zero. Pairwise contrasts were conducted using the 'btt=' argument within each model. The dataset and code used are available in Supplementary Files 3 and 4, respectively, both deposited in the online repository, Zenodo[59].

Full methodological details, including literature searches, study selection, effect size calculation and R scripts, can be found in Supplementary Information.

Reporting summary

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

Data availability

All data supporting the findings of this study and used to produce the figures are available within the paper and its Supplementary Information (Supplementary Files 2 and 3). All data sheets (Supplementary Files 1–3) have been deposited to the online repository, Zenodo[59].

Code availability

The R code used in the analyses is available in Supplementary File 4. Correspondence and requests for materials should be addressed to A.J.L. The R code (Supplementary File 4) has been deposited to the online repository, Zenodo[59].

References

1. Schmeller, D. S., Courchamp, F. & Killeen, G. Biodiversity loss, emerging pathogens and human health risks. *Biodivers. Conserv.* **29**, 3095–3102 (2020).
2. Comte, L. & Lenoir, J. Decoupled land–sea biodiversity trends. *Nat. Ecol. Evol.* **4**, 901–902 (2020).
3. Nagelkerken, I. & Connell, S. D. Ocean acidification drives global reshuffling of ecological communities. *Glob. Change Biol.* **28**, 7038–7048 (2022).
4. Vincent, C. et al. Climate and land-use changes reshuffle politically-weighted priority areas of mountain biodiversity. *Glob. Ecol. Conserv.* **17**, e00589 (2019).
5. Sovacool, B. K., Geels, F. W. & Iskandarova, M. Industrial clusters for deep decarbonization. *Science* **378**, 601–604 (2022).
6. *G7 2030 Nature Compact* (G7 Cornwall UK, 2021).
7. *Decommissioning and Repurposing Taskforce* (North Sea Transition Authority, 2022).
8. Camarasa, C. et al. A global comparison of building decarbonization scenarios by 2050 towards 1.5–2 °C targets. *Nat. Commun.* **13**, 3077 (2022).
9. Gourvenec, S., Sturt, F., Reid, E. & Trigos, F. Global assessment of historical, current and forecast ocean energy infrastructure: implications for marine space planning, sustainable design and end-of-engineered-life management. *Renew. Sustain. Energy Rev.* **154**, 111794 (2022).
10. Bugnot, A. B. et al. Current and projected global extent of marine built structures. *Nat. Sustain.* **4**, 33–41 (2021).
11. Topham, E., Gonzalez, E., McMillan, D. & João, E. Challenges of decommissioning offshore wind farms: overview of the European experience. *J. Phys. Conf. Ser.* **1222**, 012035 (2019).
12. Knights, A. M. et al. To what extent can decommissioning options for marine artificial structures move us toward environmental targets? *J. Environ. Manage.* **350**, 119644 (2023).
13. Sommer, B. et al. Decommissioning of offshore oil and gas structures – environmental opportunities and challenges. *Sci. Total Environ.* **658**, 973–981 (2019).
14. Bull, A. S. & Love, M. S. Worldwide oil and gas platform decommissioning: a review of practices and reefing options. *Ocean Coast. Manage.* **168**, 274–306 (2019).
15. Degraer, S. et al. Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. *Oceanography* **33**, 48–57 (2020).
16. Glarou, M., Zrust, M. & Svendsen, J. C. Using artificial-reef knowledge to enhance the ecological function of offshore wind turbine foundations: implications for fish abundance and diversity. *J. Mar. Sci. Eng.* **8**, 332 (2020).
17. Smyth, K. et al. Renewables-to-reefs? – Decommissioning options for the offshore wind power industry. *Mar. Pollut. Bull.* **90**, 247–258 (2015).
18. *London Convention and Protocol/UNEP: Guidelines for the Placement of Artificial Reefs* (UNEP, 2009).
19. Bartholomew, A., Burt, J. A. & Firth, L. B. Artificial reefs in the Arabian Gulf: benefits, challenges and recommendations for policy-makers. *Reg. Stud. Mar. Sci.* **56**, 102723 (2022).
20. Higgins, E., Metaxas, A. & Scheibling, R. E. A systematic review of artificial reefs as platforms for coral reef research and conservation. *PLoS ONE* **17**, e0261964 (2022).
21. Vivier, B. et al. Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness. *Glob. Ecol. Conserv.* **27**, e01538 (2021).
22. Hooper, T., Austen, M. & Lannin, A. Developing policy and practice for marine net gain. *J. Environ. Manage.* **277**, 111387 (2021).
23. Lemasson, A. J. et al. Evidence for the effects of decommissioning man-made structures on marine ecosystems globally: a systematic map. *Environ. Evid.* **11**, 35 (2022).
24. Lemasson, A. J. et al. Challenges of evidence-informed offshore decommissioning: an environmental perspective. *Trends Ecol. Evol.* **38**, 688–692 (2023).
25. Wright, S. R. et al. Structure in a sea of sand: fish abundance in relation to man-made structures in the North Sea. *ICES J. Mar. Sci.* **77**, 1206–1218 (2020).
26. 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).
27. Moschella, P. S. et al. Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. *Coast. Eng.* **52**, 1053–1071 (2005).
28. Becker, A., Taylor, M. D., Folpp, H. & Lowry, M. B. Managing the development of artificial reef systems: the need for quantitative goals. *Fish Fish.* **19**, 740–752 (2018).
29. Paxton, A. B. et al. Meta-analysis reveals artificial reefs can be effective tools for fish community enhancement but are not one-size-fits-all. *Front. Mar. Sci.* **7**, 282 (2020).

30. Vivier, B. et al. Diversity, structures assemblages and production of benthic communities on artificial reefs, a comparative case study in the English Channel. *Mater. Sci. Eng. Conf. Ser.* **1245**, 012003 (2022).
31. Paxton, A. B., Steward, D. N., Harrison, Z. H. & Taylor, J. C. Fitting ecological principles of artificial reefs into the ocean planning puzzle. *Ecosphere* **13**, e3924 (2022).
32. Galparsoro, I. et al. Reviewing the ecological impacts of offshore wind farms. *npj Ocean Sustain.* **1**, 1 (2022).
33. Sih, T. L., Cure, K., Yilmaz, I. N., McLean, D. & Macreadie, P. I. Marine life and fisheries around offshore oil and gas structures in southeastern Australia and possible consequences for decommissioning. *Front. Mar. Sci*. https://doi.org/10.3389/fmars.2022.979212 (2022).
34. ter Hofstede, R., Driessen, F. M. F., Elzinga, P. J., Van Koningsveld, M. & Schutter, M. Offshore wind farms contribute to epibenthic biodiversity in the North Sea. *J. Sea Res.* **185**, 102229 (2022).
35. Dodds, K. C. et al. Material type influences the abundance but not richness of colonising organisms on marine structures. *J. Environ. Manage.* **307**, 114549 (2022).
36. Becker, A., Lowry, M. B., Fowler, A. M. & Taylor, M. D. Hydroacoustic surveys reveal the distribution of mid-water fish around two artificial reef designs in temperate Australia. *Fish. Res.* **257**, 106509 (2023).
37. Gül, B. et al. Comparison of fish community structure on artificial reefs deployed at different depths on Turkish Aegean Sea coast. *Braz. J. Oceanogr.* **59**, 27–32 (2011).
38. Şensurat-Genç, T., Lök, A., Özgül, A. & Oruç, A. Ç. No effect of nearby natural reef existence on fish assemblages at shipwrecks in the Aegean Sea. *J. Mar. Biol. Assoc. UK* **102**, 613–626 (2022).
39. Barber, J. S., Chosid, D. M., Glenn, R. P. & Whitmore, K. A. A systematic model for artificial reef site selection. *N. Z. J. Mar. Freshw. Res.* **43**, 283–297 (2009).
40. Tseng, C.-T., Chen, S.-C., Huang, C.-S. & Liu, C.-C. GIS-assisted site selection for artificial reefs. *Fish. Sci.* **67**, 1015–1022 (2001).
41. Carral, L., Lamas, M. I., Cartelle Barros, J. J., López, I. & Carballo, R. Proposed conceptual framework to design artificial reefs based on particular ecosystem ecology traits. *Biology* **11**, 680 (2022).
42. Mavraki, N., Degraer, S. & Vanaverbeke, J. Offshore wind farms and the attraction–production hypothesis: insights from a combination of stomach content and stable isotope analyses. *Hydrobiologia* **848**, 1639–1657 (2021).
43. Bulleri, F. & Airoldi, L. Artificial marine structures facilitate the spread of a non-indigenous green alga, *Codium fragile* ssp. *tomentosoides*, in the north Adriatic Sea. *J. Appl. Ecol.* **42**, 1063–1072 (2005).
44. Techera, E. J. & Chandler, J. Offshore installations, decommissioning and artificial reefs: do current legal frameworks best serve the marine environment? *Mar. Policy* **59**, 53–60 (2015).
45. Knights, A. et al. Rethink plans for the world's ageing oil and gas platforms. *Nature* **627**, 37 (2024).
46. Ditton, R. B., Osburn, H. R., Baker, T. L. & Thailing, C. E. Demographics, attitudes, and reef management preferences of sport divers in offshore Texas waters. *ICES J. Mar. Sci.* **59**, S186–S191 (2002).
47. Firth, L. B. et al. Make a difference: choose artificial reefs over natural reefs to compensate for the environmental impacts of dive tourism. *Sci. Total Environ.* **901**, 165488 (2023).
48. McLean, D. L. et al. Influence of offshore oil and gas structures on seascape ecological connectivity. *Glob. Change Biol.* **28**, 3515–3536 (2022).
49. Firth, L. B. et al. Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. *J. Appl. Ecol.* **57**, 1762–1768 (2020).
50. Langhamer, O., Wilhelmsson, D. & Engström, J. In *Proc. ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering* Vol. 4 Parts A and B 855–859 (American Society of Mechanical Engineers, 2009).
51. Bender, A., Langhamer, O. & Sundberg, J. Colonisation of wave power foundations by mobile mega- and macrofauna – a 12 year study. *Mar. Environ. Res.* **161**, 105053 (2020).
52. Langhamer, O. & Wilhelmsson, D. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes – a field experiment. *Mar. Environ. Res.* **68**, 151–157 (2009).
53. Pauly, D. Anecdotes and the shifting baseline syndrome of fisheries. *Trends Ecol. Evol.* **10**, 430 (1995).
54. *Guidelines and Standards for Evidence synthesis in Environmental Management* Version 5.0. (Collaboration for Environmental Evidence, 2018).
55. Lemasson, A. J. et al. Evidence for the effects of decommissioning man-made structures on marine ecosystems globally: a systematic map protocol. *Environ. Evid.* **10**, 4 (2021).
56. Nakagawa, S. et al. The orchard plot: cultivating a forest plot for use in ecology, evolution, and beyond. *Res. Synth. Methods* **12**, 4–12 (2021).
57. R Core Team. *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2022).
58. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* **36**, 1–48 (2010).
59. Lemasson, A. J. et al. Datasets and R code for Lemasson et al. A global meta-analysis of ecological effects from offshore artificial structures. *Zenodo* https://doi.org/10.5281/zenodo.10563392 (2024).

Acknowledgements

We thank and remember P. J. Somerfield, who sadly passed away during the revision of this manuscript following a short illness. We acknowledge the financial and technical support provided by NERC, Cefas and the INSITE programme. We also thank D. Maxwell for internally reviewing this manuscript before journal submission. This map was undertaken within the agreed work of DREAMS (Decommissioning – Relative Effects of Alternative Management Strategies, INSITE 2 programme; https://www.insitenorthsea.org), which is financed by the UK Natural Environment Research Council, Grant Nos. NE/T010843/1 and NE/T010835/1 awarded to the University of Plymouth (to A.M.K.) and Plymouth Marine Laboratory (to P.J.S.). Cefas was supported through its own strategic science investment fund (DP4000A awarded to M.S.).

Author contributions

A.J.L., A.M.K., M.S. and P.J.S. designed the study. A.J.L. and A.M.K. wrote the initial manuscript, with discussions and revisions from L.B.F., C.L.M., C.P., M.S., P.J.S., S.C.L.W., M.S.A.T. and E.C. A.J.L., A.M.K., J.N., C.P., C.L.M. and S.C.L.W. participated in data extraction. A.J.L., A.M.K. and M.S.A.T. performed statistical analyses. All authors approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-024-01311-z.

Correspondence and requests for materials should be addressed to Anaëlle J. Lemasson.

Peer review information *Nature Sustainability* thanks Lena Bergström, Andrew Gates and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

nature portfolio

Corresponding author(s): Anaelle Lemasson

Last updated by author(s): Jan 31, 2024

Reporting Summary

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☐	☒	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

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	Data were collected using WebPlot Digitizer (version 4.5) and Microsoft Excel (Microsoft® Excel® for Microsoft 365 MSO (Version 2205 Build 16.0.15225.20172) 64-bit)
Data analysis	All statistical analyses were run in the R environment (R version 4.2.1) using the rma.mv() function in the {metafor} package (version 3.8.1) (code provided in Supplementary File 4). Data were visualised using the {orchaRd} package. The R code used in the analyses is available in Supplementary File 4. Correspondence and requests for materials should be addressed to AJL. The R code (Supplementary File 4) has been deposited to the online repository Zonedo.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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

All data supporting the findings of this study and used to produce the figures are available within the paper and its Supplementary Information (supplementary files 2 and 3). All data sheets (Supplementary Files 1-3) have been deposited to the online repository Zonedo.

Human research participants

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

Reporting on sex and gender	NA
Population characteristics	NA
Recruitment	NA
Ethics oversight	NA

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 is a meta-analysis of 531 data points obtained from 109 scientific peer-reviewed articles. We several models to answer different questions. The most complex model had a random-effect structure, with multiple additive moderators (~factors), and effect size identifier nested within article identifier (because some articles provided more than one effect size to the analysis).
Research sample	This study is a meta-analysis of 531 data points (effect sizes) obtained from 109 scientific peer-reviewed articles describing the effects of the presence of marine artificial structures on components of the ecosystem (diversity, abundance, biomass, reproduction, behaviour, survivorship). The 109 articles were selected using tailored filtered applied to an existing database of relevant publications (Lemasson et al. 2022 https://doi.org/10.1186/s13750-022-00285-9) and are listed in Supplementary File 1.
Sampling strategy	The number of effect sizes included was dependent of the number of articles selected for consideration. These articles were selected using a specific methodology based on PICO components and on whether they provided the necessary information to calculate effect sizes (sample size, mean, variance).
Data collection	From the identified relevant literature, information necessary to calculate effect sizes were (where possible) were extracted by several co-authors of this manuscript (AJL, AMK, JN, CP, LM, and SW). Sample sizes, means, and variances were extracted from each article and entered into an Excel spreadsheet (supplementary file 3) where effect sizes were then calculated.
Timing and spatial scale	The peer-reviewed published literature used in our study was identified by Lemasson et al. (2022) as part of a systematic map exercise. The searches for this map were targeted all relevant literature published up to February 2021. The full methodology is provided in Lemasson et al. (2022). The geographic scope was global (studies undertaken anywhere). From this database of relevant literature, information to calculate effect sizes were (where possible) were extracted between February and July 2022.
Data exclusions	Effect sizes stemming from one article initially selected for the meta-analysis were excluded. This was decided following an outlier analysis, showing that effect sizes from this specific articles were outliers that biased the outcome. This is explained fully in the full methodology in Supplementary Information.
Reproducibility	The full methodology is provided in Supplementary Information, following state-of-the-art reporting guidelines for evidence synthesis and meta-analysis in environmental sciences (Collaboration for Environmental Evidence), to ensure transparency and reproducibility.

Randomization	Randomization is not applicable to our study as this is a meta-analysis for existing data from the literature.
Blinding	Blinding is not applicable to our study as this is a meta-analysis for existing data from the literature.

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