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Governing through inscription: eDNA biodiversity monitoring in North Sea offshore wind energy parks

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A B S T R A C T

The planned expansion of wind energy in the North Sea holds significant implications for marine biodiversity. Wind energy infrastructure can enhance biodiversity by providing hard substrates and reef-like habitats or degrade it by disturbing existing benthic habitat. However, it remains unclear what kinds of biodiversity will in practice be enhanced, in whose interest and for what purpose. To assess the effects of offshore wind energy parks on biodiversity, a range of new monitoring technologies are being developed, including monitoring technologies that incorporate environmental DNA (eDNA). However, which biodiversities eDNA sampling strategies can observe starts with their design; with different assumptions, priorities, material affordances, and ways of knowing biodiversity inscribed into material sampling technologies and their deployment. Using a framework to examine processes of inscription, this paper explores how assumptions and priorities, conditioned by the material affordances of eDNA, affect the design of a monitoring strategy assessing biodiversity enhancement. We show that the process of inscription constitutes a form of de facto governance, whereby the design of an eDNA monitoring strategy in the present shapes how biodiversity is governed in the future. We conclude that inscription is an open-ended process that allows for reflexivity on the socio-material dimensions of monitoring technologies such as eDNA, providing an opportunity to (re) imagine ways that biodiversity can be inscribed, opening up how it is conceptualised, measured and enhanced.

1. Introduction

The Dutch North Sea is undergoing a mass transition towards large scale deployment of offshore wind energy parks while simultaneously experiencing a biodiversity crisis (GoN, 2022). The Netherlands has ambitions to quadruple its current offshore wind production by 2030/2031, supporting its green energy mission (European Commission, 2020; van Nieuwpoort et al., 2023). However, there is uncertainty around the impacts that upscaling offshore wind energy may have on marine biodiversity. To address this uncertainty, the Dutch government has mandated marine biodiversity enhancement as a mitigation measure within offshore wind energy deployment (Altaghlibi, 2024; GoN, 2022). The overriding assumption behind biodiversity enhancement is that offshore wind energy, combined with restoration measures, may even provide opportunities for so-called ‘nature-positive impact’ surrounding offshore infrastructures in the North Sea.

Biodiversity is usually taken as a neutral and widely accepted concept, yet it is underpinned by a range of assumptions that shape how it is known and governed (Cochrane et al., 2016). The term broadly refers to the variety of lifeforms and their interactions, either at the level of ecosystems, within different species, or in terms of genetic diversity (Boero and Bonsdorff, 2007). Biodiversity is thus - depending on the context, objectives and goals - open to different interpretations that subsequently inform what kind of biodiversity is being ‘enhanced’ (Pauwelussen and Vandenberg, 2024). For example, enhancement may imply increasing the abundance of a species in a given area, increasing its (genetic) variety (Martins et al., 2016; Russ and Alcala, 2011) or prioritising charismatic, native or economically valued species (Boero and Bonsdorff, 2007). In the offshore wind context, enhancement could occur through passive interventions, such as natural recruitment on and around offshore infrastructure (Langhamer, 2012) or through nature-inclusive redesign of existing infrastructure, such as the use of Reef Cubes® for scour protection at the base of wind turbine monopiles (Kingma et al., 2024), to attract targeted species (Hickling et al., 2023).

A pivotal way in which biodiversity enhancement is governed is through the process of monitoring – that is, knowing, measuring,

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quantifying and qualifying changes in biodiversity over time (Solman et al., 2022). The design of biodiversity monitoring programmes is shaped by both implicit and explicit assumptions and priorities, or "taken-for-granted beliefs about the world and our place within it that guide our actions" (Brookfield, 2017, p. 5), shaping what matters most (Henle et al., 2013). These assumptions and priorities are 'inscribed' into *what* (taxonomy), *when* (temporal) and *where* (spatial) biodiversity is surveyed and monitored, influencing which biodiversities count and what realities may exist (Boucquey et al., 2019; Roturier and Beau, 2022; Scott, 2020; Weber et al., 2004). At the same time, monitoring is shaped by the material affordances of monitoring technologies, which condition what data is collected and used to decide which biodiversity counts and is ultimately enhanced. Inscription, as such, emphasises that epistemic communities of scientists, policymakers, and engineers are more than mere technical 'designers' of monitoring surveys and technologies (Beck and Forsyth, 2020). They play a key de facto governing role by inscribing assumptions and priorities over biodiversity and biodiversity enhancement through - and in response to - the material affordances of monitoring technologies (Faraj and Azad, 2012; Fayard and Weeks, 2014; Orlikowski and Scott, 2008). Building on Braverman (2020) and Schadeberg et al. (2023), the process of designing monitoring technologies therefore plays a key role in shaping how certain kinds of species and habitats are made visible, accounted for and enhanced, enacting future (yet unknown) biodiversities.

In this paper, we identify how assumptions and priorities on marine biodiversity are inscribed in, and shape, the design and material affordances of an environmental DNA (eDNA) monitoring technology – a sampling technology developed to monitor and shape decisions around enhancement in offshore wind parks. eDNA refers to genetic material shed by organisms and found in "any type of environmental sample (such as soil, water or air)" (Taberlet et al., 2012, p. 1789). It offers the potential for a holistic approach to biodiversity monitoring by capturing a wide spectrum of organisms in often inaccessible ecosystems, such as oceans, in a cost-effective and timely manner (Capurso et al., 2023; Lodge et al., 2012; Seymour, 2019; Yang et al., 2024). At the same time, eDNA is not a single thing; it is mutually constituted by both 'social' (i.e. meaning, activities, contexts, outcomes) and 'material' (i.e. artifacts, techniques, systems) elements (Hutchby, 2001; Introna, 2013; Latour, 2005). We explore how the socio-materialities of eDNA – negotiated through its design – shape how biodiversity is monitored and, in turn, how future biodiversities are known and governed through inscription in the present (Faraj and Azad, 2012). Furthermore, by examining how assumptions, priorities and affordances change over the course of the design process, we identify moments of governance through inscription and discuss their implications for alternative, and potentially more inclusive, applications of biodiversity monitoring.

The following elaborates a framework for understanding processes of inscribing biodiversity in novel technologies like eDNA. We then present our results on the design of an eDNA-based strategy for monitoring marine biodiversity enhancement in offshore wind parks in the Dutch North Sea by a transdisciplinary consortium of marine ecologists, social scientists and engineers. In doing so we illustrate how assumptions, priorities, material affordances and ways of knowing biodiversity enhancement both enable and shape the inclusion and exclusion of species (taxonomy), as well as the temporal and spatial dimensions of monitoring North Sea biodiversity. Finally, we discuss the implications of governing biodiversity through inscription in shaping, enacting and adapting expectations for future biodiversities surrounding offshore wind energy in the marine environment.

2. Inscribing biodiversity

The design and application of environmental monitoring technologies, including those used for biodiversity, directly reflect both the materialities of the technologies as well as the values and knowledge of designers, and the political and institutional contexts in which they are embedded (Hutchby, 2001; Introna, 2019; Latour, 2005; Lehman and Johnson, 2022; Roturier and Beau, 2022). The networked agency of these social and material elements that constitute technologies (Latour, 2005) in turn exert agency by prescribing roles and competences through 'scripts' (Akrich, 1992) and 'affordances'; the properties of an object (eDNA technology) that reflect and condition how it can be used (Hutchby, 2001). These affordances are, as such, embedded in the capability of the technology (i.e. what can the technology do?; see Markus and Silver, 2008), which are both shaping and shaped by the practices of epistemic communities designing them. From this perspective, assumptions and priorities related to biodiversity are relational constructs that link the affordances of eDNA technologies to the needs of designers over time (Faraj and Azad, 2012; Orlikowski, 2007).

The way in which assumptions, priorities and material affordances interact to shape the design of monitoring technologies, and subsequently include or exclude ways of knowing and enacting future biodiversity, can be understood as a process of inscription (Latour, 1992). Inscription, introduced by Latour and Woolgar (1986), involves the configuration of scientific instruments and other 'mediating' technologies (see de Boer, 2021) to "transform a material substance into a figure or diagram which is directly usable" by other social actors (p. 51). In doing so, outputs created by these instruments become immutable epistemic mobiles – knowledge perceived as fact that can move or be translated without being changed or 'corrupted' (Latour, 1986).

Inscription extends to the design of technologies such as eDNA and the development of strategies for their application. Through iterative rounds of design, assumptions, priorities and material affordances – underpinned by physical properties of eDNA as well as the knowledge and values of designers and prevailing policy and regulation – shape the design, development and use of monitoring technologies (Akrich, 1992). The immutable epistemic objects created through this design process, such as lists, databases and sampling protocols, then anticipate and/or enact certain outcomes and constrain others (Akrich, 1992; Latour, 1987; Leonardi and Barley, 2010; Orlikowski, 2000). In parallel, the material affordances of monitoring technologies also (re)shape the assumptions, priorities and knowledge of designers (Hutchby, 2001; Orlikowski, 2007). Seen as such, the process of inscription relationally constructs – knowingly or not – how assumptions, priorities and knowledge are afforded by mediating technologies such as eDNA. Also, the inscription process conditions the ways eDNA transforms material substance, such as biodiversity, into an object of concern and governance.

To analyse the process of transforming assumptions, priorities and material affordances into the design of mediating technologies used to monitor biodiversity we delimit three stages of inscribing biodiversity (Fig. 1). We argue that the inscription process is a socio-material process, highlighting that pre-existing assumptions, priorities and affordances can come from both the social and material. We developed three stages of inscribing biodiversity iteratively over the course of the research to better understand how (1) interactions between assumptions, priorities and material affordances shape (2) different ways of knowing and understanding biodiversity that is made available to decision makers which in turn (3) anticipates and enacts specific kinds of future biodiversity. We explore the relative role of 'social' assumptions and priorities and the 'material' affordances of eDNA over the course of the design process, thereby assuming an iterative and cyclical nature of inscription.

First, inscription involves transforming assumptions, priorities and affordances related to biodiversity into the design and application of monitoring technologies. The inherent complexity of biodiversity means that it is commonly reduced to orderly, legible assumptions that are held by and shape the actions of various societal groups (Doebeli et al., 2021; Mol et al., 2020; Scott, 2020; Turnhout, 2018; Turnhout et al., 2013). Such assumptions, underpinned by the values and worldviews of epistemic communities, and conditioned by the affordances of technologies (including epistemic objects such as species lists, databases and

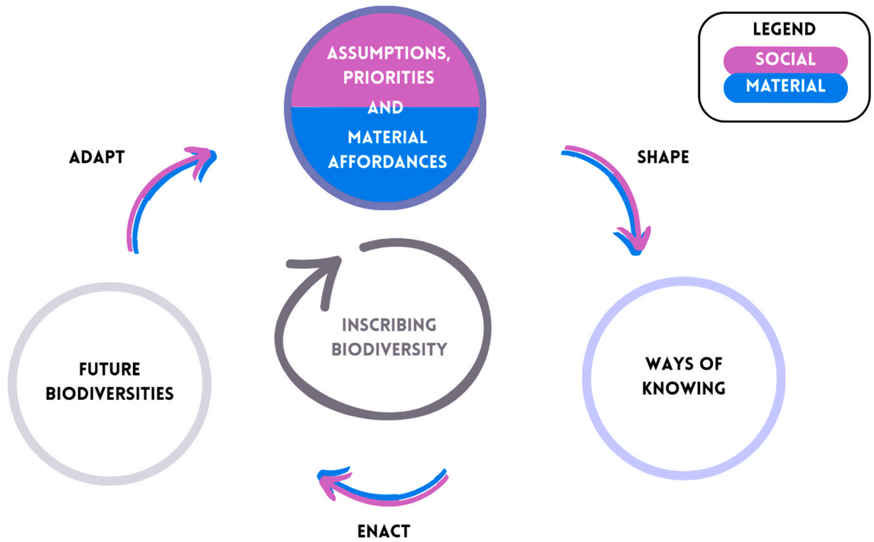

Fig. 1. Process of inscribing biodiversity, highlighting the social (in pink; assumptions & priorities) and material (in blue; material affordances).

protocols), guide how such monitoring and allocation is undertaken, with consequences for future actions such as biodiversity restoration or enhancement (Akrich, 1992; Gibson, 2014; Hutchby, 2001; Pascual et al., 2021). For example, setting biodiversity restoration or enhancement targets entails assumptions about the prioritisation of certain species and habitats over others (Elias et al., 2021). Similarly, preferences for certain kinds of data collection and sampling methodologies affect which biodiversities are observed and quantified (Beck and Forsyth, 2020; Callon and Law, 2005; Lippert, 2018; Nost and Goldstein, 2022). Assumptions are also embedded in the materialities of eDNA (e.g. reference databases), which in turn affect how epistemic communities make monitoring decisions and how biodiversity is ultimately quantified and governed (Callon and Law, 2005; Lippert, 2018). Our analysis focuses on how these assumptions and priorities, in combination with material affordances, shape the design and application of eDNA-based sampling.

Second, inscription involves the translation of these assumptions, priorities and affordances into the design of monitoring technologies and strategy. All monitoring strategies for biodiversity have material limitations, contouring the decisions on how a mediating technology like eDNA is to observe which taxonomy, at what temporal scale, and at which spatial extent (Deiner et al., 2021). The outcome of taxonomy, temporal and spatial decisions reflect policy and scientific assumptions and priorities – such as enhancement or restoration – as well as material affordances – such as focusing on genetically identifiable species. Furthermore, as Lehman (2020) argued, the vast scale and fluidity of oceans mean that sensing any biophysical dimension requires setting clear parameters for what can be observed, when and where. Even for eDNA, which holds the potential for identifying any and all species in a water sample, there are clear spatial and temporal material affordances in terms of the constant displacement and coherence of eDNA before it has been sampled (Shen et al., 2023). We assume that these combined decisions, and their underlying assumptions, priorities and affordances ultimately inscribe biodiversity through mediating sampling technologies.

Third, inscription involves the ways in which mediating monitoring technologies like eDNA affect the governance of future, and yet to be known, types of biodiversities and their enhancement. Monitoring in this sense is more than the mere collection and representation of immutable knowledge. It is also a performative practice that enacts the assumptions, priorities and affordances that make specific biodiversities knowable, quantifiable and governable, while excluding others (Coopmans, 2018; Dencik et al., 2019; Mol, 2002). This third dimension of inscription also shows how specific ways of knowing and monitoring biodiversity determine what can be enhanced, from what and in whose interest (Law, 2015). We further argue that these processes are not fixed or deterministic but instead open acts of governance (Gupta and Möller, 2019). Following Adamo and Willis (2022) and others (Braverman, 2016; Gray et al., 2020) it is through this socio-material process of governing that implicit and explicit decisions are made that affect ways of knowing and ordering certain kinds of biodiversity enhancements over others. As argued by Law and Singleton (2000), making the dimension of inscription explicit can open up debate around how biodiversity is affected by the socio-material nature of governing through inscription, which can in turn enable alternative processes of inscription for plural future biodiversities.

3. Methodological approach

We analysed the design and development of an eDNA-based sampling technology for monitoring biodiversity enhancement in offshore wind energy parks in the Dutch North Sea. The technology was designed through a project funded by the Mission-driven Research, Development and Innovation (MOOI) subsidy from the Ministry of Economic Affairs and Climate and implemented by the Netherlands Enterprise Agency (RVO). The project, starting in January 2023, consisted of a transdisciplinary consortium of ecological and social scientists, NGOs, marine wind turbine and tower engineers, marine geotechnical engineers, seafloor cable engineers, and a wind park developer and owner, with varying expertise on eDNA monitoring (from no experience to specialised experts).

The authors of this paper were members of the consortium and therefore engaged with the work as project partners. Over a one-year period, data was collected through applied ethnography (Ball and Ormerod, 2000); namely participant observation at consortium meetings, informal discussions, and through semi-structured interviews by the first author (see Tables 1 and 2). The applied objective of our empirical work was to investigate how biodiversity is inscribed in the design process of an eDNA monitoring strategy by epistemic communities as well as the affordances of eDNA technology. We began by identifying the social aspects of eDNA, namely, the assumptions, priorities and ways of knowing, to iteratively distinguish moments where assumptions, priorities and ways of knowing were defined by material affordances of eDNA. This meant that our research was specified towards topics related to biodiversity and the design process of the monitoring strategy. This resulted in us targeting observations to

Table 1
List of participants involved in consortium meetings.

List of participants	Abbreviation
Marine Ecologist A	MEA
Marine Ecologist B	MEB
Molecular Marine Ecologist (interviewed)	MME
Junior Marine Ecologist (interviewed)	JME
Design Engineer A (interviewed)	DEA
Design Engineer B	DEB
Innovation Manager Robotics	IMR
Geophysicist	GEO
Project Manager	PM
Senior Project Manager	SPM
Offshore Wind Biodiversity Solution Owner	OWBSO
Agile Product Owner	APO
Senior Environmental Scientist	SES

Table 2
Consortium meetings observed.

Consortium Meeting	Date
March Consortium Meeting	14th March 2023
May Consortium Meeting	9th May 2023
Biodiversity Baseline Meeting 1	17th May 2023
Biodiversity Baseline Meeting 2	23rd May 2023
June Consortium Meeting	16th June 2023
July Consortium Meeting	11th July 2023
September Consortium Meeting	12th September 2023
October Consortium Meeting	10th October 2023
November Consortium Meeting	14th November 2023

specific moments and topics (Ball and Ormerod, 2000). For example, we observed and participated in collective settings that served a specific purpose (i.e. consortium meetings) rather than exploring individuals' everyday practices. Doing so, we aimed to understand the collective practices and deliberations of the consortium community while also recording how individual perspectives affected decisions on what biodiversity to monitor, when and where.

We participated in and observed consortium meetings, both online and in person. These consortium meetings were held monthly and were recorded by the main project partner, requesting permission from all participants each meeting. Informed consent forms were provided and signed by the consortium partners for the collection and use of data from the recordings. Each consortium meeting entailed updates from all project partners, with opportunities for feedback and questions. In addition to consortium meetings, we also participated in other relevant meetings on the biodiversity baseline and technology development, mostly by asking questions. The ongoing meetings enabled us to iteratively frame our research scope and objectives, narrowing down on our objective to investigate how biodiversity is inscribed in the design process of an eDNA monitoring strategy.

The first author also conducted informal discussions and semi-structured interviews with project partners on an individual basis for further information. These interviews substantiated initial findings from the consortium meetings that were transcribed and thematically coded (using Atlas.ti). Through the coding process, three categories emerged as a pattern in the way that deliberations and decision-making evolved over time in the consortium, namely the taxonomy, spatial and temporal decisions. These emerged as suitable analytical categories that enabled us to unpack the inscription process. We iteratively cross-checked the data and analysis with the consortium, sharing ideas and brainstorming practical implications of our findings with project partners.

4. Inscribing eDNA-based biodiversity monitoring

4.1. Taxonomy

The first step in designing the monitoring strategy involved determining what kind of biodiversity eDNA could make observable around offshore wind parks. Although consortium partners were enthusiastic about the potential of eDNA to sample 'everything', they recognised that biodiversity would need to be reduced into measurable taxonomic categories. Indeed, the first consortium meeting in March 2023 revolved around the question of 'How do we define biodiversity?', revealing different assumptions and priorities regarding which aspects of North Sea biodiversity should be enhanced. One project partner emphasised the importance of enhancing specific habitats (the environment where a species lives), while another focused on increasing species richness. As these discussions continued with subsequent questions of 'what kind of biodiversity do we want?' and 'how do we accomplish that?', it became clear that decisions were necessary to begin designing a monitoring strategy. These decisions on the design of eDNA-based monitoring were guided by discussions around two key assumptions.

First, institutional and legal requirements were used to determine what biodiversity to prioritise in the monitoring strategy. The consortium quickly acknowledged that assumptions and priorities in European assessment and measurement frameworks are leading in defining a baseline for enhancement monitoring. The decision to focus on habitat and species for monitoring was largely based on pre-established institutional regulations. The European nature information system (EUNIS) habitat classification was used as a baseline for the sampling methodology, in addition to Dutch North Sea Programme (GoN, 2022), Natura 2000 (European Commission, 2019), and Birds and Habitats Directive (European Commission, 1992). The priorities in these policies emphasised the role of biodiversity monitoring for enhancement around hard substrates associated with offshore wind turbines rather than biodiversity conservation or restoration. This shaped a priority for a species-habitat understanding of biodiversity and a version of enhancement that was not just "more species" (JME, July 2024), but also "more trophic levels". This, according to one ecologist, would reveal "a more complex ecosystem which is more resilient" (JME, July 2024; corroborated by MME, July 2024; DEA, August 2024). Together, these assumptions prioritised species and trophic levels as a measure of an assumed more complex, resilient and, as such, enhanced ecosystem.

Further technical discussions were motivated by the affordances of eDNA, asking 'what can eDNA do for us?', as many consortium members were not familiar with the technology. A molecular marine ecologist shared that, at least in theory, eDNA has the potential to capture a wide range of species – including fish, but also other ecologically important organisms such as bacteria and algae. However, it can only make the data legible if the eDNA sequence matches to eDNA sequences available in a reference database. As argued by another member of the consortium, the database in fact predetermines the affordances of eDNA monitoring because the absence of species in the database means "you have a DNA sequence that is not matching anything" (MME, July 2024). Instead of monitoring everything, what can be monitored is whatever biodiversity exists in the eDNA database. While the consortium partners were aware of this, they also thought that water samples "contains all eDNA present in the water, and decisions only have to be made in the lab on how to amplify certain sequences" (MME, July 2024). This shows that although the material affordances of eDNA became more evident, collecting a water sample for eDNA monitoring was still understood as a neutral practice removed from the socio-materialities of the technology.

With the reference database in mind, and having established institutional regulations, the consortium then asked themselves; 'what can *we* do with eDNA monitoring?', highlighting the relationalities of eDNA and the consortium in designing a monitoring strategy. The reference database is more established for some species (i.e. fish) as opposed to others (i.e. benthos), pre-inscribing what kinds of biodiversity can be monitored. Furthermore, eDNA sampling and sequencing is expensive. Given the comprehensiveness of the database for fish, and the costs associated with sampling, fish became the focus of monitoring as a proxy for habitat complexity, as opposed to monitoring the habitats itself or other aspects of the ecosystem. As expressed by a molecular marine ecologist within the consortium, "we're not looking at bacteria and algae because we say we want to know more about the fish and benthos, but these bacteria and algae are relevant for the ecosystem" (MME, July 2024). The decision to monitor fish, rather than monitoring bacteria and algae, shows that project partners recognised the affordances of eDNA monitoring and the complexity of biodiversity. However, given financial and reference database limitations, they needed to prioritise. The interplay between assumptions, priorities and material affordances shaped which biodiversities will become identifiable through monitoring and thereby measured for enhancement into the future.

As the consortium started to make decisions on what biodiversity to monitor, they asked 'what kind of biodiversity do we *wish* to monitor with eDNA?'. In response, ecologists and NGO partners created a 'wish list' guiding which North Sea biodiversity is deemed "essential for a healthy North Sea Reef" (MME, July 2024). Most species were prioritised for habitat enhancement due to their 'reef building' role or protected status under the EU Habitats Directive or OSPAR's List of Threatened and/or Declining Species. For example, the Deadman's finger, a soft coral found on undisturbed rocky reefs was included as indicative of hard substrate disturbance (MME; July 2024). The list also reflected consortium expertise and interests. One partner requested *Sabellaria alveolata*, a reef-forming honeycomb worm, but it was initially excluded as it was presumed to not belong to the Dutch North Sea (MEA, May 2023). The iterative wish list allowed new assumptions and priorities to further inscribe biodiversity over time. For example, some nudibranch species were added based on their assumed link to enhancing fish-habitat insights (MME; July 2024). As the reference database grew over time, it was assumed that the wish list will be adapted to include previously unidentifiable species (MME; July 2024), thereby extending eDNA's affordances and highlighting the iterative nature between the technical and the social. These examples demonstrate key moments of inscription that determine what kinds of North Sea biodiversity are monitored and, in turn, contribute to future enhanced healthy North Sea ecosystems.

4.2. Temporal

Once the consortium agreed on taxonomy they had to decide on the timing of monitoring. eDNA has the promise of real-time, holistic monitoring, however, in practice, sampling is done at specific times and intervals, leading to temporal gaps in eDNA monitoring. Acknowledging these material affordances, the consortium discussed when sampling had to be done, guided by comparability, the dependencies the consortium had on other parties for financial capacity, and boat time.

Through their deliberations, it became clearer to the consortium that the chosen sampling time was associated with comparability of data over time and to a specific location. The ecologists wanted to sample during slack tide due to their preference to sample close to benthic habitat and nature-enhancing interventions made by the consortium. This is because slack tide is seen as the moment in the day with the least amount of current and water movement. The argument for sampling as close to slack tide as possible is to mitigate influences from strong tides and currents, making the comparability of data about enhancement "more accurate to that specific location" (MME, July 2024; JME, July 2024). This highlights the epistemic assumption that sampling at slack tide at specific locations allows for accurate readings about place-based enhancement, leading to the development and practice of place-based eDNA monitoring despite its holistic promises.

Temporal decisions about sampling were also influenced by financial and regulatory constraints. Discussions highlighted that many decisions were based on practicalities, such as available boat time, financial resources, and regulatory permits, highlighting how eDNA's material affordances translate into what biodiversity can be monitored, when and how often. First, as sampling is part of a larger project, financial resources allocated to sampling were limited, resulting in the sampling strategy being 'spread out' to four months intervals. The ecologists acknowledged this as a limitation, stating that sampling should ideally be more frequent or continuous to compare enhancement over time (MME, July 2024; JME, July 2024). eDNA monitoring is as such not holistic, as temporal and spatial gaps are inevitable. Second, Dutch regulation prevents nighttime sampling. This affects the type of eDNA capture; for instance, fish are more mobile – and more likely to release eDNA – at night (MEA, May 2023). However, consortium members expressed uncertainty about how this timing would influence monitoring outcomes related to habitat enhancement. These constraints illustrate how material and practical conditions shape the way eDNA can be used for monitoring, highlighting the socio-material nature of temporal inclusion and exclusion in biodiversity monitoring.

The consortium also made explicit choices on how eDNA could enable retroactive baseline assessments in the future, acknowledging the socio-material relationality of eDNA. These discussions reflected an explicit acknowledgement that eDNA infrastructures are continuously developing and the importance of collecting samples in the present to avoid foregoing opportunities for understanding biodiversity at a later time. This anticipatory dimension of sampling was most clearly detailed by a molecular marine ecologist who argued that the reference database (only) limits the sampling decisions *for now*, however, in the future "once it [reference database] is better populated, we can take them [samples] back from the freezer and realise it" (MME, July 2024). In this sense, the ecologist and the consortium anticipate the role of eDNA to not only monitor baselines of current biodiversity, but also future biodiversity. As MME illustrated, "with one sample, you can answer questions you have now and other questions that you may have in the future". This 'keeping a sample for the future' highlights the anticipation associated with eDNA sampling, raising questions about how future biodiversities may inevitably be inscribed in repetitive monitoring practices that are being developed today.

The temporal deliberations above highlight how epistemic communities govern biodiversity through the decisions they make in the design of a sampling strategy. Yet, whether these communities are reflective of it or not, they are also being governed by the capacity of eDNA to afford certain ways of monitoring biodiversity. In this case, financial and regulatory constraints have implicitly shaped the timeframes in which biodiversity can be monitored. Due to the novelty of eDNA monitoring, there is no standard protocol for monitoring, resulting in discussions about what biodiversity can be inscribed given the affordances of eDNA to temporally monitor biodiversity, which predominantly affords a static and fragmented biodiversity. However, acknowledging these limitations, the idea of continuous eDNA monitoring on a monopile (i.e. the foundation for offshore wind turbines) was proposed as an alternative application of eDNA at the August 2024 consortium meeting, a year after the initial biodiversity and sampling discussions. This proposition acknowledges that current static modes of monitoring may not provide sufficient information about biodiversity enhancement. This shows that in the development of an eDNA monitoring strategy, there appears to be tensions unbeknownst to those engaging in it, with new challenges and opportunities arising along the way. What these tensions highlight is how the assumptions, priorities and affordances of eDNA and the epistemic communities using it are used to manoeuvre through these uncertainties, shaping biodiversity in ways that have real consequences for how biodiversity is inscribed in monitoring technologies such as eDNA, which in turn influences future biodiversities.

4.3. Spatial

In addition to taxonomy and temporal decisions, the consortium needed to agree on the spatial element of sampling, namely, where to monitor and how. Despite the anticipation of eDNA to do holistic monitoring, decisions still must be made on *where* to sample, in terms of which sites and at what depth. This inevitably leads to the exclusion of certain spatial dimensions of the marine environment and with these, certain versions of biodiversities. Recognising these limitations, the consortium chose sampling sites based on project objectives while also brainstorming other ways of visualising and monitoring space with complementary technologies (i.e. visual aids).

To determine whether they would be able to accomplish their goal of biodiversity enhancement, the consortium discussed which specific sites to monitor and how. According to one ecologist, "the best way to count biodiversity is to drain the whole North Sea but that's of course not feasible" (MME, March 2023). Therefore, in their deliberations on where to sample, the ecologists considered their monitoring objectives, the potential of biodiversity enhancement at that specific site, and the availability of resources (i.e. boat time, sampling capacity). In the end, they chose six sites (out of sixty-nine sites); three nature-inclusive scour protection designs (i.e. designs that enhance marine biodiversity by creating complex habitats for various species around the monopiles of wind turbines, see Kingma et al., 2024) and three control sites. Within these sites, they sampled as close as possible to the benthic habitat and nature-inclusive scour design (i.e. within 5 m of the monopile) to identify species on and around the scour protection of wind turbines. The ecologists wanted to know whether biodiversity was enhanced at these specific sites, especially to measure and prove whether the consortiums' biodiversity enhancement intervention was successful or not.

This example reflects wider institutional assumptions that offshore wind energy parks have the potential to restore biodiversity through the infrastructures they introduce, and that they should do so to be 'nature positive'. For example, the Dutch North Sea Programme 2022–2027 prescribes win-win situations that addresses both the biodiversity and energy crisis through nature-inclusive offshore wind energy parks (GoN, 2022). Due to this, monitoring tends to focus on specific sites and locations as proof of enhancement, which has implications for what kinds of biodiversity are monitored, especially when considering the material affordances of eDNA monitoring. For instance, some species release more eDNA (i.e. fish) than others (i.e. crabs) due to their mobility. A fish that is moving around releases more eDNA than "a crab hidden in the rock, hardly breathing" (MME, July 2024), which has implications for the density of species identified (i.e. the epistemic assumption is that more eDNA captured in a sample could be an indicator for the density of that species in that area).

In the finalisation of the monitoring strategy, it became clear that specific sites would be prioritised as evidence of biodiversity enhancement. However, eDNA does not inherently afford a site-specific logic, requiring ecologists to standardise and simplify sampling. The consortium proposed a 'dual approach' combining eDNA with video camera imagery. However, eDNA cannot pinpoint enhancement to a specific habitat or location, nor can it confirm whether a specific location is being enhanced or not. In August 2024 the consortium considered the introduction of three-dimensional (3D) point cloud imagery - a set of data points that collectively form a 3D representation of the marine environment (Newcastle Measured Survey, 2022) - and two or three dimensional Ortho mosaic georeferenced maps created by stitching high-resolution images together, (JOUAV, 2025). These technologies were seen as addressing spatial – and hence habitat and species – gaps created by eDNA sampling. For example, ensuring that crabs and lobsters that release less eDNA are not excluded (JWE, July 2024) or that not only the presence of Sabellaria but also the spatial extent and 'health' of its reef structure would be recognised. These examples highlight how eDNA's social and material affordances shape deliberations over which kinds of biodiversity *can* be measured, and how complementary technologies render monitoring results more representative and spatially grounded in the context of biodiversity enhancement.

The decision to monitor at specific sites (i.e. nature-inclusive scour design) and to use visual aids (or not) and at what complexity level highlights how eDNA's affordances and epistemic communities are inscribing biodiversity through practices of monitoring. The consortium in this case has acknowledged the situatedness and limitations of eDNA monitoring, which they also realise results in place-based monitoring for enhancement. In response to this, the consortium had creative discussions around using three-dimensional monitoring or continuous monitoring which may provide new information and may be promising. This inscription process therefore highlights how these tensions between what eDNA is anticipated to monitor and what eDNA is actually monitoring are dealt with.

5. Discussion

The results demonstrate how taxonomic, temporal and spatial challenges – each incorporating both social and material affordances of the technologies that make up eDNA – shape the ways in which biodiversity is inscribed with particular socio-material assumptions and priorities. Institutional demands, technological limitations, and financial constraints combined to shape which taxonomies are rendered quantifiable and measurable for species-habitat monitoring and, ultimately, enhancement. Temporal biodiversity was inscribed with assumptions related to sampling frequency, where institutional demands and technological cost efficiency led to periodic rather than continuous monitoring. Spatially, biodiversity was inscribed as site specific, aligning wider demands for monitoring place-based enhancement in the vicinity of offshore wind infrastructure, with limitations of what eDNA can 'see'. Together, these moments of inscription highlight three different ways that immutable epistemic mobiles (Latour, 1986) – i.e. the reference database, wish list, and sampling methodology – condition the way that assumptions, priorities and material affordances shape how future biodiversity is measured, known and governed in the present (see Fig. 2).

First, the taxonomic reference database (pre)inscribes assumptions and priorities about which species can be recorded and, consequently, prioritised over others, highlighting how the affordances of eDNA governs biodiversity in the inscription process. Despite the potential for eDNA to detect 'all species', the database restricts identification to those already registered. Although it is continuously populated with new references, the database carries inherent biases – both taxonomic (e.g. fish vs. benthos) and geographic (e.g. entries sourced from Europe vs Africa) (Belle et al., 2019; Weigand et al., 2019). Acknowledging the material affordances that eDNA infrastructures embody, decisions to use fish as a proxy for measuring the development of habitat – due to completeness of fish species in the database – meant that a particular species-habitat way of knowing biodiversity was prioritised to the exclusion of ecosystem or trophic level based ways of knowing (Díaz et al., 2019; Duffy et al., 2007; Pascual et al., 2021). These deliberations show how the database, as a generic rather than tailored set of species, implicitly prescribes and affords certain assumptions and priorities that shape which biodiversity is measurable and as such 'enhanced' in the Dutch North Sea (c.f. Pascual et al., 2021). If unreflexively applied, the biodiversity that has been previously prioritised will continue to be prioritised, and the biodiversity that can be monitored will continue to be monitored.

Second, the creation and adoption of the species wish list was shaped by epistemic assumptions and priorities, inscribing what constitutes as 'enhanced' North Sea biodiversity and thereby governable. The wish list allowed ecologists and NGOs to set a normative guideline for 'desirable' biodiversity around offshore wind infrastructures. As noted above, desirability was defined through the anticipation of species considered 'essential' for 'healthy reefs' or those expected to provide the clearest indicators considered essential for 'species-based biodiversity enhancement'. This can reflect a form of (bio)politics (Foucault et al., 2008): where some versions of biodiversity are attributed greater value over others and are thus prioritised for enhancement (Pauwelussen and

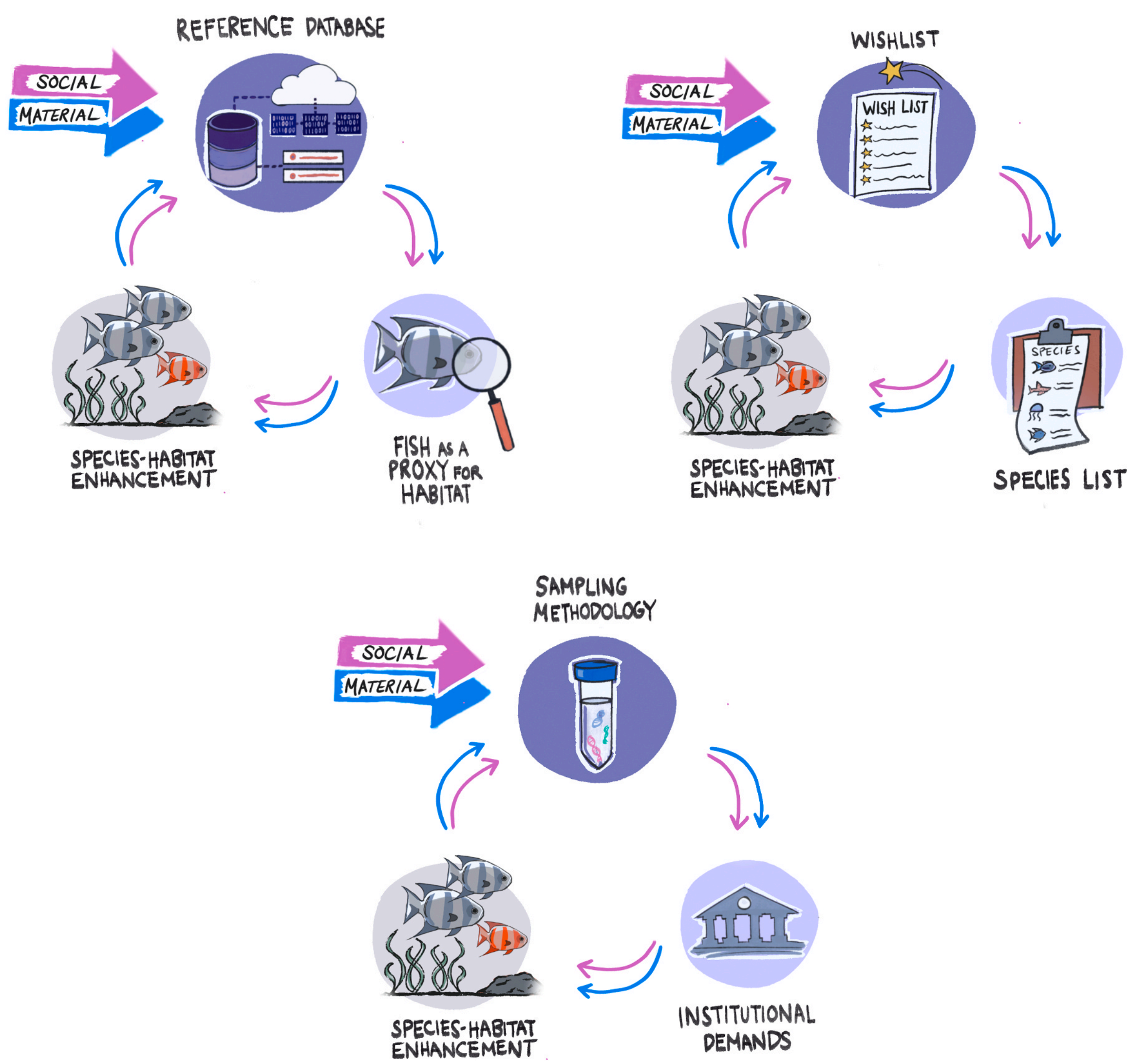

Fig. 2. Inscription of biodiversity through three immutable epistemic mobiles – reference database, wish list and sampling methodology – resulting in species-habitat enhancement.

Vandenberg, 2024). Like the reference database, the wish list inscribes normative assumptions - albeit based on expert opinion - at the species level, thereby excluding alternative ways of understanding biodiversity enhancement, such as food webs, ecosystem function and services (e.g. IPBES, 2019, 2022). Its use further highlights the socio-material de facto governing role of the consortium and eDNA as a technology in inscribing assumptions and specific kinds of anticipation and desirability of biodiversity (Gupta and Möller, 2019; Schadeberg et al., 2023). It also demonstrates (following Introna, 2019; Lehman and Johnson, 2022; Roturier and Beau, 2022) how eDNA and the way it is being designed and used together shape which forms of biodiversity are deemed desirable for enhancement in marine infrastructure interventions like offshore wind energy.

Finally, the inscription of biodiversity in the eDNA sampling methodology illustrates that, although the interdependencies of eDNA's affordances and epistemic communities are de facto governing future biodiversity, their decisions are embedded within pre-established visions of biodiversity shaped by economic interests and government policy. For instance, the Dutch government promotes biodiversity enhancement as a 'win-win' solution for both the biodiversity and energy transitions (GoN, 2022). In addition, legally protected biodiversity is prioritised through legislative frameworks and obligations (i.e. Natura 2000 (European Commission, 2019) and Habitat Directive (European Commission, 1992)). The consortium could define the specifics of the sampling methodology – such as prioritising place-based enhancement or visualising habitat development (e.g. Sabellaria reef development). However, the broader objectives of monitoring for enhancement were pre-inscribed prior to the design of the eDNA sampling methodology. The primary aims, including the monitoring of nature-inclusive intervention or the testing of technological solutions to biodiversity loss, remain embedded in the government's win-win rhetoric.

Moreover, the technologies that co-constitute eDNA also afford a particular version of biodiversity – one prioritising species present in reference databases and amenable to sampling. Following Dencik et al. (2019), biodiversity enhancement and its monitoring should therefore be understood not as the neutral collection and representation of immutable knowledge, but as an assemblage of assumptions, priorities and conditioning material affordances that enacts politically embedded assumptions and priorities that make specific biodiversities knowable and governable while ignoring others. This means that the reference database, wish list and sampling methodology should not be assumed to be immutable but moments in which eDNA is affording possibilities to shape future biodiversities in combination with those designing it. These mobiles therefore change and adapt, resulting in different inscriptions. Considering these changes and adaptations sheds light on how these affect the way biodiversity is inscribed.

These three epistemic mobiles that incorporate eDNA-based monitoring show how assumptions, priorities and material affordances inscribe certain ways of anticipating and governing future biodiversity. Previous research on actor network theory (Latour, 2005), affordances (Hutchby, 2001; Zammuto et al., 2007) and scripts (Akrich, 1992) has stressed the importance of unpacking the 'black box' of technology to understand how social and material dimensions of inscription promote certain ways of knowing over others. The findings extend these efforts by demonstrating how inscription functions as a governance process that continuously adapts to both the social and material affordances of novel technologies like eDNA. Understanding inscription as an act of governance also highlights the (bio)political agency of epistemic communities in enacting the enhancement of some biodiversities while excluding others (Biermann and Anderson, 2017). As our results show, although eDNA expands possibilities for inclusive biodiversity monitoring, its application inscribed biodiversity in terms of site-specific species-habitat relations. Within the consortium, this outcome was interpreted as a cost-effective response to the growing needs of the offshore wind energy sector. Yet as this sector expands, and biodiversity enhancement becomes integrated in tendering processes (James et al., 2023; Pardo et al., 2023) and biodiversity offset markets (Greaker et al., 2024; Vaissière et al., 2014), recognising inscription processes as an act of governing biodiversity can help to better anticipate how technologies and decisions made now affect which biodiversities are made possible (and which are not) in the future.

The inscription process is neither fixed nor deterministic but an open-ended process that allows for reflexivity on the relationship between the socio-material affordances of eDNA and those designing it (Fig. 3). Changes in how inscription is performed can help develop more reflexive approaches for making assumptions, priorities and affordances in the design and implementation of eDNA monitoring explicit (Gahoonia, 2024; Gray et al., 2020). Failure to adopt such reflexivity, particularly at the design stage, risks amplifying the socio-material affordances of eDNA, replicating not only sampling practices within eDNA's technological boundaries and features but also the assumptions and priorities that privilege certain biodiversity and ecosystem effects over others (see Fig. 3) (Bennett et al., 2022; Maalsen, 2023; Pritchard et al., 2022). For instance, questioning priorities that favour place-based enhancement while preferencing ecosystem or trophic level monitoring may open up wider possibilities for plural biodiversities to be enacted through enhancement or conservation. Materially, questioning the technical capacity for eDNA to afford these pluralities allows reflection on how eDNA as a social-material entity affords certain biodiversity futures over others. More radically, inscription could involve different ways of knowing – such as fishers, beach combers, diving clubs and/or citizens - to contribute to species wish lists, databases or sampling practices. Inscription should therefore consider how not only assumptions of actors are inscribed, but also how the material affordances of technologies like eDNA condition and (re)shape how those assumptions are inscribed. Approaching inscription in this way would enable reflexivity on the socio-material nature of epistemic mobiles which might help better understand how it is not scientists alone that are de facto governing future biodiversities, but also the socio-material dimensions of that de facto governance process.

6. Conclusion

Future biodiversities are being imagined and enacted through the inscription of current socio-material assumptions, priorities and affordances about biodiversity. By detailing the design process of an eDNA monitoring strategy, we have shown how the design of monitoring strategies inscribes and thus shapes ambitions for enhancing biodiversity. The assumptions, priorities and material affordances that are inscribed in monitoring strategies and technologies shape the way that biodiversity becomes known, enacted and ultimately governed. Inscription therefore holds implications for how 'biodiversity enhancement' can be understood and monitored, especially when embedded in the implementation of infrastructural interventions such as offshore wind energy.

The results demonstrate how the inscription of biodiversity through eDNA based monitoring is a form of de facto governance – whereby both the social and material dimensions of technologies such as eDNA afford what biodiversity is, with input from epistemic communities, institutional demands, market demands, and practical limitations. Biodiversity monitoring is thereby subject to prevailing assumptions and priorities in regulation and the wider market for wind energy and biodiversity, as well as the materialities of monitoring technologies such as eDNA. However, there is room for reflexivity in negotiating the extent that biodiversity is inscribed within this context, which may either broaden or limit different forms of biodiversity into the future. There is as such no

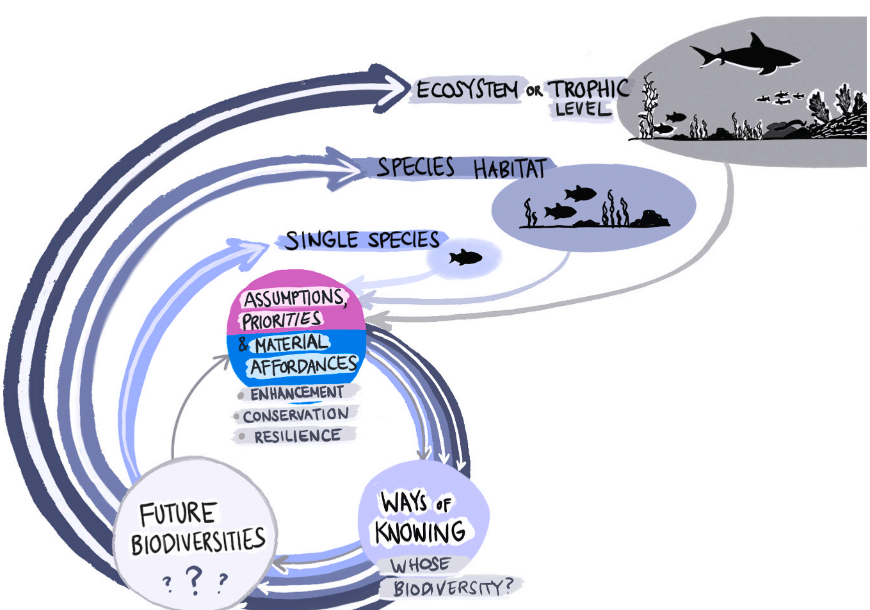

Fig. 3. Illustrating the potential for different biodiversity futures based on adapting and changing assumptions and priorities in consideration with material affordances as well as different ways of knowing.

given pathway for which biodiversity enhancement should be inscribed. Instead, by shaping more reflexive processes of inscription, it is possible to (re)imagine the ways in which biodiversity is inscribed, opening up how biodiversity is conceptualised, measured and enhanced. This may involve making the consequences of technological affordances, and institutional and epistemic assumptions and priorities explicit in the design of eDNA monitoring programmes. It may also, however, lead to more socially inclusive approaches for design – that builds directly on the technical capacity of eDNA to enable more plural future biodiversities.

Future research could further explore different inscriptions of biodiversity and at different levels, and how they may impact each other. For instance, attention could be given to the assumptions and priorities of organisations or institutions and how they may influence the inscription process. This may include how science-policy interfaces prescribe approaches to biodiversity enhancement, and whether it allows for plural biodiversities. As we have argued, institutional assumptions and priorities greatly influence the enactment of future biodiversities. For future research we recommend comparing how different countries inscribe biodiversity in different ways to better understand what future biodiversities are included and/or excluded in the current enactment of biodiversity enhancement within the offshore wind sector.

CRediT authorship contribution statement

Annet P. Pauwelussen: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Samantha G. Kristensen:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Simon R. Bush:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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