Downloaded from orbit.dtu.dk on: Sep 08, 2026

DTU Library

Rethinking the responsible application of nature-inclusive design in marine infrastructure to restore ecosystems and enhance biodiversity

Degraer, Steven; Cornacchia, Loreta; Ziemba, Alex; Agardy, Tundi; van den Burg, Sander W. K.; van de Braak, Karin; van Duren, Luca A.; Declercq, Annelies; Eggermont, Mieke; Van Gerven, Annaik

Total number of authors:
19

Published in:
ICES Journal of Marine Science

Link to article, DOI:
10.1093/icesjms/fsag050

Publication date:
2026

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Degraer, S., Cornacchia, L., Ziemba, A., Agardy, T., van den Burg, S. W. K., van de Braak, K., van Duren, L. A., Declercq, A., Eggermont, M., Van Gerven, A., Kerkhove, T. R. H., Moulaert, I., Patel, T., Petersen, J. K., Poelman, M., Stratigaki, V., Strothotte, E., Vanaverbeke, J., & El Serafy, G. (2026). Rethinking the responsible application of nature-inclusive design in marine infrastructure to restore ecosystems and enhance biodiversity. *ICES Journal of Marine Science*, *83*(4), Article fsag050. https://doi.org/10.1093/icesjms/fsag050

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

ICES Journal of Marine Science, 2026, Vol. 83, Issue 4, fsag050
https://doi.org/10.1093/icesjms/fsag050
Quo Vadimus

Rethinking the responsible application of nature-inclusive design in marine infrastructure to restore ecosystems and enhance biodiversity

Steven Degraer [1,*], Loreta Cornacchia[2], Alex Ziemba[2,3], Tundi Agardy [4], Sander W.K. van den Burg [5], Karin van de Braak[6], Luca A. van Duren [2], Annelies Declercq[7], Mieke Eggermont[7], Annaïk Van Gerven[1], Thomas R.H. Kerkhove[1], Ine Moulaert[8], Tasnim Patel [1], Jens Kjerulf Petersen[9], Marnix Poelman [10], Vasiliki Stratigaki[11,12], Eva Strothotte[13], Jan Vanaverbeke[1], Ghada El Serafy[2,3]

[1]Royal Belgian Institute of Natural Sciences (RBINS), Operational Directorate Natural Environment, Marine Ecology and Management, 1000 Brussels, Belgium
[2]Deltares, Department of Data Science and Water Quality, Delft 2600 MH, The Netherlands
[3]Delft University of Technology, Applied Mathematics, Delft 2628 CD, The Netherlands
[4]Sound Seas, Bethesda MD 20816 , USA
[5]Wageningen Social and Economic Research, Wageningen Research, 2595 BM Den Haag, The Netherlands
[6]Sustainable Aquaculture Solutions, 5976PB Kronenberg, The Netherlands
[7]Laboratory of Aquaculture and Artemia Reference Center, Faculty of Bioscience Engineering, Ghent University, 9000 Ghent, Belgium
[8]Flanders Marine Institute (VLIZ), 8400 Ostend, Belgium
[9]National Institute of Aquatic Resources, Technical University of Denmark, Section for Coastal Ecology, DK-2800 Kgs Lyngby, Denmark
[10]Wageningen Marine Research, Wageningen University and Research, 4400 AB Yerseke, The Netherlands
[11]Jan De Nul Group, 9308 Hofstade-Aalst, Belgium
[12]Coastal Engineering Research Group, Faculty of Engineering and Architecture, Ghent University, 9052 Ghent-Zwijnaarde, Belgium
[13]R&D Centre University of Applied Sciences Kiel GmbH, 24149 Kiel, Germany
*Corresponding author. Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management, Vautierstraat 29, 1000 Brussels, Belgium. E-mail: steven.degraer@naturalsciences.be

Abstract

Nature-inclusive design (NID) of marine infrastructure comes in different forms, but always refers to the creation of optimized artificial habitat to locally enhance biodiversity. In essence, NID comprises the local addition of something non-natural to infrastructure with the aim of providing habitat for biodiversity assets in its widest sense. In its purest sense, NID is inspired by how the local environment would be without the infrastructure being present. NIDs of marine infrastructure, however, often comprise actions that promote biodiversity which does or did not naturally occur at that location. To ensure consistent use of terminology, we recommend adopting an NID trichotomy when reflecting on the appropriateness of NID applications in the marine realm, distinguishing between (i) restorative NID, linked to the restoration of lost local ecosystem values, and (ii) creative NID, referring to artificially created ecosystem assets and containing either (a) optimized infrastructure or (b) add-on structures. Restorative NID refers to measures which facilitate and speed-up nature restoration, while creative NID refers to measures to boost biodiversity 'beyond the natural'. Beyond the importance of distinguishing different types of NID, it is important to also reflect on which biodiversity assets we elect to boost. Nowadays, much focus is placed on species richness or select species of commercial or conservational interest, while a focus on functional ecosystem assets may be more effective. A focus on functional ecosystem assets also provides better options for climate-proof NID designs. To adopt NID in an offshore renewables context, it is imperative to hold our horses and carefully consider what is the target to be achieved and how to get there. This requires a careful selection of the ecological assets that we aim to promote, while preserving the functional purpose of the marine infrastructure and incorporating the differing societal viewpoints on any potentially negative ecological consequences that may be incurred by NID solutions. In summary, restorative NID can be actively promoted, whereas creative NID requires more careful reflection; NID preferably prioritizes functional ecosystem assets and explicitly considers which ecological values to promote and why.

Keywords nature-inclusive design typology, marine infrastructure, offshore wind, green consumerism

Received: 8 September 2025. **Revised:** 24 March 2026. **Accepted:** 25 March 2026
© The Author(s) 2026. Published by Oxford University Press on behalf of International Council for the Exploration of the Sea. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

Nature-inclusive design-related terminology

Confronted with the biodiversity crisis for many decades now (Johnson et al. 2017, Schickhoff et al. 2024), people have begun actively manipulating built structures with the aim of restoring selected natural values (Sia et al. 2023, Peuling et al. 2024) in addition to implementing conventional nature conservation and restoration. Presently, the concept of manipulating artificial structures or built areas with the aim of both promoting or restoring selected natural assets is often referred to as nature-inclusive design (NID; Table 1). Introducing this kind of mimicked habitat in exploited and/or built areas has proven successful in both promoting and restoring selected natural assets (e.g. see Paxton et al. 2025). Particularly in the marine environment, considering the rapid development of offshore wind farms, NID has become a major topic, especially as some countries have required NID in offshore wind tenders (Portela de Carvalho 2025, van Sluis et al. 2025).

When interpreting what are truly NIDs, it is difficult to find a common definition; they are rather manifestations of a design approach that is applied in different areas or disciplines, such as in terrestrial areas or constructions. As with other terms that enter public discourse, it is easy to get confused by the range of nomenclature used to describe NID in scientific publications as well as in policy documents and recommendations, especially as it is also used for branding (cf. green consumerism). The often-associated term nature-based solutions (NBSs) has seen a shift in nomenclature, reflecting both confusion and willful manipulations as described in Jordan and Fröhle (2022) and Pardo et al. (2023).

Within the scope of this paper, NID refers to options that can be integrated into or added to the design of marine infrastructure to create suitable habitat for native species (or communities) whose natural habitat has been degraded or reduced, following the definition of Hermans et al. (2020). Inherently, NID creates an optimized artificial habitat which boosts biodiversity. To avoid confusion with other nature-positive measures (Table 2), we refine the definition of NID, in line with the definition of ecological enhancement, as:

'any intentional measure that creates optimized artificial habitat with the aim of enhancing selected biodiversity assets', with:

- Intentional measure: an active and deliberate human intervention.
- Creates: something non-natural is being constructed.
- Optimized: serving beyond the primary goal of the infrastructure.
- Artificial habitat: the built infrastructure or area in benthic or pelagic habitat.
- Selected biodiversity assets: selection of life forms, ecological functions and/or processes.

The measures we are concerned with in this manuscript, regarding optimization of artificial habitat, do not include site selection for infrastructure. Generally, the sites for infrastructure (e.g. offshore wind farms) are designated in marine spatial planning directives (Jansen et al. 2023). Conversely, NID should take into account local habitat suitability for biodiversity assets and set targets and design measures accordingly.

The current focus is specifically on NID as a structured and deliberate approach for enhancement of biodiversity through incorporation of artificial structures. Broader conservation strategies such as habitat protection, passive ecological restoration, or the rewilding of landscapes without direct human intervention and the broader dimensions of NBSs are not considered in this paper. Sustainability measures that primarily aim at reducing environmental impact without actively creating habitat, such as carbon-neutral construction and eco-friendly design are not considered NID and are not included in the overview. Furthermore, this paper primarily focuses on scientifically supported ecological enhancements rather than marketing-driven sustainability features or claims. And lastly, although NID can contribute to ecosystem services or disservices and climate resilience, the focus of this paper is on its ecological and design principles.

While many terms are interconnected and sometimes used interchangeably with NID (Table 2), it is important to distinguish NID from related concepts such as NBS, net positive/net gain solutions, nature positivity or ecological enhancement. NID can be seen as a specific type of NBS that focuses on optimizing infrastructure to enhance biodiversity. For a comprehensive overview and glossary of concepts related to NID, see Cornacchia et al. (2025).

Nature-inclusive design in the terrestrial versus the marine realm

The application of NID finds its origin in terrestrial built structures and areas, with e.g. garden sheds with integrated shelters for European hedgehogs or bats (Gazzard et al. 2021, Gazzard and Baker 2022), or even larger buildings and cities with nesting facilities for peregrine falcons *Falco peregrinus* in urban South Africa (Altwegg et al. 2013). In the terrestrial, urban realm, NID is most often inspired by how the local environment would look like without the human constructions being present. It tends to integrate or create habitats for species that would naturally prevail if that area would not have been developed, e.g. a residential garden which may once have been an open deciduous forest.

As we increase the level of exploitation of the marine environment, NID has also found its way into the marine realm, such as with abandoned Norwegian oil and gas rigs repurposed as nesting sites for black-legged kittiwake *Rissa tridactyla*, a species of conservation interest (Christensen-Dalsgaard et al. 2020) or offshore wind farm turbine foundations and scour protection layers designed to provide habitat for species of commercial interest, such as Atlantic cod *Gadus morhua* in Dutch North Sea waters (Kingma et al. 2024). When the NID concept is translated to the marine context, it includes a widening of the type of measures observed: NID then also includes introducing habitat that does and did not necessarily naturally occur at the location of action to promote biodiversity beyond what would naturally prevail. While terrestrial NID usually aims to recreate natural conditions predating built structures, marine NID is often broader in scope, also targeting ecological functions and biodiversity enhancement that may not have naturally occurred at the location.

Ocean sprawl, i.e. the extensive development and construction in marine and coastal systems (Duarte et al., 2013), has boosted the interest in marine NID: eco-designed harbour walls in the UK (Naylor et al. 2011), eco-engineered armouring units (Gutiérrez et al. 2023) and other hybrid and natural systems reviewed within Morris et al. (2018) are examples of how marine artificial habitat is deliberately designed in such a way that selected ecological

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

Table 1 Selected definitions of nature-inclusive design (sometimes referred to as biodiversity-inclusive design) as extracted from literature.

Ways that people conceive nature-inclusive design	Source
'…options that can be integrated in or added to the design of … infrastructure … to create suitable habitat for native species (or communities) whose natural habitat … has been degraded or reduced'.	Hermans et al. (2020)
'…the objectives of the plan or project include nature protection measures'.	Law Insider Dictionary (2025)
'…implies that social, economic and nature conservation objectives are integrated in one project'.	
'…an approach to design that seeks to foster functional ecological systems, enable species' persistence in human-dominated landscapes, and (re)connect people with nature'.	Hernandez-Santin et al. (2022)
'…leads to a healthier and more beautiful living environment, where people and animals live in harmony'.	Van Ommeren Associates (2025)

Table 2 Concepts related to nature-inclusive design.

Concept	Definition	Connected to nature-inclusive design?
Nature-based solutions (NBS)	Actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems, which address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits (United Nations Environment Programme, 2022). NBSs address societal challenges through the protection, sustainable management and restoration of ecosystems, benefiting both biodiversity and human well-being (IUCN 2022). NBSs are inspired and supported by nature, they are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience; such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. NBS must benefit biodiversity and support the delivery of a range of ecosystem services (European Research Executive Agency 2023).	Although NID and NBSs are sometimes used interchangeably, they are different. NID are a specific type of NBS that focus on optimizing infrastructure to enhance ecological functions
Net positive/net gain solution	An approach to development that aims to leave the environment in a measurably better state than before. This involves protecting existing habitats and ensuring that lost or degraded environmental features are nullified or, if not possible, compensated by restoration (UK Green Building Council; IUCN 2023). For a solution to be considered net positive, it should incorporate the restoration of the original habitats that have been degraded.	NID may be one of the approaches contributing to a nature-positive future
Ecological enhancement	Habitat creation aimed at enhancing selected ecosystem assets. More specifically, ecological enhancement modifies a site to either increase or improve habitats for animals and plants, while protecting human health and the environment (ITRC 2006), thereby restoring or increasing the ecological value of an area.	Some NID can be considered a subtype of ecological enhancement
Ecological engineering	A technique that combines ecological processes and organisms with technological solutions to predict, design, construct or restore and manage ecosystems, with the aim of integrating human society with its natural environment to the benefit for both (Jørgensen and Mitsch 1989).	NID is not connected to ecological engineering

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

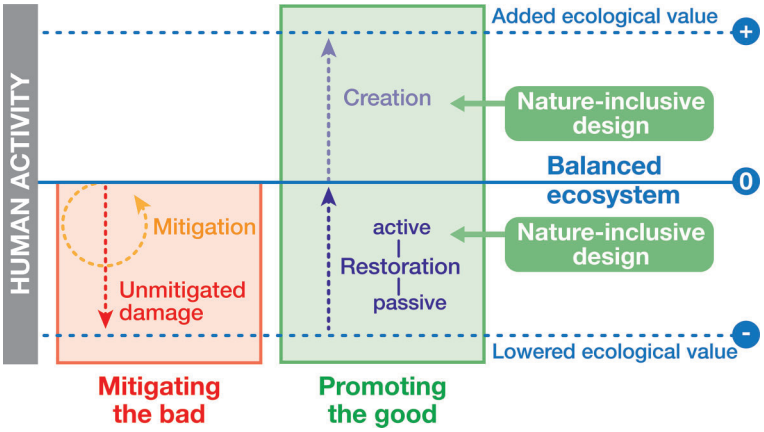

Figure 1 Conceptual scheme of mitigating the bad and promoting the good. Illustration by Hendrik Gheerardyn.

Table 3 The nature-inclusive design trichotomy.

Restorative NID	Creative NID	
	Optimizing infrastructure	Add-on structures
Measures to facilitate and speed-up nature restoration	Measures to boost biodiversity "beyond nature"	Measures to boost biodiversity "beyond nature"
Focus on naturally occurring ecosystem assets	Focus on artificially created ecosystem assets	Focus on artificially created ecosystem assets
"Eternal" effect envisaged	Temporary engagement	Temporary engagement
Gain of locally natural ecosystem assets	No gain nor loss of locally natural ecosystem assets	Loss of locally natural ecosystem assets

assets are also promoted. Nowadays, the race for alternative ways of producing electricity through offshore wind farms (Pettersen et al. 2023), combined with the wish for its co-location with other activities like aquaculture (Maar et al. 2023), is adding a new dimension to NID because marine structures are developed at an unprecedented pace, that is to be reconciled with the societal demand to do so without harm to and if possible, with positive impact on natural values (Hermans et al. 2020, Cosgrove 2024, Windt et al. 2024).

The nature-inclusive design trichotomy

Since the 1970's, when globally, the environmental legislation started becoming common practice (Lazarus 2022), people have tried minimizing and if possible, nullifying human impact on the natural environment. Mitigating negative impacts, varying from avoidance of impact at source to compensation (Niner et al. 2018), has been common practice for many decades now. More recently, potentially positive impacts of human activities at sea have gained increasing attention. For example, the risk of damage to infrastructure has led several European countries to prohibit bottom trawling within offshore wind farms (European Commission 2020). This exclusion will (albeit unintentionally) lead to a passive restoration of natural values lost due to trawling pressure (Teilmann and Carstensen 2012, Coates et al. 2016). Furthermore, offshore wind farms may equally offer options for actively restoring locally lost natural values, e.g. introducing European flat oyster *Ostrea edulis* spat to restore oyster beds where they historically prevailed in the North Sea. And finally, they can be designed in such a way that they promote selected ecological values beyond what the local ecosystem would naturally offer (Fig. 1).

It is important to reflect on what goals to strive for when considering the application of NID. We propose to make a distinction between NID that will contribute to restoring lost ecological values (i.e. restorative NID) and NID that will promote or boost ecological values beyond what the local environment may naturally offer (i.e. creative NID) (Table 3, Fig. 2). Examples of restorative NID include the relocation of boulders removed during the installation phase of Danish offshore wind farms to similar habitat inside the offshore wind farm (Dahl et al. 2016) or the introduction of oysters in infrastructural elements in Southern North Sea areas of historical oyster reefs occurrence to enhance larval supply (Ter Hofstede et al. 2023). Because this kind of NID targets regaining local natural ecosystem assets, this type of NID will likely be labelled positive. When considering creative NID, a more nuanced view and a more in-depth reflection is needed. Discriminating between two subtypes aids these considerations. The first subtype, i.e. creative NID optimizing infrastructure, aims at ecologically optimizing the design of the necessary infrastructure, such as the scour protection of an offshore wind turbine, to locally promote selected ecologi-

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

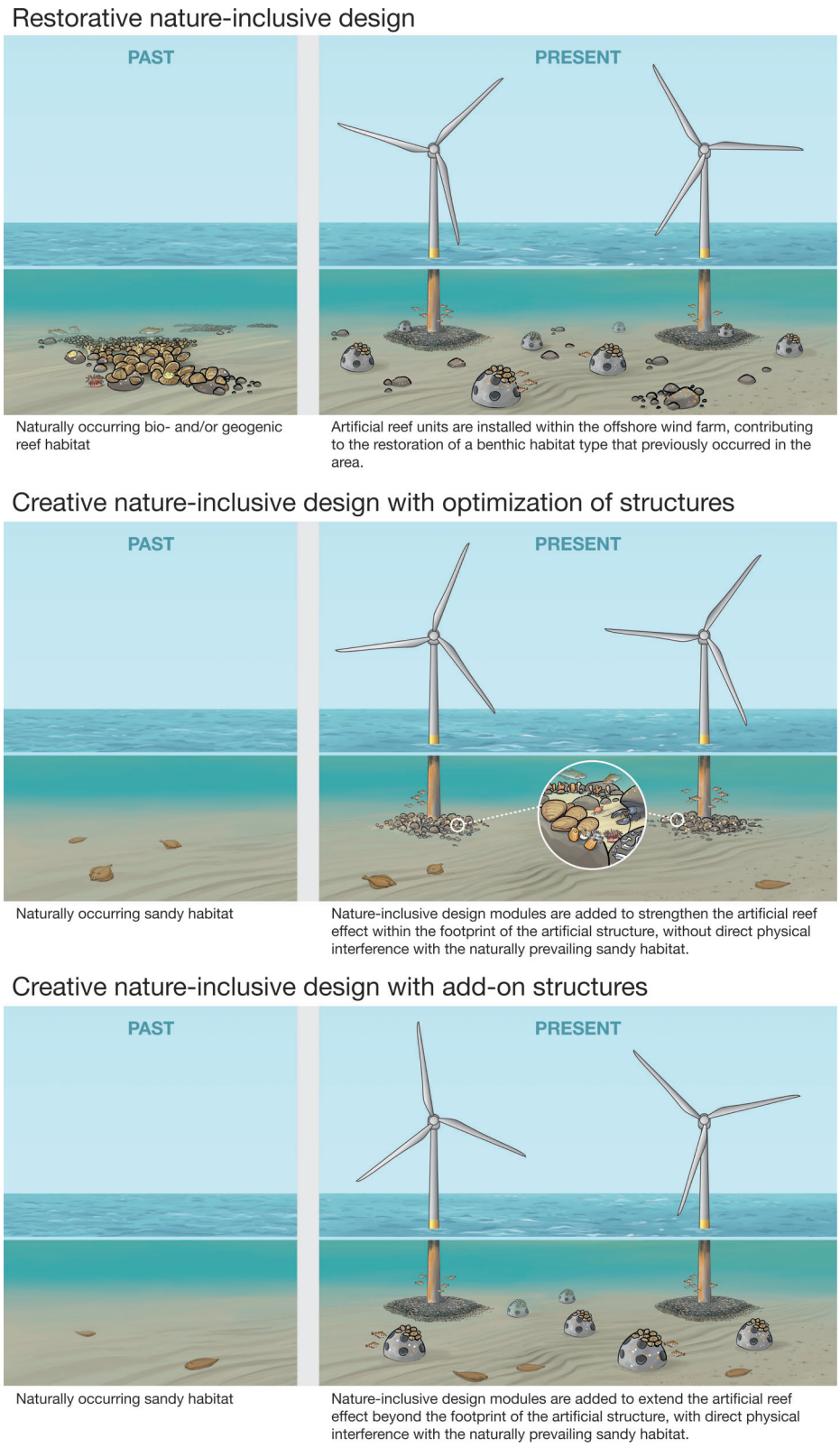

Figure 2 Illustration of the three different types of nature-inclusive design. Illustration by Hendrik Gheerardyn.

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

cal values. This NID subtype includes adding larger stones, pipes or artificial reef structures to scour protection layers to increase habitat complexity or the installation of cod hotels on offshore wind farm foundation piles (Hermans et al. 2020). While this subtype artificially boosts selected ecological values, it may be expected that it will not directly do physical harm to nearby natural values. The second subtype, i.e. creative NID as add-on structures with a footprint beyond that of the infrastructure, also seeks to enhance selected ecological values, but does so by artificializing natural habitat that would otherwise remain outside the physical footprint of the infrastructure itself. An example is the creation of artificial reef structures in between the turbines of a Dutch offshore wind farm to provide habitat for Atlantic cod (Hermans et al. 2020), where boosting selected ecological values coincided with a direct loss of natural habitat. In summary, restorative NID can be actively promoted, whereas creative NID requires more careful reflection: depending on the goals and consequences, optimization of infrastructure may be appropriate in some cases; by contrast, creative NID that substitutes natural habitat with artificial habitat (referred to here as creative NID with add-on structures) should generally be avoided. Whereas the trichotomy offers a useful framework for reflecting on NID, we acknowledge that depending on the NID option and the environmental conditions, a unequivocal allocation across the trichotomy may occasionally be challenging.

Responsibly applying nature-inclusive design in the marine environment

Think carefully about selecting nature-inclusive design goals

While biodiversity covers all aspects of life on Earth, i.e. the structures and functions of life from genes to ecosystems, communication about biodiversity is often narrowed down to structural characteristics, especially focusing on species richness, i.e. number of species. While species richness has a strong communicative value, it poorly describes biodiversity as a whole or the variety of all living things and their interactions. This descriptor, however, most likely is the easiest way to communicate about biodiversity because most layman people are aware of the importance of not losing species; this as a symbol of the biodiversity crisis (Lindemann-Matthies and Bose 2008, Appeltans et al. 2012, Luypaert et al. 2020). Species richness still is one of the frequently used arguments for opting for NID. In the marine offshore context, this most likely stems from observations of increased species richness around shipwrecks (Paxton et al. 2024), North Sea oil and gas rigs (Coolen et al. 2020) or offshore wind turbines (Degraer et al. 2020). While other structural descriptors of biodiversity, such as density or biomass, are more informative than species richness, maximizing these values is still a poor justification for applying NID. High density or biomass does not necessarily indicate a healthy habitat, as is observed in artificial hard substrates in the English Channel dominated by only a few, opportunistic species (Taormina et al. 2024) or in a species-rich habitat dominated by high densities of non-indigenous species (Klein and Verlaque 2008). Furthermore, habitats that are naturally poor in species richness, density or biomass also contribute to global biodiversity. Sandy beaches e.g. represent species-poor habitat but are critical nursery habitat for flatfish (Beyst et al. 2001). We therefore suggest that NID should not target structural aspects of biodiversity. A more ecologically meaningful target would be to support ecological functions, such as nursery, spawning and shelter functions, and processes including trophic interactions, secondary production, or nutrient and carbon cycling. Although the effect of NID may be at play only for the lifetime of its supporting structure, any contribution to ecological functions and processes will have had an impact on the marine ecosystem. Since ecological functions and processes are also more directly linked to ecosystem services, this makes them promising NID goals also from a societal perspective.

Evaluate nature-inclusive design success and failure

To allow for the evaluation of success or failure, NIDs should have SMART goals, i.e. characterized by specific, measurable, achievable, relevant and time-bound (Doran 1981) variables indicative for the success or failure of the applied NIDs. For example, the success of scour protection layers ecologically optimized to promote the nursery function by the addition or use of larger stones offering shelter for juvenile fish (Coolen et al. 2019, Glarou et al. 2020) is (i) specific (cf. to promote juvenile fish survival), (ii) measurable (e.g. juvenile fish counts), (iii) achievable (cf. realistic goal founded by ecological knowledge), (iv) relevant (cf. contributing to ecosystem functioning) and (v) time-bound (i.e. lifetime of the scour protection layer). SMART NID monitoring ensures collecting those data needed to audit the aspired outcome (Wilding et al. 2017). Next to the effectiveness of NID, monitoring should also target possible unintended effects, some of which may be negative like the colonization by non-indigenous species contributing to their further spread. Such monitoring programs are yet to be executed for many, if not most types of NID; this to be able to assess the effectiveness and efficiency of the different NID types. While a replication of monitoring and auditing is needed for every NID type, it is not required to develop monitoring programs for every single NID at every site where it is applied. Monitoring data and auditing results should be maximally publicly shared (e.g. published), to achieve a generalized view on the performance of different types of NID, in different types of environments. This knowledge will inform the selection of suitable NID for future marine infrastructures.

NIDs are not necessarily applicable in all physical environments. For example, hydraulically stable scour protection layers will benefit biodiversity, but the hydraulic stability of scour protection layers largely depends on the local hydrodynamic conditions. A panacea cannot apply to NID solutions in practice (Chambel et al. 2024). It is therefore required to share knowledge on the physical boundary conditions of NIDs as to ensure selected NIDs are fit-for-purpose at a specific location for a specific goal.

When developing monitoring programs for NID assessment, not only near-field effects are to be measured, as far-field effects can be just as relevant. For example, applying NID to promote Atlantic cod production may be measured at the local scale by surveying condition indices of Atlantic cod individuals collected close to the NID but such information will not provide insights into a potential promotion of the production at the level of the Atlantic cod population. Attraction versus production enhancement are diffi-

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

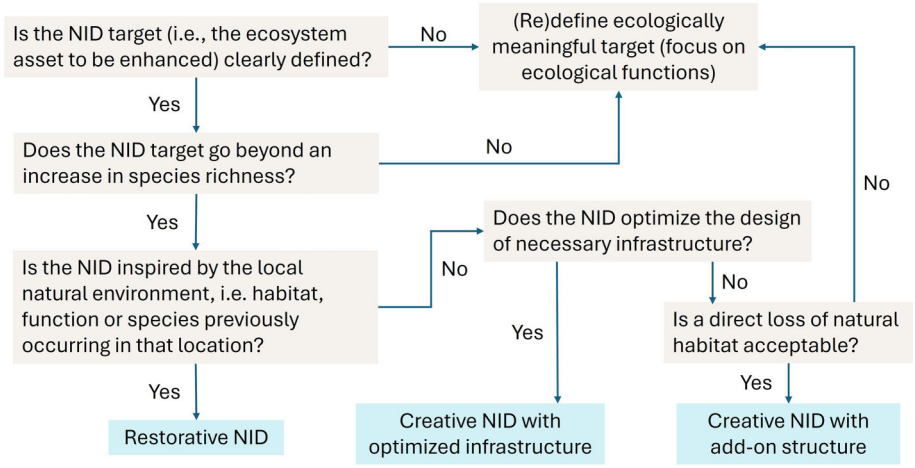

Figure 3 Nature-inclusive design decision tree, assisting an objective selection and communication about nature-inclusive design measures.

cult to tease apart (Gilby et al. 2021). While the latter is ecologically more relevant than the former, it will be challenging to collect sufficient data to demonstrate a potential effect at the population level which is likely to be small. It may be even more difficult to separate the additional effect of NIDs from the potentially larger effect of the infrastructure, e.g. the impact of the presence of the offshore wind farm (Degraer et al. 2020, Christiansen et al. 2022). Not only does an offshore wind farm provide additional habitat and shelter, most current wind farms also cannot be fished with bottom trawling gear. Hence, there are not only impacts from additional, artificial substrate, but also the exclusion effect of bottom trawling will have an impact on the local benthic and pelagic community (Buyse et al. 2022). The additional far-field effects of NIDs may be very difficult to quantify. Sharing data, as to increase the power of the analysis, will help and is key in understanding the role of NID in the larger ecosystem dynamics at play.

Acknowledge the reality of climate change when opting for nature-inclusive design

NID can provide long-term ecological benefits, with deployment periods of 25–30 years (for instance, NID scour protection layers in offshore wind farms). However, the marine environment is undergoing rapid changes due to climate change, resulting in e.g. increased average sea water temperatures, ocean acidification. For instance, there is increased awareness of the occurrence of more frequent and intense marine heatwaves (Masson-Delmotte et al. 2021). Climate-driven redistribution of benthos (Weinert et al. 2021), plankton and fish is anticipated, with key species such as *Calanus finmarchicus* and Atlantic cod in the North Sea facing declines (Sandø et al. 2024). Additionally, marine heatwaves can drive temperatures beyond species' thermal thresholds, disrupting physiology and thermoregulation at the individual level and ultimately impacting populations of benthic invertebrates, fish and marine megafauna (Smith et al. 2023). As such, NID targeting specific species (e.g. cod hotels) that are present at the time of deployment can become irrelevant as the area occupied by the species of interest can change due to climate change. NID should therefore be rooted in universal ecological principles, linking habitat design and complexity to relevant ecological functions (e.g. provisioning of habitat and shelter for prey and predators, spawning and nursery habitat) independent of the currently prevailing communities. Design of NID should follow climate-smart marine spatial planning principles (Frazao-Santos et al. 2023) that allow for harnessing what is known about species distribution shifts, functional changes, and other climate change-related effects to develop scenarios and plan with the future in mind.

Conclusions

NID is increasingly utilized to boost biodiversity in human-altered environments, made possible by incorporating ecological principles into infrastructure development. Such design is important also in marine settings, where the need for marine infrastructure like offshore wind farms and coastal defence is rapidly increasing. By designing this infrastructure to also support ecological functions, NID may help restoring and enhancing marine ecosystems.

To underpin the choice whether or not to implement NID and if the decision is made to implement it, to support the selection of targets, we developed an NID trichotomy: NID that will contribute to restoring lost ecological values (i.e. restorative NID) (type 1), and NID that will boost natural values beyond what the local environment may naturally offer (i.e. creative NID), either through ecologically optimized infrastructure (type 2a) or add-on structures (type 2b). Therefore, when opting for NID, it is essential to make informed choices that either take inspiration from the natural local environment, or go beyond what the local environment has to offer. These choices must be well-considered and with explicit goals, as illustrated in Fig. 3. First, we need to define ecologically meaningful targets that focus on ecosystem functions, acknowledging that biodiversity goes well beyond species richness. Second, when considering opting for type 2a or type 2b NID, there should be careful consideration of potential negative impacts as well as the ecological benefits. This includes factors such as (i) whether the NID incurs a direct loss of natural habitat (on top of any habitat loss due to the presence of infrastructure), (ii) whether the NID is a likely stepping stone for non-indigenous species, (iii) whether there are substantial additional costs in terms of carbon footprint and (iv) whether the NID can incur shifts in the food web with potential negative impacts on other ecosystem components.

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

The latter issue will be strongly scale-dependent. These risks need to be weighed against the potential benefits.

In summary, NID is not a one-size-fits-all solution but a flexible method that requires clear goals, careful planning and regular evaluation. The use of NID should be predicated on a transparent and clear statement of the purpose for using NID, and what are reasonable expectations about outcomes of their deployment. By deepening our understanding of marine ecosystems and applying this knowledge to infrastructure design, NID can help us live more harmoniously with nature, benefiting both biodiversity and human needs. We therefore recommend adopting the trichotomy to resolve conceptual ambiguity around NID. Clear and shared definitions enable both marine managers and offshore industries to objectively select and clearly communicate NID measures, thereby supporting the adoption of a green consumerism, i.e. the practice of choosing products and services that minimize environmental harm and support sustainable production, attitude towards NID while avoiding greenwashing, i.e. the practice of giving a false impression of the environmental impact or benefits of a product, which can mislead consumers.

Acknowledgements

This work was developed under the ULTFARMS project, financed by the European Union's Horizon Europe Research and Innovation Program under Grant Agreement no. 101093888, and the Blue4all project, financed by the European Union's Mission "Restore our Ocean and Waters" under Grant Agreement no. 101094014. The authors would like to thank all members of the ULTFARMS Nature-inclusive Design working group for their contributions to the discussion that informed the development of this work. This article benefited from the meaningful comments made by the ICES Journal of Marine Science reviewers.

Author contributions

Steven Degraer (Conceptualization [lead], Data curation [equal], Investigation [equal], Visualization [equal], Writing – original draft [lead], Writing – review & editing [equal]), Loreta Cornacchia (Conceptualization [equal], Data curation [equal], Investigation [equal], Writing – original draft [equal], Writing – review & editing [equal]), Alex Ziemba (Conceptualization [equal], Writing – review & editing [equal]), Tundi Agardy (Conceptualization [equal], Writing – review & editing [equal]), Sander van den Burg (Conceptualization [equal], Writing – review & editing [equal]), Karin van de Braak (Conceptualization [equal], Writing – review & editing [equal]), LUCA Ancel VAN DUREN (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Annelies Declercq (Conceptualization [equal], Writing – review & editing [equal]), Mieke Eggermont (Conceptualization [equal], Writing – review & editing [equal]), Annaïk Van Gerven (Conceptualization [equal], Visualization [equal], Writing – review & editing [equal]), Thomas R.H. Kerkhove (Conceptualization [equal], Writing – review & editing [equal]), Ine Moulaert (Conceptualization [equal], Writing – review & editing [equal]), Tasnim Patel (Conceptualization [equal], Writing – review & editing [equal]), Jens Kjerulf Petersen (Conceptualization [equal], Writing – review & editing [equal]), Marnix Poelman (Conceptualization [equal], Writing – review & editing [equal]), Eva Strothotte (Conceptualization [equal], Writing – review & editing [equal]), Jan Vanaverbeke (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Ghada El Serafy (Conceptualization [equal], Writing – review & editing [equal]).

Conflicts of interest

None declared.

Funding

This research has received funding from the European Union's Horizon Europe Research and Innovation Program under Grant Agreement no. 101093888 and the European Union's Mission "Restore our Ocean and Waters" under Grant Agreement no. 101094014. Views and opinions are those of authors only and do not necessarily reflect those of the European Union. Neither the European Union nor the Granting Authority can be held responsible for them.

Data availability

No data were generated or analysed in support of this research.

References

Altwegg R, Jenkins A, Abadi F. Nestboxes and immigration drive the growth of an urban Peregrine Falcon *Falco peregrinus* population. *IBIS* 2013;**156**:107–15. https://doi.org/10.1111/ibi.12125 (7 March 2026, datelast accessed).

Appeltans W, Ahyong ST, Anderson G *et al.* The magnitude of global marine species diversity. *Curr Biol* 2012;**22**:2189–202. https://doi.org/10.1016/j.cub.2012.09.036

Beyst B, Hostens K, Mees J. Factors influencing fish and macrocrustacean communities in the surf zone of sandy beaches in Belgium: temporal variation. *J Sea Res* 2001;**46**:281–94. https://doi.org/10.1016/S1385-1101(01)00087-9

Buyse J, Hostens K, Degraer S *et al.* Offshore wind farms affect the spatial distribution pattern of plaice *Pleuronectes platessa* at both the turbine and wind farm scale. *ICES J Mar Sci* 2022;**79**:1777–86. https://doi.org/10.1093/icesjms/fsac107

Chambel J, Fazeres-Ferradosa T, Miranda F *et al.* A comprehensive review on scour and scour protections for complex bottom-fixed offshore and marine renewable energy foundations. *Ocean Eng* 2024;**304**:117829. https://doi.org/10.1016/j.oceaneng.2024.117829

Christensen-Dalsgaard S, Langset M, Anker-Nilssen T. Offshore oil rigs—a breeding refuge for Norwegian Black-legged Kittiwakes *Rissa tridactyla*? *Seabird J* 2020;**32**:20–32. https://doi.org/10.61350/sbj.32.20

Christiansen N, Daewel U, Djath B *et al.* Emergence of large-scale hydrodynamic structures due to atmospheric offshore wind farm wakes. *Front Mar Sci* 2022;**9:** 818501. https://doi.org/10.3389/fmars.2022.818501

Coates DA, Kapasakali DA, Vincx M *et al.* Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. *Fish Res* 2016;**179**:131–8. https://doi.org/10.1016/j.fishres.2016.02.019

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

Coolen JWP, Lengkeek W, Have T *et al.* Upscaling Positive Effects of Scour Protection in Offshore Wind Farms: Quick Scan of the Potential to Upscale Positive Effects of Scour Protection on Benthic Macrofauna and Associated Fish Species. (Wageningen Marine Research report; No. C008/19). Wageningen Marine Research. 2019https://doi.org/10.18174/475354

Coolen JWP, Weide B, Cuperus J *et al.* Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES J Mar Sci* 2020;**77**:1250–65. https://doi.org/10.1093/icesjms/fsy092

Cornacchia L, Degraer S, van Duren L *et al.* ULTFARMS NID Glossary—Glossary of terms and common definitions related to nature-inclusive design. 2025, Zenodo.https://doi.org/10.5281/zenodo.15149198

Cosgrove S. Data-driven planning for the co-existence of offshore wind and nature-inclusive designs. 277–81in *OCEANS 2024-Halifax*. IEEE, Halifax 2024. https://doi.org/10.1109/OCEANS55160.2024.10754210

Dahl K, Støttrup JG, Stenberg C *et al. Best Practice for Restoration of Stone Reefs in Denmark (Codes of Conduct)*. Aarhus University, Department of Bioscience, Aarhus 2016

Degraer S, Carey DA, Coolen JWP *et al.* Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. *Oceanography* 2020;**33**:48–57. https://doi.org/10.5670/oceanog.2020.405

Doran GT, There's a SMART. Way to Write Managements's Goals and Objectives. *J Manag Rev* 1981;**70**:35–6.

Duarte CM, Pitt KA, Lucas CH *et al.* Is global ocean sprawl a cause of jellyfish blooms? *Front Ecol Environ* 2013;**11**:91–7. https://doi.org/10.1890/110246

European Commission. *Recommendations for Positive Interactions between Offshore Wind Farms and Fisheries*. European Commission, Directorate-General for Maritime Affairs and Fisheries (DG MARE), Brussels 2020:26.

European Research Executive Agency (European Commission). *Nature-based Solutions: EU-funded NbS research projects tackle the climate and biodiversity crisis*. 2023, https://op.europa.eu/en/publication-detail/-/publication/eda b5ab8-94b7-11ee-b164-01aa75ed71a1 (7 March 2025, date last accessed).

Frazão Santos C, Agardy T, Aheto D *et al.* Advancing interdisciplinary knowledge for ocean sustainability. *npj Ocean Sustain* 2023;**2**:18. https://doi.org/10.1038/s44183-023-00026-6

Gazzard A, Baker PJ. What makes a house a home? Nest box use by West European hedgehogs (*Erinaceus europaeus*) is influenced by nest box placement, resource provisioning and site-based factors. *PeerJ*. 2022;**10**:e13662. https://doi.org/10.7717/peerj.13662

Gazzard A, Boushall A, Brand E *et al.* An assessment of a conservation strategy to increase garden connectivity for hedgehogs that requires cooperation between immediate neighbours: a barrier too far? *PLoS One* 2021;**16**:e0259537. https://doi.org/10.1371/journal.pone.0259537

Gilby BL, Olds AD, Chapman S *et al.* Attraction versus production in restoration: spatial and habitat effects of shellfish reefs for fish in coastal seascapes. *Restor Ecol* 2021;**29**:e13413. https://doi.org/10.1111/rec.13413

Glarou M, Zrust M, Svendsen JC. Using artificial-reef knowledge to enhance the ecological function of offshore wind turbine foundations: implications for fish abundance and diversity. *J Mar Sci Eng* 2020 332, **8**. https://doi.org/10.3390/jmse8050332

Gutiérrez J, Bezner M, Molenkamp A *et al.* Physical evaluation of the hydrodynamic stability of an eco-engineered armouring unit. *Coast Engin Proc*. 2023;**37**:, 35.

Hermans A, Bos OG, Prusina I. Nature-inclusive design: a catalogue for offshore wind infrastructure (technical report No. 114266/20–004.274). Witteveen+Bos, 2020.https://edepot.wur.nl/518699

Hernandez-Santin C, Amati M, Bekessy S *et al.* A review of existing ecological design frameworks enabling biodiversity inclusive design. *Urban Sci* 2022;**6**:95. https://doi.org/10.3390/urbansci6040095

ITRC (Interstate Technology & Regulatory Council). Making the case for ecological enhancements: Planning and promoting ecological land reuse of remediated sites (ECO-1 White Paper). Interstate Technology & Regulatory Council. 2006. Retrieved fromhttps://itrcweb.org/wp-content/uploads/2024/09/ECO-2.pdf

IUCN. Ensuring effective nature-based solutions. 2022. Retrieved from IUCN website:https://iucn.org/resources/issues-brief/ensuring-effective-nature-based-solutions (7 March 2025, date last accessed).

IUCN. Nature positive for business: Developing a common approach (IUCN Commission on Ecosystem Management Technical Paper No. 2023-023). 2023. Retrieved fromhttps://portals.iucn.org/library/sites/library/files/documents/2023-023-En.pdf (7 March 2025, date last accessed).

Jansen HM, van der Burg SWK, van Duren LA *et al.* Food for thought: a realistic perspective on the potential for offshore aquaculture in the Dutch North Sea. *J Sea Res* 2023;**191**:102323. https://doi.org/10.1016/j.seares.2022.102323

Johnson CN, Balmford A, Brook BW *et al.* Biodiversity losses and conservation responses in the Anthropocene. *Science* 2017;**356**:270–5. https://doi.org/10.1126/science.aam9317

Jordan P, Fröhle P. Bridging the gap between coastal engineering and nature conservation? *J Coast Conserv* 2022;**26**:4. https://doi.org/10.1007/s11852-021-00848-x

Jørgensen SE, Mitsch WJeds. *Ecological Engineering: An Introduction to Ecotechnology*. New York: Wiley, 1989

Kingma EM, ter Hofstede R, Kardinaal E *et al.* Guardians of the seabed: nature-inclusive design of scour protection in offshore wind farms enhances benthic diversity. *J Sea Res* 2024 102502, **199**, https://doi.org/10.1016/j.seares.2024.102502

Klein J, Verlaque M. The Caulerpa racemosa invasion: a critical review. *Mar Pollut Bull* 2008;**56**:205–25. https://doi.org/10.1016/j.marpolbul.2007.09.043

Law Insider Dictionary. 2025 Nature inclusive design definition. https://www.lawinsider.com/dictionary/nature-inclusive-design (7 March 2025, date last accessed).

Lazarus RJ. *The Making of Environmental Law*. University of Chicago Press, Chicago, IL, USA 2022https://doi.org/10.7208/chicago/9780226695594.001.0001.

Lindemann-Matthies P, Bose E. How many species are there? Public understanding and awareness of biodiversity in Switzerland. *Hum Ecol* 2008;**36**:731–42. https://doi.org/10.1007/s10745-008-9194-1

Luypaert T, Hagan JG, McCarthy ML *et al.* Status of marine biodiversity in the Anthropocene. In: Jungblut S., Liebich V., Bode-Dalby M. (eds) *YOUMARES 9–The Oceans: Our Research, Our Fu-*

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026

ture. Springer, Cham. https://doi.org/10.1007/978-3-030-20389-4_4 2020

Maar M, Holbach A, Boderskov T *et al.* Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. *Commun Earth Environ* 2023;**4**:447. https://doi.org/10.1038/s43247-023-01116-6

Masson-Delmotte V, Zhai P, Pirani A *et al. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. 2021; Intergovernmental Panel on Climate Change. 2391.

Morris R.L., Konlechner T.M., Ghisalberti M., Swearer S.E.. From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence Glob. *Chang. Biol.* 2018;**24**:1827–1842.

Naylor L, Venn O, Coombes M *et al. Including ecological enhancements in the planning, design and construction of hard coastal structures: A process guide. Report to the UK Environment Agency*. University of Exeter 2011:66 pp.

Niner HJ, Ardron JA, Escobar EG *et al.* Deep-Sea mining with no net loss of biodiversity—an impossible aim. *Front Mar Sci* 2018;**5**:53. https://doi.org/10.3389/fmars.2018.00053

Pardo JCF, Aune M, Harman C *et al.* A synthesis review of nature positive approaches and coexistence in the offshore wind industry. *ICES J Mar Sci* 2023:fsad191.

Paxton AB, McGonigle C, Damour M *et al.* Shipwreck ecology: understanding the function and processes from microbes to megafauna. *Bioscience* 2024;**74**:12–24. https://doi.org/10.1093/biosci/biad084

Paxton AB, Runde BJ, Smith CS *et al.* Leveraging built marine structures to benefit and minimize impacts on natural habitats. *Bioscience* 2025;**75**:172–83. https://doi.org/10.1093/biosci/biae135

Pettersen SS, Aarnes Ø, Arnesen B *et al.* Offshore wind in the race for ocean space: a forecast to 2050. *J Phys Conf Ser* 2023;**2507**:012005.

Peuling S, Boon AR, Rovers I. Nature-inclusive biobased facades—a comprehensive guide to design, evaluate and redesign. 2024https://doi.org/10.13140/RG.2.2.10354.31685

Portela de Carvalho T. Incorporating Qualitative Criteria in Offshore Wind Tenders: experiences in Denmark, Finland, Germany, and the Netherlands. *Ocean Dev Int Law* 2025;**56**:616–44. https://doi.org/10.1080/00908320.2025.2587356

Sandø AB, Hjøllo SS, Hansen C *et al.* A multi-scenario analysis of climate impacts on plankton and fish stocks in northern seas. *Fish Fish*. 2024;**25**:711–32.

Schickhoff U, Bobrowski M, Offen IA *et al. The Biodiversity Crisis in the Anthropocene*. Istanbul University Press Istanbul, Turkey 2024https://doi.org/10.26650/B/SS19.2024.001.05

Sia A, Tan PY, Er KBH. The contributions of urban horticulture to cities' liveability and resilience: insights from Singapore. *Plants, People*. *Planet* 2023;**5**:828–41.

Smith KE, Burrows MT, Hobday AJ *et al.* Biological Impacts of Marine Heatwaves. *Ann Rev Mar Sci* 2023;**15**:119–45. https://doi.org/10.1146/annurev-marine-032122-121437

Taormina B, Leclerc J-C, Rusig A-M *et al.* Diversity and structure of epibenthic communities across subtidal artificial hard habitats in the Bay of Cherbourg (English Channel). *Biofouling* 2024;**40**:847–61. https://doi.org/10.1080/08927014.2024.2419572

Teilmann J, Carstensen J. Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—Evidence of slow recovery. *Environ Res Lett* 2012;**7**:045101. https://doi.org/10.1088/1748-9326/7/4/045101

Ter Hofstede R, Williams G, Koningsveld Mv. The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster (*Ostrea edulis*) reef development in the southern North Sea. *Aquatic Living Resources* 2023;**36**:4. https://doi.org/10.1051/alr/2023001

UK Green Building Council. *Definitions for biodiversity and environmental net gain*. UKGBC. 2026https://ukgbc.org/our-work/topics/biodiversity-environmental-net-gain/definitions-for-biodiversity-and-environmental-net-gain/ (7 March 2025, date last accessed).

United Nations Environment Programme. 2022. *Annual Report 2022 | UNEP—UN Environment Programme*. https://www.unep.org/resources/annual-report-2022 (7 March 2025, date last accessed).

Van Ommeren Associates. 2025 *Nature-inclusive design for the built environment*. https://www.vo-a.com/en/tools-and-knowledge/natuurinclusief-ontwerp-voor-de-gebouwde-omgeving (7 March 2025, date last accessed).

van Sluis CJ, van Onselen E, Airoldi L *et al.* Financing marine restoration through offshore wind investments. *Bioscience* 2025;**75**:856–64. https://doi.org/10.1093/biosci/biaf092

Weinert M, Mathis M, Kröncke I *et al.* Climate change effects on marine protected areas: projected decline of benthic species in the North Sea. *Mar Environ Res* 2021;**163**:105230. https://doi.org/10.1016/j.marenvres.2020.105230

Wilding TA, Gill AB, Boon A *et al.* Turning off the DRIP ('Data-rich, information-poor')—rationalising monitoring with a focus on marine renewable energy developments and the benthos. *Renew Sustain Energy Rev* 2017;**74**:848–59. https://doi.org/10.1016/j.rser.2017.03.013

Windt C, Goseberg N, Schimmels S *et al. Integrated designs for future floating offshore wind farm technology–towards nature inclusive innovations*. *Innovations in Renewable Energies Offshore*. Edited by Carlos Guedes Soares, Shan Wang CRC Press, London 2024,775–83

Handling editor: Henn Ojaveer

Received: 8 September 2025. **Revised:** 24 March 2026. **Accepted:** 25 March 2026

© The Author(s) 2026. Published by Oxford University Press on behalf of International Council for the Exploration of the Sea. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

Downloaded from https://academic.oup.com/icesjms/article/83/4/fsag050/8664664 by DIFRES user on 21 May 2026