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Opportunity Knocks: Leveraging Offshore Wind Development as a Natural Experiment to Address the Ecological Function of Artificial Reefs

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Received: 26 September 2024 | **Revised:** 18 March 2025 | **Accepted:** 5 May 2025

Funding: This work was supported by the National Oceanic and Atmospheric Administration's RESTORE Science Program, NA22NOS4510203.

Keywords: artificial reef | attraction-production | ecological trap | offshore wind | renewable energy | secondary production

ABSTRACT

Artificial structures deployed in marine environments as reefs are often presumed to increase fish production. However, our literature review found a lack of evidence, with only 12 studies empirically quantifying secondary production at artificial reefs, and only three studies using a control site. We propose the forthcoming large-scale construction of offshore wind (OSW) energy structures presents a natural experiment to examine the ecological function of artificial reefs, including their effects on fish production. To provide causal inferences of OSW effects, studies must obtain appropriate 'before' data, per before-after-control-impact and related designs. This requirement dictates that society must begin planning and collecting data now, prior to OSW deployment. We also highlight that responses beyond fish biomass measures, including life stage specific survival, site fidelity and trophic dynamics, must occur at appropriate spatial and temporal scales to maximise causal inference. By leveraging a timely opportunity and natural experiment with OSW development, the long-running 'attraction–production debate' about artificial reef ecological function may be addressed.

1 | Artificial Structures and Fish Production

Marine artificial structures are deployed for reasons including offshore energy extraction, habitat restoration and recreation opportunities, but may incidentally affect fisheries due to addition of hard substrate, which may increase structural complexity (refuge), nutrient cycling, food availability and eventually secondary production (Hixon and Beets 1993; Grossman et al. 1997; Layman and Allgeier 2020). Artificial reefs, however, are deployed specifically to enhance fisheries production (Becker

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et al. 2018). These structures are common in certain marine ecosystems (Ramm et al. 2021) and widely supported by fishermen (Schuett et al. 2016). We therefore use the term 'artificial reef' broadly, as any artificial structure may function as an artificial reef. High catch rates and/or densities of key fishery species are observed at artificial reefs around the world, including red snapper (*Lutjanus campechanus*) in the U.S. Gulf of America (hereafter GoA, formerly the Gulf of Mexico) (Karnauskas et al. 2017; Gallaway et al. 2021), Australasian snapper (*Chrysophrys auratus*) in Australia (Mills et al. 2017; Ramm et al. 2021) and Atlantic cod (*Gadus morhua*) in the North Sea (Bergström et al. 2013). Recent reviews further highlight that artificial reefs produce higher abundances and biomasses of fish relative to controls (Lemasson et al. 2024; Watson et al. 2024). However, it is unclear whether high catch rates and abundances are due to increased fish production or behavioural affinities of fishes for more complex artificial reefs (i.e., attraction).

Changes in ecological function via artificial reefs may increase production; however, attraction in the absence of enhanced production can create ecological traps, leading to reduced fitness and/or survival (Reubens et al. 2013; Swearer et al. 2021). Traps may arise when habitat is not limiting, but recruits are redirected to poorer quality artificial reef habitat, thereby decreasing fitness (Komyakova et al. 2021). Traps may also arise when habitat is limiting, leading to initial recruitment and/or biomass pulses at artificial reefs that are eventually depleted due to high catch rates, yielding reduced survival (Chong et al. 2024). Ecological traps present management concerns, as biomass aggregation (rather than increased productivity) and spatially focused fishing activity may cause localised depletion and increase fishing mortality beyond sustainable levels (Chong et al. 2024). Although not a true dichotomy, there is uncertainty whether artificial reefs create ecological traps or enhance production, that is, the 'attraction–production debate' (Bohnsack 1989; Powers et al. 2003). Nevertheless, recreational fishing communities, particularly in the U.S., often advocate for artificial reefs due to perceived fisheries enhancements (Grossman et al. 1997).

Resolving the 'attraction–production debate' is becoming increasingly important as humans continue to deploy artificial reefs, including structures used for offshore energy extraction. Recent expansions in offshore renewable energy, including offshore wind (OSW), particularly highlight a need to assess how artificial reefs affect secondary production (Reubens et al. 2013; Soares-Ramos et al. 2020). Adequate assessments require empirical experiments of large spatial and temporal scales, so much so that few attempts exist. Given these notions, we aim, via a literature review, to assess the scientific evidence supporting the idea that artificial reefs increase secondary production.

2 | The Lack of Evidence

We used Web of Science to identify journal articles, Master's theses, and PhD dissertations published between 1970 and 2024 related to artificial reefs and biological production (i.e., biomass fluxes of any faunal species) in marine environments. See https://github.com/shaynasura/osw_ghoti_lit for further literature review details. Our search returned 915 potentially relevant records (Figure 1A) with 695 records reporting on primary or secondary production in marine environments. Of these, 276 (39.7%) records reported on primary or secondary production related to artificial reefs (Figure 1B), and only 12 records (1.7% of 695) provided empirical estimates of secondary production from observational data (Table 1). Ten additional records used simulation modelling (e.g., Ecopath with Ecosim; Christensen and Walters 2004) to estimate secondary production. Two records quantified primary production and then inferred secondary production based on the theory of primary production constraining secondary production (Layman et al. 2016; Layman and Allgeier 2020).

The 12 records quantifying secondary production occurred in five countries: U.S. (7), Australia (2), Japan (1), Portugal (1) and the Bahamas (1) (Table 1). Artificial reefs with low vertical relief (< 10 m) were assessed in all five countries, while high vertical relief (> 10 m), large-scale (> 200 m^2 footprint) artificial reefs (specifically petroleum platforms) were only assessed in the U.S. and Australia (Table 1). Only three of these 12 studies quantified secondary production at control sites, all reporting greater production at artificial reefs than control sites (Table 1). Claisse et al. (2014, 2015) were able to estimate production effects by leveraging extensive size-at-age time series data (up to 15 years) and site fidelity information to estimate size-specific survival, somatic production, and recruitment production. Steimle et al. (2002) were able to estimate artificial reef effects on epifauna and infauna production via 2 years of sample data and using previously published P:B ratios. No studies quantified secondary production before artificial reef deployment. Estimated secondary production rates varied by five orders of magnitude and are not comparable across studies due to differing estimation methods and target organisms (e.g., finfishes and epifaunal invertebrates) (Table 1). All three studies including controls found higher production rates at artificial reefs, with control sites varying from natural reefs to benthic sand habitat (Table 1). While all three studies demonstrated higher production at artificial reefs, a sample size of three does not permit the broad conclusion that artificial reefs enhance secondary production. The state of artificial reef science therefore needs to evolve to provide valuable information to fisheries management.

3 | The Difficulty of Assessment: Function, Causal Inference and Scale

Many underlying processes, including recruitment, habitat availability, movement and density-dependent mortality and/or growth at different life stages determine if and how artificial reefs affect fish production (Bohnsack 1989; Osenberg et al. 2002; Lorenzen and Camp 2019). For example, artificial reefs may enhance fish production if they increase juvenile survival and if recruitment is a key limitation for the population, as earlier life stages can be most affected by density-dependent mortality (Lorenzen and Camp 2019). This ecological complexity contributes to difficulties in assessing artificial reef effects on fish production, and may explain our findings that only 12 studies provide empirical estimates of secondary production on artificial reefs. Moreover, addressing the 'attraction–production debate' requires an assessment of the ecological function of artificial reefs whereby responses beyond measures of biomass of individual life stages are needed to assess secondary production.

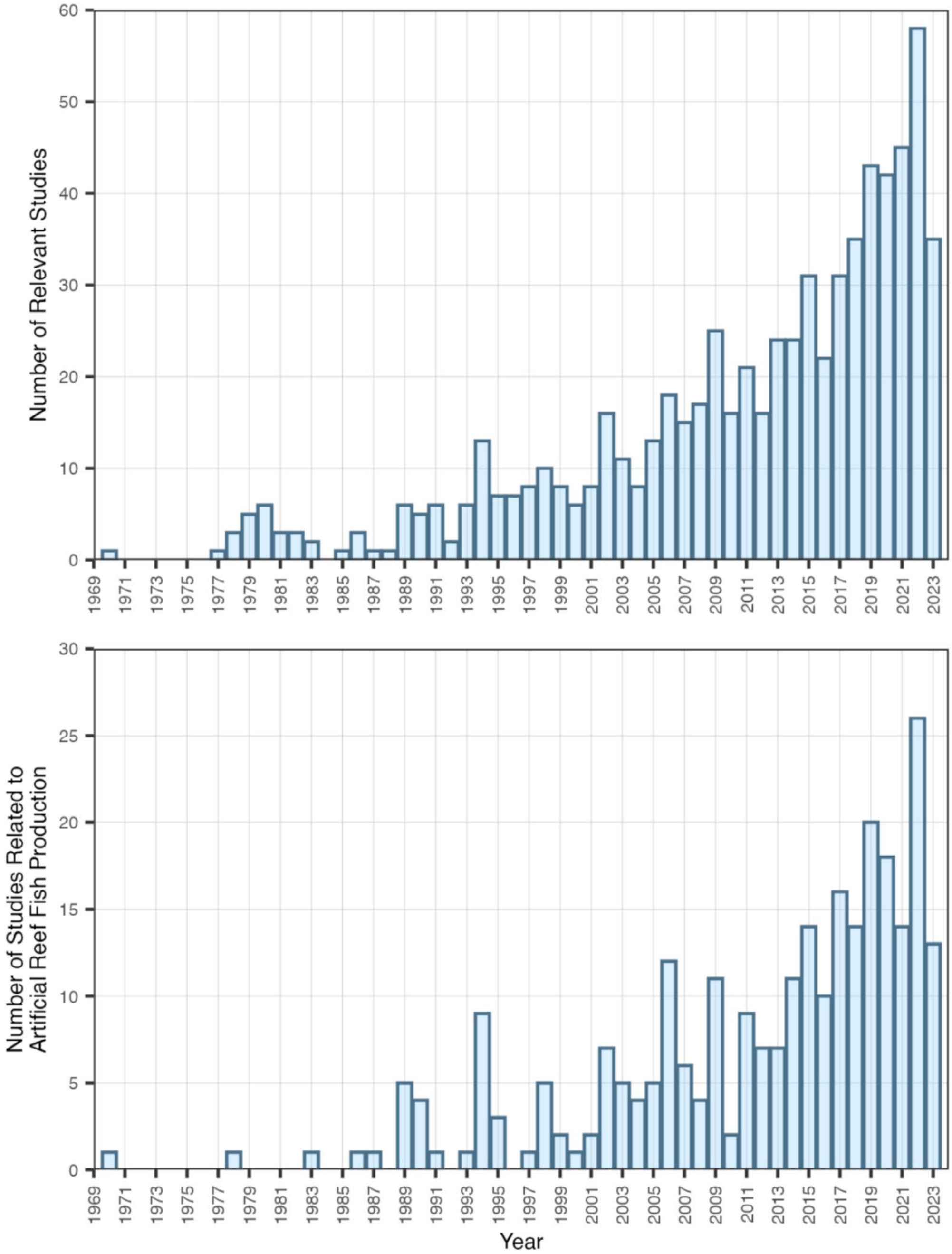

FIGURE 1 | Number of published studies per year that were relevant to biological production in marine environments (A) and that provide empirical, biological data in the context of artificial reefs and marine organism production (B). The data for this literature search as presented in both A and B above, was conducted on February 2, 2024 using as Web of Science search string of 'TS=(ship-wreck OR shipwreck OR (sunken NEAR/2 ship) OR ((oil OR gas OR petrol*) NEAR/5 (platform OR rig OR structure OR infrastructure)) OR (rig NEAR/2 reef) OR (wind* NEAR/2 (farm OR turbine OR structure)) OR manmade structure OR man-made structure OR (artificial NEAR/2 (reef OR structure))) AND TS=(production*) AND TS=(fish*) NOT TS = (lake OR river OR pond)'.

Alternatives include a pluralistic approach whereby multiple, individual processes (including those listed above) are evaluated, quantified and synthesised (Osenberg et al. 2002).

Artificial reef deployments can serve as natural experiments, with controls established by obtaining data before deployment and at similar sites lacking artificial reefs, per before-after-control-impact (BACI) designs. BACI designs enable causal inference via temporal (before/after the intervention) and spatial (inside/outside impact sites) controls. Causal inference is difficult to assess in the context of intervention effects on ecological function due to uncertainty about when and where to intervene (Runge et al. 2023). This difficulty, however, is removed with adequate planning before artificial structure deployment. Relatedly, before-after-gradient (BAG) designs allow for assessments of the extent of artificial reef effects and enhance statistical power by modelling distance as a continuous independent variable (Methratta 2020). BACI and BAG designs have been implemented for artificial reef studies; however, only fish biomass or density responses are typically assessed (Vandendriessche

TABLE 1 | List of 12 publications that quantify secondary production as biomass fluxes at artificial reefs. Artificial reef type, location, temporal scale, response data acquired, organism type and production rates (converted to $g/m^2/year$ where possible) at the artificial reef and comparators (e.g., before installation or control site), if applicable, are reported. We also include quoted text from each study indicating the article author(s)' conclusion(s) regarding their reported artificial reef production rate in relation to other habitats.

Article	Location	AR Type	Temp. scale	Response data	Organism	Prod. rate at AR	Prod. rate at comparator (Before or Control)	Article author(s)' conclusion(s) regarding their reported production rate
Beaver (2002)	U.S. (Gulf of America)	Petroleum platform	2 years	Biomass (dry weight), size-frequency	Invert. (fouling)	0.05–89.1 $g/m^2/year$	Control: n/a Before: n/a	'Annual productivity of cryptic epifaunal organisms was generally lower than levels reported for similar species in near-shore environments [reported from published literature]'.—page 95
Claisse et al. (2014)	U.S. (CA)	Petroleum platform	5–15 years	Density, size at age	Finfish	14.8–2608 $g/m^2/year$	Control: 0.9–46.1 $g/m^2/year$ Before: n/a	'The mean annual Total Production per square meter of seafloor for complete platforms was significantly greater than, and 27.4 times as much as is produced per square meter on natural rocky reefs located at similar depths in the study region'.—page 15463
Claisse et al. (2015)	U.S. (CA)	Petroleum platform	5–15 years	Density, size at age	Finfish	106.6–697.4 $g/m^2/year$	Control: 4.4–22.4 $g/m^2/year$ Before: n/a	'Partially removed [oil and gas] platforms [and the shell mound habitats they create] would still have some of the highest production values... of any marine habitat globally [reported from published literature]'.—page 13

(Continues)

TABLE 1 | (Continued)

Article	Location	AR Type	Temp. scale	Response data	Organism	Prod. rate at AR	Prod. rate at comparator (Before or Control)	Article author(s)' conclusion(s) regarding their reported production rate
Gillam (2016)	U.S. (Gulf of America)	Oyster shell & concrete blocks	6 weeks	Biomass (dry weight), P-B ratios	Invert. (all benthic)	14.6–47.9 g/m^2/year	Control: n/a Before: n/a	'The four artificial reefs examined in this study represent areas of increased secondary production [comparison is unclear], and so can be considered valuable, particularly since the reef benthos comprises important links in the food web'.—pages 53–54
Johnson et al. (1994)	U.S. (CA)	Quarry rocks	1 year	Density, gamete counts	Finfish	0.6–17.7 g/m^2/year	Control: n/a Before: n/a	'Artificial reefs not only produce fish, but do so at a substantially higher rate than does the surrounding soft-bottom habitat [reported from published literature]'.—page 722
Komai and Itosu (2002)	Japan	Variable steel and concrete modules	4 years	Biomass (wet weight)	Invert. (all benthic)	30,376–95,417 g/reef/year	Control: n/a Before: n/a	Authors made no statement comparing production rate on artificial reefs to other habitats

(Continues)

TABLE 1 | (Continued)

Article	Location	AR Type	Temp. scale	Response data	Organism	Prod. rate at AR	Prod. rate at comparator (Before or Control)	Article author(s)' conclusion(s) regarding their reported production rate
McLean et al. (2022)	Australia	Petroleum platform & pipelines	2 years	Density, length, P-B ratios	Finfish	105.2 g/m^2/year	Control: n/a Before: n/a	'Here, it is not possible to state whether the production and biomass of fish on subsea wells are significant relative to natural reefs or potential fishery contribution. Comparable surveys and fish production estimates across natural habitats are required in addition to temporal studies to better quantify variability in fish abundances at these structures'.—page 20
Moura et al. (2011)	Portugal	Variable concrete modules	1 year	Biomass (dry weight), P-B ratios	Invert. (epifaunal)	98–128 g/m^2/year	Control: n/a Before: n/a	'[Artificial reefs] apparently may enhance benthic secondary production per unit area on the southern coast of the Algarve, but further studies over a longer period of time are called for'.—page 94
Pondella et al. (2015)	U.S. (CA)	Petroleum platform	5 years	Density, weight-length	Finfish	194–3539 g/m^2/year	Control: n/a Before: n/a	'The results presented here indicate that, even if [partially removed] the potential contribution of platform habitat to biological resources (e.g., fish production) in this region is significant'.—page 584

(Continues)

TABLE 1 | (Continued)

Article	Location	AR Type	Temp. scale	Response data	Organism	Prod. rate at AR	Prod. rate at comparator (Before or Control)	Article author(s)' conclusion(s) regarding their reported production rate
Smith et al. (2016)	Australia	Steel panels	3.5 years	Density, weight-length	Finfish	384 g/m^2/year	Control: n/a Before: n/a	'Our results show that like oil platforms, designed artificial reefs can be very productive marine habitats, but may not greatly increase the net fish production in a system'.—page 1
Steimle et al. (2002)	U.S. (DE)	Concrete panels	3 years	Biomass (dry weight), P-B ratios	Invert. (epi- and infaunal)	3990–9555 kcal/m^2/year	Control: 215–249 kcal/m^2/year Before: n/a	'...artificial reefs apparently may enhance benthic secondary production per unit area in estuarine areas [compared to benthic sand habitat], such as lower Delaware Bay, by up to 2 or more orders of magnitude'.—page S104
Yeager et al. (2012)	Bahamas	Concrete cinder blocks	1 year	Density, weight-length	Finfish	135–2246 g/reef/year	Control: n/a Before: n/a	'...secondary production of juvenile white grunts associated with these artificial reefs likely represents new production'.—page 237

Abbreviations: AR, artificial reef; invert., invertebrates; n/a, not applicable; P-B, production-biomass; Prod., production; Temp., temporal.

et al. 2015; Streich et al. 2017). Responses including recruitment, growth and survival would enable stronger conclusions regarding mechanisms of fish production changes.

In addition to including controls and assessing responses beyond standing biomass, experiments conducted at sufficiently large spatial scales can differentiate local versus regional responses, which are needed to understand population- and ecosystem-wide changes (Carr and Hixon 1997). These could be accomplished with multiple-BACI (mBACI) designs of multiple impact and control sites, inherently increasing spatial scale (Kingsford 1999). mBACI designs are particularly applicable for OSW, as multiple turbines and/or wind farms can serve as replicate experimental units. Including multiple sites can expand spatial scales to tens of kilometres to account for larger-scale processes, including larval dispersal and steppingstone effects (Methratta 2021). Applying these study designs requires foresight and time to collect prior data, which likely explains the paucity of BACI studies examining artificial reef effects on production. However, with planned offshore renewable energy, including OSW development, we know when and where these interventions are coming, and we have the knowledge of relevant ecological theory to plan and act accordingly. OSW development thus presents an opportunistic natural experiment to apply pluralistic approaches, and mBACI and BAG designs, to examine causal inference of the ecological function of artificial reefs.

4 | Offshore Wind Development and Experimental Management

The development of OSW energy is one of the next major steps in humankind's transformation of Earth's oceans. In Europe, OSW development has rapidly expanded since the early 2000s, with >25 gigawatts (GW) of energy per year (>5000 turbines) currently deployed (Soares-Ramos et al. 2020). In the U.S., the first OSW farm was deployed off New England in 2016 (Wilber et al. 2022), with >2.2 million acres of Atlantic continental shelf waters leased (Williams et al. 2024). More recently, three areas were leased (142,352 acres) in GoA state (Louisiana) and federal waters (Baurick 2023). OSW expansion in the European Union is expected to reach 100 GW of energy per year by 2030 (Soares-Ramos et al. 2020) and is expected to increase as technological capacities increase and production costs decrease (Offshore Wind Market Report 2021). U.S. development increased rapidly between 2021 and 2023, with total land and wind-based energy in 2023 accounting for 9% (43 of 477 GW) of total U.S. electricity production (Unites States Energy Information Administration 2024). However, the speed at which U.S. OSW develops may vary due to national priorities for energy production.

Scientists have begun identifying ecological effects of OSW, including increased biofiltration, biodeposition and abundances of commercially important finfish and shellfish (Watson et al. 2024; Degraer et al. 2020, and references therein). With anticipated OSW development, now is the time to consider further ecological questions, and valuable and novel natural experiments associated with OSW. We propose seizing this opportunity to critically examine long-standing questions in the 'attraction–production debate' (Bohnsack 1989; Powers et al. 2003; Cowan et al. 2011) with empirical, experimental assessments of the ecological function of OSW infrastructure as artificial reefs.

We highlight the GoA as an opportunity to conduct these studies due to its potential OSW development by 2030 (Baurick 2023). Moreover, there are over 20,000 known artificial reefs in the GoA (Paxton et al. 2024) with strong connections to fisheries, including red snapper, which is a highly valuable and contentious fishery in the GoA (Gallaway et al. 2009; Gardner et al. 2022). Red snapper fisheries management is controversial in the U.S. partially due to allocation disputes between recreational and commercial fisheries (Cowan et al. 2011), uncertainty in landings and discard estimates, and challenges in balancing objectives between commercial and recreational sectors (Farmer et al. 2020). Artificial reefs are deliberately deployed as management tools for red snapper, and estimates of exploitation rate based on tag recaptures are highest in the Alabama Artificial Reef Zone (Sackett et al. 2018), elevating the concern about implications of the 'attraction–production debate'. U.S. Congress augmented monitoring surveys with the goal of assisting fishery assessments, including the Congressional Supplemental Sampling Program (Campbell et al. 2012; Karnauskas et al. 2017) and the Great Red Snapper Count (Stunz et al. 2021). Even given specialised attention and resources, artificial reef effects on red snapper population dynamics remains heavily debated and unresolved (Karnauskas et al. 2017; Gardner et al. 2022).

A critical shortcoming for assessing how artificial reefs affect GoA red snapper is the lack of 'before' data. Many studies quantified red snapper biomass, abundance, trophic habits or site fidelity after, but not before, artificial reef deployment (Karnauskas et al. 2017; Powers et al. 2018; Tarnecki and Patterson III 2015; Froehlich et al. 2021). However, lacking population dynamic data before artificial reef deployment has prohibited quantitative assessments of how artificial reefs affect red snapper production. Planned GoA OSW development presents a unique opportunity of a 'redo' of past lost opportunities. This opportunity is predicated upon utilising the crucial window before OSW structure deployment. In the GoA, functional OSW turbines may be expected by 2030 or later (Baurick 2023). Foresight informed with knowledge of past lost opportunities should inspire societies to employ a cause-and-effect framework to assess the ecological function of artificial reefs. While we highlight the GoA as a case study, our proposed design considerations apply to any region expecting OSW deployment and containing fisheries linked to artificial reefs.

Many OSW farms, including but not limited to those in the GoA, may deploy >100 turbines per site, with expected turbine spacing of one nautical mile (United States Coast Guard 2020; Bureau of Ocean Energy Management 2024). Although size and location factors, including interior vs. edge effects and windward vs. leeward turbine sides, create spatial complexity potentially affecting habitat suitability, inherent replication may exist in constructing identical structures. More broadly, there is replication across regional and even global scales, since wind farms are designed in a grid pattern. These levels of replication may promote mBACI designs and allow for evaluation of artificial reef dynamics at larger spatial scales than previous artificial reef deployments, which typically have low (< 10) replicates on small (100–1000 s of m^2) spatial scales, or may be haphazardly placed within an area (e.g., petroleum platforms; Arney et al. 2017; Babcock et al. 2020). The inherent replication and scale of OSW development will further improve causal inference abilities.

In the GoA, OSW farms are expected to be open to fishing, other than *de facto* fishing exclusion (due to gear fouling issues) or tie-up constraints (tying up to turbines) during operations and installation. Therefore, controlled experiments will require differential treatments for fishing and nonfishing and cooperation between fishermen, scientists and stakeholders. Such fishery exclusion experiments could maintain fishing opportunities while providing controlled scientific designs assessing how fishing pressure affects the ecological function of large-scale artificial reefs. The GoA also hosts many long-term monitoring programs (LTMPs) that can be leveraged for large spatial and temporal scale assessments (Grüss et al. 2018). Future studies assessing OSW impacts on fish production may consider replicating sampling approaches of LTMPs but at higher spatial and temporal resolution/replication in and around OSW farms (discussed by Karnauskas et al. 2017). This may allow for easy integration of LTMP data with future data sets, thereby increasing the spatial and temporal scales of inference.

5 | The Opportunity

The U.S. Bureau of Ocean Energy Management (BOEM) suggests 2 years of preconstruction environmental monitoring for OSW leases. These efforts may provide a foundation for 'the opportunity'. However, coordination is needed among a consortium of stakeholders including BOEM, National Marine and Fisheries Service, private developers and leaseholders to expand upon these mandates to produce data enabling robust mBACI and BAG designs. Our initial minimum recommendation is to monitor for one decade, including at least 6 years of 'after' data, to account for succession, as climax communities at OSW structures are often reached after 6 years (Degraer et al. 2020), although this value pertains to the North Sea and likely varies among global regions. Sampling beyond a decade will likely be needed to distinguish effects caused by artificial reefs against other sources of variability (e.g., environmental variability and natural fluctuations in spawning stock biomass). We also recommend sampling metrics beyond standing biomass, specifically size-specific survival, growth and recruitment. Expanded monitoring should consider how different OSW infrastructure, including foundation type and scour protection material type and depth, affect fish production. Capitalisation upon these natural experiments is needed to determine immediate effects of OSW, but also to predict and mitigate long-term impacts, including those coinciding with ongoing ocean changes and fisheries management. This opportunity extends beyond the scientific community to society as a whole, including policymakers, stakeholders and the public. By engaging in this natural experiment with foresight and collaboration, we can ensure OSW development proceeds in an environmentally sustainable manner, does not lead to ecological traps and enhances our understanding of marine ecosystems. The lessons learned here can inform future ocean interventions to optimise how we balance human needs with ecological preservation.

Acknowledgements

This paper is a result of research funded by the National Oceanic and Atmospheric Administration's RESTORE Science Program (ROR—https://ror.org/0042xzm63) under award NA22NOS4510203 to the National Center for Ecological Analysis and Synthesis at the University of California, Santa Barbara and part of the Impacts of Offshore Wind on Gulf of Mexico Fish and Fisheries working group of the Gulf Ecosystem Initiative. We thank all working group participants for sparking conversations that led to the development of this paper. We especially thank Mariana Steen (Bureau of Ocean Energy Management) for her participation in our working group, and for the valuable insights, knowledge and feedback she provided for this paper. We also thank Nathan Bacheler and Elizabeth Methratta for their feedback and suggestions. Lastly, we thank two anonymous reviewers for their insightful and helpful feedback. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. All efforts are made to use "Gulf of America" per E.O. 14172. However, previous documents/bodies of work (cited herein) may have referred to this water body as the "Gulf of Mexico."

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Literature review data are available via the GitHub accounts of the first authors (see Section 2 - The Lack of Evidence).

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