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Quo Vadimus

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

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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

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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

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'. '…implies that social, economic and nature conservation objectives are integrated in one project'.	Law Insider Dictionary (2025)
'…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

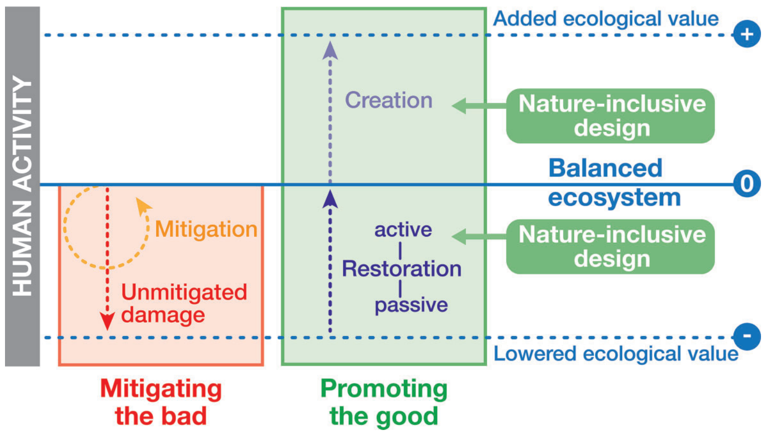

Figure 1 Conceptual scheme of mitigating the bad and promoting the good. Illustration by Hendrik Gheerardyn.

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-

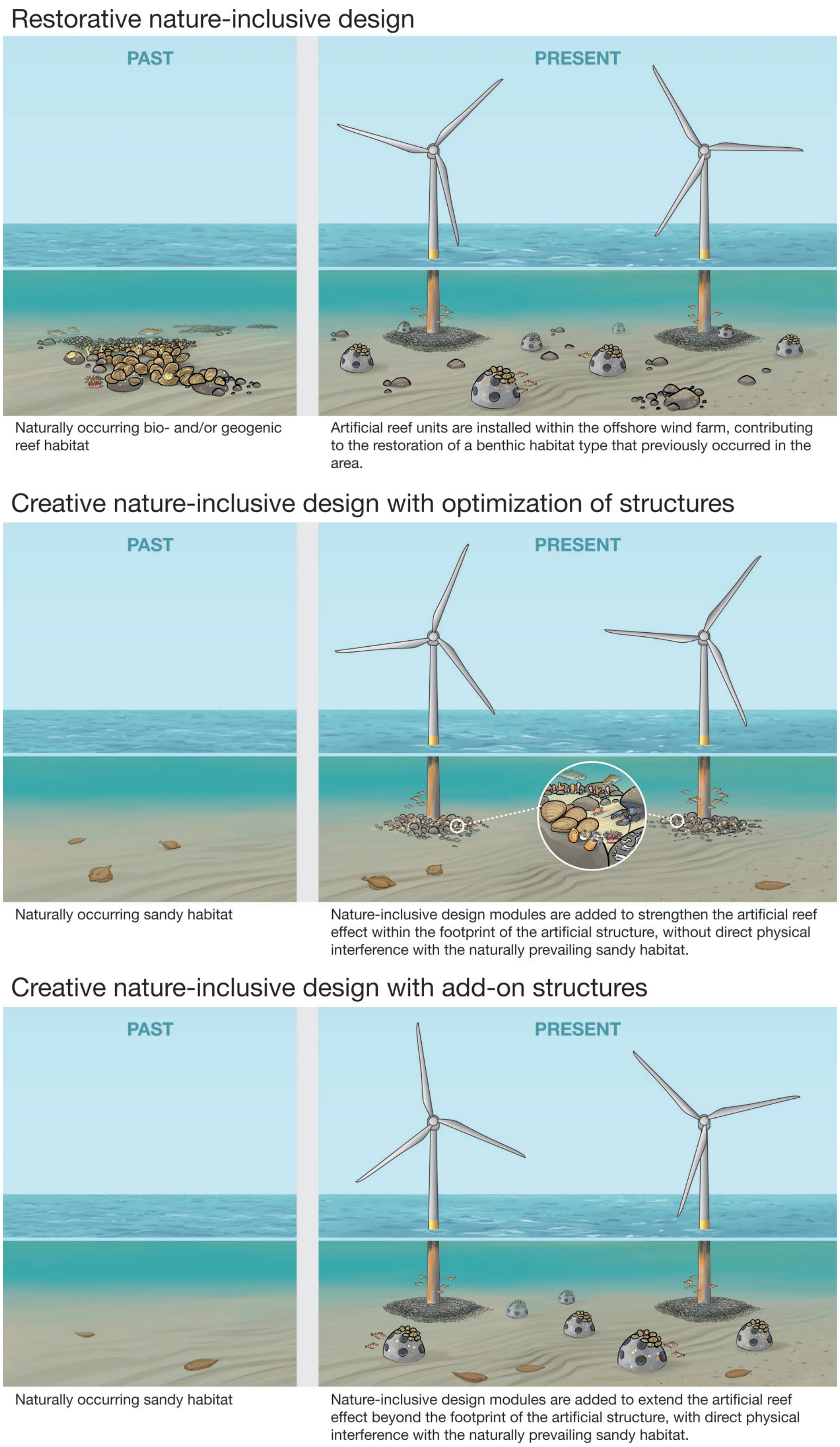

Figure 2 Illustration of the three different types of nature-inclusive design. Illustration by Hendrik Gheerardyn.

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-

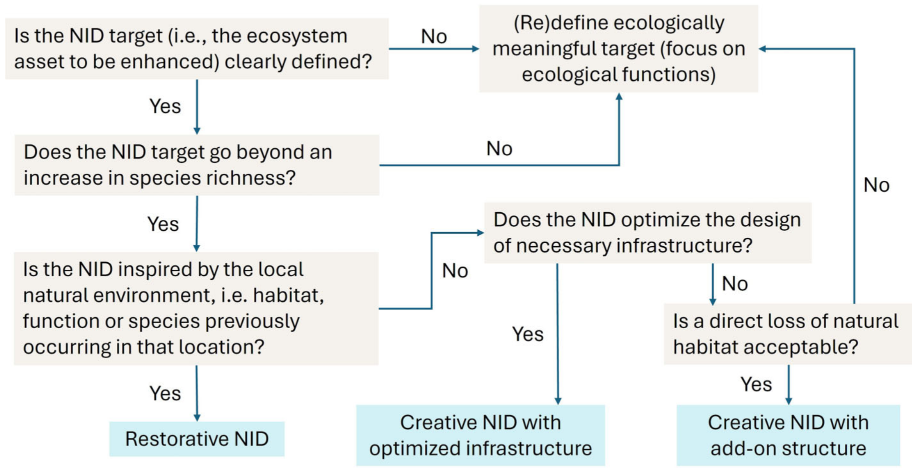

Figure 3 Nature-inclusive design decision tree, assisting an objective selection and communication about nature-inclusive design measures.

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.

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.

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Conflicts of interest

None declared.

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Data availability

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

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