30-05-2023

Indicators for marine and coastal ecosystem services of the Dutch north sea

Literature review F.M. Kirsten – 8895309

Utrecht University – BINN Supervisor: Jaco Appelman

ABSTRACT

Marine and coastal ecosystems in the North Sea provide essential ecosystem services, supporting habitat provision, erosion control, and food production for local species, while also delivering economic value to humans. However, these ecosystems are continuously disrupted by various human activities, including energy harvesting, fishing, and coastal development. As a result, restoration efforts and investments in research and protection have gained significance. To effectively monitor changes in ecosystem health and evaluate the effectiveness of conservation efforts, the identification of relevant indicators is crucial. This literature review aims to gather the most pertinent indicators for marine ecosystem services, with a specific focus on the coastal ecosystems of the Dutch North Sea. The selected key factors for analysis include Shellfish and Oyster beds, Seagrass beds, Biodiversity and species richness, Food web integrity, Carbon sequestration, Erosion control and natural hazard protection, and Waste breakdown and detoxification. Recent literature was reviewed to identify relevant indicators, which were subsequently categorized into Wildlife (Biological indicators), Sea water, Sediment, Carbon cycle, geographical, social, and economic indicators. This compilation of indicators will assist stakeholders and researchers in establishing specific monitoring parameters to assess ecosystem health effectively.

LAYMAN´S SUMMARY

The marine and coastal ecosystems of the North Sea play an important role in providing various services that benefit both the environment and human well-being. However, the impacts of human activities such as energy production, fishing and coastal development have disturbed the delicate balance of these ecosystems. To restore and effectively monitor the health of coastal ecosystems, it is essential to identify and use specific indicators. This literature study focuses specifically on the coastal ecosystems of the Dutch North Sea and aims to compile the most relevant indicators for assessing the provision of marine ecosystem services. These indicators cover a range of factors, including the presence and condition of mussel and oyster beds, the overall health and vitality of seagrass beds, species diversity and biodiversity richness, food web integrity, carbon sequestration capacity, erosion control capacity and the effectiveness of waste disposal processes. By monitoring these indicators, stakeholders and researchers can assess the success and effectiveness of restoration efforts and ensure the long-term sustainability of these valuable ecosystems. Knowing the current status of these indicators allows for informed decision-making regarding the protection and management of marine ecosystems in the Dutch north sea, ultimately promoting their health and maximising the benefits they provide to nature and human society.

INTRODUCTION

Marine ecosystem services encompass the benefits that humans and nature derive from the ocean and its ecosystems. These services include a wide range of essential goods and services for human well-being, including food, clean water, climate regulation, cultural and recreational opportunities, and biodiversity conservation (Barbier, 2017). Marine ecosystems provide habitats for a variety of species, many of which have commercial importance (Stithou et al., 2023), and contribute to the functioning of Earth's ecosystems. The ocean also plays an important role in oxygen production and climate regulation and acts as a significant carbon sink. Therefore, the provision of marine ecosystem services is critical to human survival and the sustainable development of our planet.

Unfortunately, human activities today pose a threat to many remaining marine ecosystems and the services they provide. Coastal development, population growth and pollution have resulted in the degradation of 50% of salt marshes, 30% of coral reefs, and 29% of seagrass beds worldwide in recent decades (Selim et al., 2016). Oyster reefs are also experiencing significant declines worldwide, which can be as high as 89% (Cobacho et al., 2020). Overfishing continues to be a growing problem in the marine environment, and the loss of fisheries is linked to the deterioration of water quality due to the increasing incidence of harmful algal blooms, marine pollution, and oxygen deficiency (Barbier, 2017). Given the rapid loss of coastal and marine environments, it is critical to understand the economic benefits and values that are lost as marine ecosystems disappear. An important aspect of these habitats is their connectivity from land to sea, which presents a challenge for future research to assess the benefits that accrue from such a connected seascape.

Coastal conservation has become increasingly important in global ecology as a means of protecting coasts from erosion and creating healthy environments that benefit both the land and the inhabitants of coastal regions. As more actors, including companies, universities, and international institutions, become actively involved in restoring marine ecosystems that have been disturbed by human activities such as fishing and energy production, the interconnections and roles among these actors are becoming tighter (Grizzetti et al., 2019; Vogel et al., 2018). While the overarching goal appears to be the protection and restoration of marine areas, local approaches to achieving this goal vary and focus on different aspects of ecosystems. Ecosystem services serve as a common metric for evaluating protected areas (Guerra-García et al., 2021). In the case of marine and coastal protected areas services can serve as a valuable indicator for improving ecosystem health, as a balance of services indicates a healthier ecosystem. While several factors can be used to validate ecosystem services provided, stakeholders need to clearly define indicators and establish direct measurement methods for each project and site to effectively assess improvements in marine protected areas (Atkins et al., 2015). In this literature review, we examined state-of-the-art methods for validating and monitoring marine ecosystem services, focusing on coastal ecosystems in the North Sea. We collected relevant literature, assessed useful indicators, and placed them in a context that stakeholders can use for monitoring.

Marine Ecosystem services - overview

The ocean is an important regulator of the Earth's climate and acts as a huge carbon sink, absorbing about one-third of human-induced carbon dioxide emissions (Schumacher et al., 2021). This important function helps to mitigate the negative impacts of climate change on the environment and human society. In addition, the ocean provides numerous natural services, including oxygen production, precipitation generation and regulation of global weather patterns through ocean currents. Among the most important services provided by the marine ecosystem is the provision of food. More than three billion people rely on the ocean as an important source of protein, and coastal communities are highly dependent on it for their food security and livelihoods (Hornborg et al., 2019). Seafood, including fish and shellfish harvested from the sea, is rich in essential nutrients such as omega-3 fatty acids, which are vital for human health. In addition, marine ecosystems support aquaculture, a fast-growing sector that provides a sustainable alternative to wild fisheries.

In addition to food, the sea provides a variety of recreational opportunities such as swimming, diving and surfing, which contribute to the social and cultural well-being of communities. Marine ecosystems also support various tourism activities such as whale watching and coral reef tourism, which contribute significantly to coastal economies. In addition, the sea serves as a source of inspiration and cultural identity, with communities drawing on its rich history and mythology to shape their cultural practices and beliefs (Barbier, 2017).

Marine ecosystems also play an important role in conserving biodiversity, providing habitats for a wide range of species, including many that are endangered or threatened. With an estimated 700,000 to one million species living in the ocean, many of which are still undiscovered or poorly studied, these species are essential for maintaining the health and resilience of marine ecosystems (Barbier, 2017). As marine ecosystem services are crucial for human well-being, these ecosystems must be protected and conserved for sustainable development of coastal areas and marine areas with human interference. Figure 1 provides a schematic overview of marine ecosystem services and illustrates the specific research focus of this review.

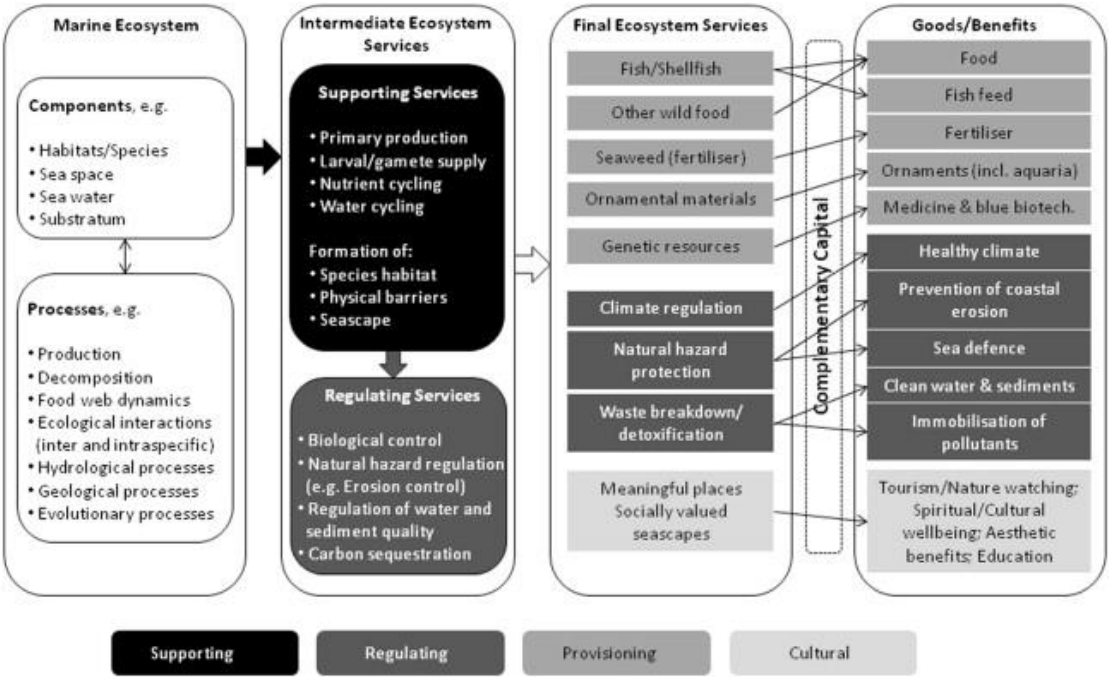

Figure 1: Marine ecosystem services as described in Luisetti et al. (2014)**. The focus of the literature research lies on intermediate and final ecosystem services as they are most relevant for the indication of ecosystem health and monitoring. Image from: Coastal zone ecosystem services: From science to values and decision making; a case study** (Luisetti et al., 2014)

The core of valuing ecosystem services is assessing the contribution of ecosystems to human well-being and the conservation of wildlife in quantifiable terms. However, quantifying and assigning value to marine ecosystem services is challenging because there is limited knowledge of how changes in ecosystem structure and function affect the production of valuable goods and services (Hattam et al., 2015). This study focuses specifically on the valuation of natural ecosystem services and gives secondary importance to socio-economic services. The selected indicators are used to monitor the recovery of a coastal ecosystem previously affected by human interventions and uses, with a focus on assessing the health of the ecosystem independently of its benefits to humans. Nevertheless, it is important to note that a healthy ecosystem can also provide a range of benefits to humans, which in turn can be considered as an indicator.

Research focus

The Dutch coastal marine ecosystem is a diverse and unique ecosystem spanning approximately 450 kilometres of coastline along the North Sea. It comprises various habitats such as sandy beaches, rocky shores, dunes, tidal flats, and salt marshes, that support a wide range of flora and fauna, and provides habitat for several threatened and endangered species, in addition to playing a crucial role in coastal protection and supporting the country's tourism industry (Bossier et al., 2018; Selim et al., 2016). Although different marine ecosystems may require different indicators to monitor their health and success, many indicators can be adapted to individual environments and circumstances if used correctly. For example, the Wadden Sea, located in the south-eastern part of the North Sea, is a unique ecosystem characterized by large tidal flats and estuaries that support a variety of wildlife and biodiversity, including oyster, shellfish beds and seagrass beds (Luisetti et al., 2014). These beds play a crucial role in restoring ecosystems and can serve as indicators for improvements, with shellfish beds acting as ecosystem engineers that build carbonate structures, facilitating the allocation of natural habitats for smaller organisms (Cobacho et al., 2020). Figure 2 shows the relevant parts of the coastal ecosystem that are the focus of this research.

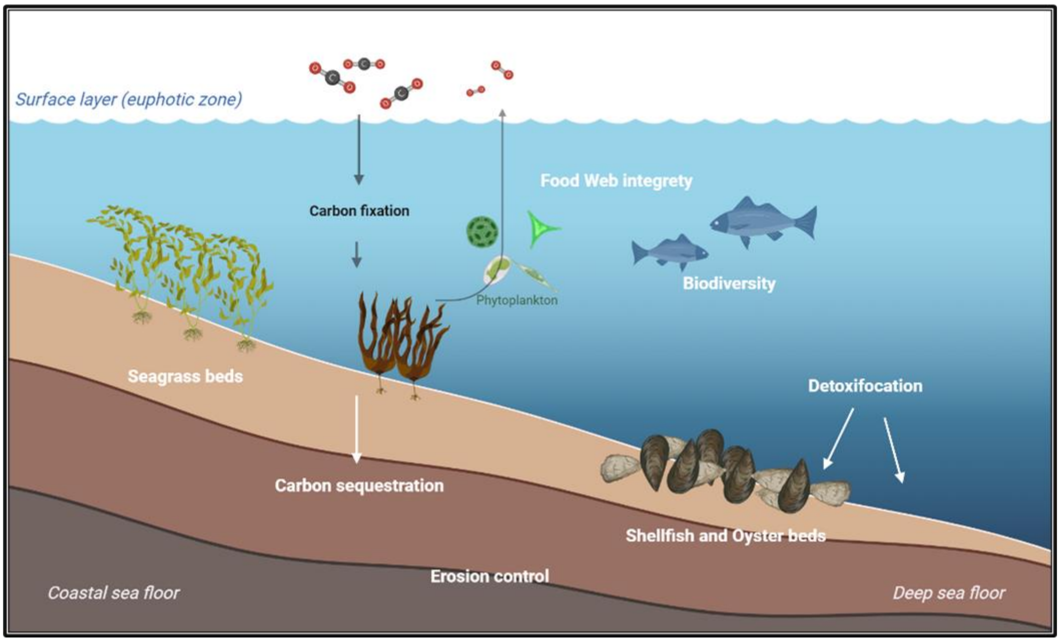

Figure 2: Core ecosystem services analysed in this review. Close to the shoreline, seagrass beds and small organisms define the ecosystem, providing carbon sequestration and erosion control. In all depths, important factors to analyse are the richness of fish species as well the health of oyster beds, which provide detoxification and influence food web integrity.

Marine ecosystems form a complex network that spans a continuous interface between land and sea. This seascape includes various habitats such as mangroves, salt marshes, seagrass beds, coral reefs and oyster reefs. The interconnectedness of these habitats is crucial as they individually provide important goods and services, while also creating functional linkages that encompass the entire seascape such as nutrient flows, material exchange and the movement of marine organisms. The Dutch North Sea coast is characterised by different habitats and typologies. Figure 3 illustrates the distribution of three important factors contributing to biomass and connectivity within these coastal ecosystems: oyster beds, seagrass beds and kelp forests. While recent research has focused primarily on oyster reefs and seagrass beds, it is important to note that kelp forests have the potential to contribute to ecosystem health similarly and are increasing interest for recent research (Schumacher et al., 2021).

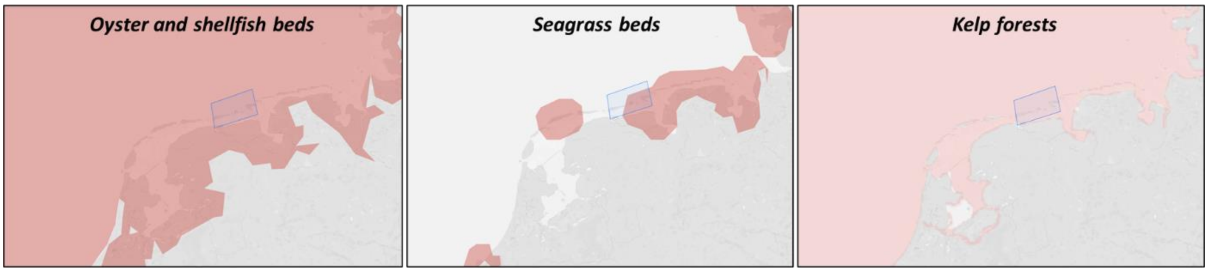

Figure 3: Area of focus of this study and the presence of oyster beds, seagrass beds and kelp forests in the surrounding coastal area. Oyster and shellfish beds show a presence in most of the Dutch North Sea and make up a main part of the ecosystem, while seagrass beds show a more limited distribution. Analysis was done with Global Ecosystem *Typology* (Keith et al., 2022)

Indicator properties

Assessing marine ecosystems through the lens of ecosystem services is a valuable approach that provides crucial insights into the state of these ecosystems and helps in monitoring protected areas and evaluating conservation initiatives. To effectively measure ecosystem services, indicators need to be established that are linked to factors that reflect the state of performance and overall well-being of the ecosystem.

Indicators serve as measures of important ecosystem properties, indicating changes in ecosystem health and providing information on how the ecosystem responds to stressors. Generally, indicators should be observable, based on well-defined theory, cost-effective to measure, supported by time series, and sensitive and responsive to changes in the ecosystem and the properties they measure (Hattam et al., 2015; Stebbings et al., 2021). Aubry and Elliott (2006) suggest that environmental indicators should fulfil three basic functions:

- **Simplify** the diverse components of an ecosystem allowing the selection of a few indicators to characterize the overall state of a marine ecosystem.

- ❖ **Quantify** and compare with reference values considered characteristic of either pristine or heavily impacted nature to determine changes from a chosen reference point or to reach expected conditions.
- ❖ **Communicate** information exchange and comparison of spatial and temporal patterns with stakeholders and policymakers.

Indicators, when placed in the right context, can represent the state, patterns or effectiveness of the marine system, as well as the stocks of natural capital and the flow of ecosystem services. They provide a reference value against which change can be assessed and integrated into concrete parameters and restoration approaches when monitored regularly and consistently.

OVERVIEW OF RELEVANT INDICATORS (RESULTS)

Many indicators to monitor marine ecosystem service can be found in recent literature, and for simpler understanding, it is important to categorize and connect the most relevant indicators for the specific area of focus. Here we have collected to most relevant indicators for the Dutch coastal ecosystem and approached to connect them with each factor of the ecosystem. Categorizing indicators can be done in several ways, here we chose to extend the approach by Atkins et al. (2015) proposes a practical approach to categorize ecosystem indicators based on their connection to ecosystem services. This categorization divides the indicators according to processes and components, intermediate services, final Services, and goods and benefits.

To facilitate the use of indicators by stakeholders, the relevant indicators from the literature have been selected and classified into environmental, social, and ecological indicators. For the Dutch north sea coast, indicators associated with the selected factors have been chosen and grouped into seven different categories: Wildlife (biological indicators), sea water, sediment, carbon cycle, geographical, social and economic.

Environmental indicators:

Wildlife (Biological indicators):

Wildlife and biological factors are good indicators for the health of a marine ecosystem and its ecosystem services as they are integral components of the marine food chain and play important roles in the functioning of the ecosystem. Marine wildlife such as fish, seabirds, and marine mammals are often at the top of the food chain, and changes in their populations can indicate changes in the overall health of the ecosystem. For example, if there is a decline in the number of fish in a particular area, it could be a sign that there is overfishing, pollution or habitat destruction occurring in that area, which could negatively impact other species in the ecosystem as well (Selim et al., 2016). Similarly, if there is a decline in the number of seabirds or marine mammals in a particular area, it could be an indication of changes in the availability of prey, changes in water quality, or changes in climate conditions.

The presence or absence of certain types of marine life can also indicate the health of specific ecosystem services. Focusing on the Dutch coastal zone, oyster and seagrass beds support a diverse array of marine life, including fish and invertebrates, and are an important habitat for many commercially valuable species. Changes in the health and abundance of these reefs can therefore have significant impacts on the fishing industry and other marine ecosystem services. Several wildlife indicators have shown to be practicable and valuable tools for monitoring and managing these ecosystems:

- **B1**: Core species (fish) abundance, biomass, density, phytoplankton index.
- **B2**: Abundance and distribution of seabirds.
- **B3**: Quantity and quality of larvae/gametes supplied to a particular location (number per m^3).
- **B4**: Competition for food and space, resilience and resistance (predator:prey, adults:juveniles).
- **B5**: Quantity (number) and quality (prevalence) of pest/disease/predator-control species.
- **B6**: Fish and shellfish population size (biomass of fish/shellfish in tonnes), age, length and health of the fish and shellfish.
- **B7**: Quantity of seaweed stock (biomass in tonnes, area of seaweed ha), health of seaweed stock (infected:healthy, mortality rates).
- **B8**: Amount of waste that can be recycled or immobilised (tonnes), Amount of organic matter in water and sediment (mg/l), amount of heavy metals in water and sediment (mg/l), amount of bacteria in water and sediments (mg/l), heavy metal (and other pollutants) content in marine organisms (concentration).

Sea water:

Poor water quality can lead to reduced populations of fish, shellfish, and other marine species, and can also harm the health of humans who consume these species or engage in recreational activities in the affected areas. Pollutants such as chemicals, excess nutrients, and plastic waste can harm marine life by disrupting their reproductive and feeding behaviours, reducing their immune system function, and causing diseases (Karydis & Kitsiou, 2013). Additionally, pollution can degrade habitat quality by altering the physical and chemical properties of the water, making it difficult for organisms to survive and reproduce. Monitoring water quality in marine ecosystems is essential for understanding the health of the ecosystem and its ecosystem services as se water connects many different factors and makes up the transport medium to connect the whole ecosystem. By maintaining good water quality, the long-term health and sustainability of marine ecosystems and their associated services can be validated. Several water quality indicators are measurable:

- **W1**: pH, Salinity, turbidity.
- **W2**: Biochemical water quality indicators (Nitrates mg/l, Phosphates mg/l, bacterial levels mg/l), total dissolved solids (mg/l), assimilative capacity.
- **W3**: Changes in output of nitrates, phosphates, silica (g per unit area/volume), denitrification (kg N/ha/yr).
- **W4**: Amount of organic matter in water (mg/l), amount of heavy metals in water (mg/l), heavy metal (and other pollutant) content in marine organisms.

Sediment:

The sea floor and coastal sands and mud are easily collected evidence, containing valuable information about the health of a marine ecosystem. Sediments provide habitat and substrate for many marine organisms, including sea weed, oysters and other invertebrates and fish, and serve as a source of nutrients and organic matter for the food chain. Excess sedimentation can smother seafloor habitats, reducing the availability of food and shelter for marine organisms. Sediment can also contain pollutants, such as heavy metals and organic chemicals, that can accumulate in the tissues of organisms and harm their health. In addition, sediment can harbour harmful pathogens and toxins, which can cause human illnesses if seafood from the affected areas is consumed.

The composition and accumulation rate of sediments allows scientists and resource managers to identify areas of concern, track changes over time, and develop strategies to mitigate the impacts of sedimentation. If sediments are in water depths within reach, which is the case for most coastal systems, they can give insights into many processes of the sea floor, but also the water above it.

- **S1**: Sediments Type, accumulation rate.
- **S2**: Changes (output of the system) in the amount of nitrates, phosphates, silica (g per unit area/volume), denitrification (kg N/ha/yr).

- **S3**: Sediment accumulation rates; beach slopes and gradients, seabed form, channel depths, erosion-deposition cycles.
- **S4**: Amount of organic matter in sediment (mg/l), amount of heavy metals in sediment (mg/l), amount of bacteria sediments (mg/l).

Carbon cycle:

The carbon cycle involves the transfer of carbon between the atmosphere, oceans and land through various processes such as photosynthesis, respiration and decomposition.

Increased carbon dioxide (CO_2) in the atmosphere can lead to ocean acidification, which poses a threat to the shells and skeletons of many marine organisms such as oysters, molluscs and plankton, disrupting the food chain. The North Sea serves as a carbon sink and actively absorbs significant amounts of CO_2 from the atmosphere. Monitoring inflows and outflows of the carbon cycle provides valuable insights into decomposition, the formation of new habitats such as oyster and seagrass beds, and carbon sequestration, which is considered by stakeholders to be one of the most important services provided by marine ecosystems.

- **C1**: Quantity of primary production (g C per unit area/volume), quality of primary production (e.g. efficiency of converting sunlight to carbon).
- **C2**: Amount of carbon dioxide sequestered (tonnes of CO_2 per m^2 or m^3), assimilative and recycling capacity, net carbon burial (tonnes per ha per year).
- **C3**: Amount of waste that can be recycled or immobilised (tonnes), Biological oxygen demand (mg O_2/litre/day), amount of organic matter in water and sediment (mg/l), amount of bacteria in water and sediments (mg/l).

Geographical:

Geographical factors include sediment measurements but extend and differ as indicators, as they include more physical and chemical properties of the marine environment, which in turn affect the distribution and abundance of marine organisms and the functioning of the ecosystem. Geographical factors can also include physical features such as coastlines, ocean currents, tides and topography, as well as climate patterns, weather events, and land use practices in surrounding areas

Factors such as changes in coastline shape and structure can have significant impacts on the flow of water and sediment in and out of estuaries and nearshore habitats (Jickells et al., 2016). These alterations can affect the availability of nutrients and influence the composition of marine communities. The attenuation of waves in near-shore coral or oyster reefs and seagrass beds is dependent on water depth above the reef or grass bed, which varies spatially. Similarly, wave attenuation in sand beaches and dunes increases exponentially with higher elevations or where there is greater vegetation cover. In addition, changes in ocean currents and temperatures can result in shifts in the distribution and abundance of marine species, potentially altering the food web and productivity of commercial fisheries.

- ❖ **G1**: Change in amount of natural barriers e.g. saltmarsh, reefs, sand dunes, reed beds etc. (% cover, ha).
- ❖ **G2**: Width or area of saltmarsh, reed bed, mudflat, dunes etc. providing natural hazard protection (m, % cover, ha), sediment stabilization properties, water retention capacity (m^3), (wave) energy dissipation capacity (joules/m^2).
- ❖ **G3**: Sediment accumulation rates; beach slopes and gradients; seabed form; channel depths; erosion-deposition cycles.

Social/human indicators

Other than environmental indicators, social impacts can often not be directly measured. They reflect human activities and practices that influence the marine environment and its ability to provide goods and services to people. Human activities can include fishing, shipping, coastal development, pollution, and climate change, among others. Landed fish catch can be easily observed and, in many cases, the fish are often marketed; reliable prices therefore exist to indicate the value of the catch (Selim et al., 2016). Recreation and tourism values can also be determined by estimating the willingness-to-pay of visitors to unique marine habitats for specific activities, such as coral reefs for recreational fishing or scuba diving, bird watching in salt marshes, and tourist visits to marine parks. Overfishing or unsustainable fishing practices can lead to declines in fish populations and reduced productivity of fisheries, which are important ecosystem services that support human livelihoods. Pollution from human activities can harm marine organisms and affect the quality and safety of seafood, affecting human health.

- ❖ **H1**: Nutrition from seafood consumption (g protein/year or g protein/year/head or per household).
- ❖ **H2**: Quantity of degradable waste deposited (tonnes by type), quantity of non-degradable waste deposited (tonnes by type), pollution damage avoided by not disposing degradable and non-degradable waste elsewhere (type and extent).
- ❖ **H3**: Amount of man-made infrastructure no longer required, people protected from flooding, number of flood-related mortalities.

- **H4**: Number of prevented hazards (number per yr), quantity of risk prevention (quantity of assets affected adjusted for risk).
- **H5**: Field trips and classes (number and number of people involved), scientific studies (number of research papers, subscriptions, library borrowing, online downloads), books (number, print run, library usage, e-book downloads), other publications including newspaper articles (circulation including on-line accessing); works of art (number of works, number of people viewing work).

Economic indicators

These indicators can reflect the economic value that society places on the goods and services provided by the marine environment. Included are economic benefits derived from commercial and recreational fisheries, tourism, shipping, and coastal development. Overexploitation of fish populations can lead to declines in fisheries production and revenue, impacting the economic well-being of coastal communities that rely on fishing, while pollution or habitat degradation can negatively affect the tourism industry (Stithou et al., 2023).

Monitoring economic factors in marine ecosystems is therefore important, even though most indicators are secondary and not primary measures for ecosystem health. By promoting sustainable practices and reducing negative impacts on the marine environment, we can help ensure the long-term health and economic sustainability of marine ecosystems and services.

- **E1**: Fish landed for human consumption (landings data at particular times and places in tonnes).
- **E2**: Mineral and other content used (e.g. N concentration in g, tonnes); quantity of biomass harvested for energy production.
- **E3**: Waste treatment and engineering works not required (type and capacity), changes in activity not implemented due to capacity to immobilise waste (quantity and/or other characteristics of activity).
- **E4**: Ornamental use (tonnes) by type, number of people/businesses who rely on ornamental artefacts (no.).
- **E5**: Amount of man-made infrastructure no longer required, businesses protected from flooding.
- **E6**: Amount of man-made infrastructure not required (length/width/height in m).

INDICATOR MATRIX

To effectively monitor improvements in a specific area with defined boundaries in marine ecosystems, simpler indicators that are reliably measurable are required. While the complexity of the ecosystem requires indicators that provide insight into the status of multiple parts of the ecosystem, combining and simplifying indicators is necessary to monitor a specific area more effectively. Proper interpretation of collected data within the system boundaries and stakeholder goals is crucial to gain valuable insights into the ecosystem's health.

Table 1 integrates the seven selected indicator groups with the most influential components of the Dutch coastal ecosystem, allowing a more direct use for stakeholders. In contrast to the division of services and their indicators into processes, intermediate and final ecosystem services, goods, and benefits, as described in Atkins et al. (2015), this approach combines indicators due to their ability to provide insights into the status of multiple factors to incorporate the complexity and interconnectedness of the ecosystem and its services. Through an analysis of the literature, it was observed that many indicators are employed for different aspects of the ecosystem, underscoring the significance of comprehending which factor a given indicator measures and which indicators offer insights about multiple factors.

Table 1: Indicator matrix to choose useful indicators for each part of the marine ESS. Green indicates directly measurable indicators, yellow represents a subsequent or secondary measurable impact.

	Environmental indicators						
Investigated Part/ Factor	**Wildlife (Biological indicators)**	**Sea water**	**Sediment**	**Carbon cycle**	**Geographical factors**	**Social/ human indicators**	**Economic indicators**
Shellfish and Oyster beds	B1, B6, B8	W1, W2, W3, W4	S1, S2, S3, S4	C2, C3	G1, G2, G3	H1,H2	E4
Seagrass beds	B1,B2, B6, B7, B8	W1, W2, W3	S2, S3, S4	C1, C2, C3	G1, G3		
Biodiversity and species richness	B1, B2, B3, B4, B5, B6, B7, B8	W3, W4	S2, S4	C1, C2		H1,H5	E1, E4
Food web integrity	B1, B2, B3, B4, B5	W3, W4	S2, S4	C1, C3		H1	E1, E2, E4
Carbon sequestration	B1, B6, B7, B8	W2, W3, W4	S1, S2, S4	C1, C2, C3			E3
Erosion control and natural hazard protection			S1, S3		G1, G2, G3	H3, H4	E2, E4, E5, E6
Waste breakdown and detoxification	B8	W1, W2, W3, W4	S1, S2, S4	C2, C3		H2	E3, E5

´Primary´ and ´Secondary´ indicators

The yellow fields in Table 1 represent secondary indicators, as they are indirectly linked to the respective factors but can be used and interpreted as consequences of other ecosystem services. For instance, a healthier fish population can initially lead to increased profitability in fisheries, provided that the fishing activities are well-regulated and sustainable. Similarly, a healthier marine environment and cleaner beaches with high water quality can enhance the attractiveness of the area for tourists, which is an indirect result of a healthier ecosystem. However, it is important to note that the focus of this study, aimed at stakeholders investing in ecosystem restoration, is not primarily on improving these human benefits but rather on utilizing ecosystem services as indicators for the health of wildlife and the marine protected area. The selection of specific indicators depends greatly on the stakeholders involved, and it is crucial to avoid relying solely on one indicator, as assumptions about improving ecosystem health should be based on monitoring and validating several indicators over time. A negative trend in one indicator does not necessarily indicate a general decline in ecosystem health. For example, a decrease in seagrass biomass could mean that more fish and small organisms have entered the food chain, and an equilibrium is yet to be reached. Therefore, it is vital to establish clear, time-dependent goals for each indicator, while acknowledging that complex ecosystems may exhibit unexpected responses to human interventions.

DISCUSSION

Using the right indicators, defining parameters

According to the literature research, indicators vary in their precision and information richness due to differing definitions between researchers, stakeholders, and policymakers. Therefore, it is essential to establish clear goals and a set of indicators for a specific area and ecosystem. Some indicators provide insight into a limited number of ecosystem factors, offering more precise evidence for the improvement of the goal. Other indicators are associated with a broader range of ecosystem services. As investors and stakeholders have limited time and monetary resources, it is crucial to select the appropriate indicators for the desired goal and using a greater quantity of indicators does not necessarily lead to clearer results. Furthermore, stakeholders must determine which ecosystem services are the most valuable to investigate. In the case of restoring a marine protected area, human benefits provided by the ecosystem may be of secondary importance and used only as an indication of the general health of the ecosystem, rather than as a desired improvement. For the Dutch coastal ecosystem, the following indicators appear to be a promising fit for restoration purposes:

- **Water quality and sediment measurements:** Most easily measurable indicators with direct results and little risk of wrong interpretation. Verifiable indicators are best used for monitoring over-time changes with regular and repeated measurements at fixed locations. Water quality indicators and sediment properties can be obtained non-expensive and time-saving, units are comparable and scientifically solid. Both water and sediment properties give insight into the state of oyster and seagrass beds, decomposition of organic material and detoxification, as well as carbon sequestration.
- **Wildlife monitoring:** Good overall indicator of ecosystem health that needs to be adapted to local species, as more background information about the local food chain is necessary for the right interpretation of indicated results. These results are verifiable, comparable and a good direct proof of positive change for the public and stakeholders, but measurements and monitoring need expertise and different approaches, making it a little more expensive and time-consuming.
- **Carbon cycle analysis:** Requires more calculation and interpretation, but tools are available and verifiable. Carbon sequestration is one of the most important factors for stakeholders and the analysis of the carbon cycle can give (indirect) insights into the food web integrity, as well as waste breakdown and detoxification. Especially useful if the goal is compensation for previous uses of the area, the ecosystem can be used as a compensator for carbon footprint and direct measurement of carbon storage and sequestration is proof for stakeholders for the success of reinvestment.
- **Social indicators**: Human indicators are the least direct indicator set, but are nevertheless of great importance to understanding the processes and interconnectivity of the ecosystem. For one, it is important to put indicators and results understandably for people influenced by the coastal ecosystem and especially for policymakers to base their decisions on an understanding of changes and necessary improvements. Secondly, the knowledge gathered by local inhabitants and experts is crucial to choose the right method of restoration and choosing simple indicators that have proven to be good locally and historically.

Although shellfish and seagrass beds are not direct indicators but intrinsic components of the ecosystem, they are important indicators for assessing the well-being of Dutch coastal ecosystems and serve as effective tools for restoration, as their analysis can provide valuable insights into various aspects of local ecosystem health. Among these, oyster beds play a particularly important role, as they overlap with all seven indicator groups derived from the literature (Table 1). Given that oyster beds have recently become the focus of restoration efforts and investments, monitoring the condition of these beds through various indicators provides direct insight into the success of restoration efforts, while also serving as a secondary indicator of many other ecosystem services, including food chain, detoxification and carbon sequestration. Oysters in particular are known to contribute to maintaining good water quality and have minimal impact on intertidal zones even under the stress of climate change. As water quality is a critical factor in the health of shellfish reefs, which are in dynamic equilibrium, it can be used as an indicator for assessing the condition of oysters and shellfish beds. In addition, oysters, as building organisms, cause changes in sediment composition over time, which can be monitored as an indicator.

Seagrass beds and salt marshes also play an important role as indicators of ecosystem health, as they store significant amounts of organic carbon that can be measured directly. While carbon, nitrogen and methane cycles may show variations in intertidal areas, they do not differ systematically between plant species or even between salt marshes and tidal flats (Apitz, 2012). Net storage capacity increases as long as sediment is available for deposition and this sediment is permanently supplied with carbon. Therefore, securing and facilitating the deposition of muddy estuarine sediments is crucial to ensure the increased value of the final ecosystem service.

From indicators to decision making

Indicators in ecosystem monitoring are inherently interconnected, and examining a single factor in isolation does not provide a comprehensive understanding of the overall state of the ecosystem. To effectively achieve carbon sequestration and ecosystem restoration goals, it is critical to use indicators that accurately capture the specific characteristics of the target area and align with stakeholder objectives. This requires a holistic understanding of the interdependencies between different factors within the ecosystem. In this context, the so-called Delphi approach (Belgrano et al., 2021) can be a valuable tool for decision-making in the establishment of marine protected areas. The Delphi method usually involves several rounds of surveys or questionnaires where experts provide feedback and revise their initial responses based on the collective responses of their peers. This iterative process helps identify areas of agreement and disagreement among experts, as well as uncertainties and risks associated with different ecosystem services. By synthesising the contributions of different experts, the Delphi approach can provide a solid basis for developing management and policy recommendations related to marine protected areas and monitoring indicators.

Restoration or Compensation

Establishing accurate indicators for ecosystem monitoring and validating their use depends on defining a clear overall objective that is consistent with stakeholders' interests. In the context of marine protected areas, it is crucial to establish a reference point or baseline from which the ecosystem can be assessed. These areas are usually selected in ecosystems that have been previously exploited, so it is necessary to define a 'point zero' to which the ecosystem should ideally return.

In a restoration approach, the goal is to return the ecosystem to the state it was in before human intervention, or to a state similar to that of ecosystems that have not experienced exploitation. The absence of previous human intervention is often considered the target condition for the natural restoration of the area. However, it is important to recognise that to achieve this goal, active intervention may be required to reverse the effects of exploitation and facilitate natural recovery processes. Alternatively, a compensation approach focuses on bringing the ecosystem to a stage where it can compensate for the losses and lack of services resulting from human interaction. Carbon sequestration is an illustrative example of this approach, which focuses on using the ecosystem to store carbon that was previously released. This involves actively encouraging the growth of plants and animals, such as oyster beds and seagrass, to create a negative carbon footprint over time and offset the effects of past human actions.

In order to select an appropriate set of indicators and set relevant parameters and targets, stakeholders must first decide on a restoration or a compensation approach and direct their efforts and investments accordingly. This decision will determine the specific indicators that will be used to monitor progress and guide management actions to achieve the desired results.

CONCLUSION

Effective monitoring and management of marine ecosystems in the Dutch north sea depend heavily on the careful selection of appropriate indicators. The review of existing literature underlines the importance of setting clear objectives and selecting indicators that accurately reflect the specific characteristics of the area and are consistent with the interests of the stakeholders involved. Indicators can vary in terms of their accuracy and the depth of information they provide, so it is crucial to prioritize those that offer meaningful insights into the overall condition of the ecosystem. Certain indicators, such as water quality and sediment measurements, are easily quantifiable and provide direct results that allow monitoring of changes over time. Wildlife monitoring, while a comprehensive indicator of ecosystem health, requires specialized expertise and careful interpretation. Analysis of the carbon cycle, including assessment of carbon sequestration, can provide valuable insights into food web integrity, degradation of wastes and detoxification processes. Among the indicators studied, oyster beds and seagrass beds are proving to be particularly important. Monitoring the condition of these habitats not only provides a direct measure of the success of restoration efforts but also serves as a secondary indicator of various ecosystem services, including the food chain, detoxification processes and carbon sequestration.

To make informed decisions, stakeholders need to recognize the interconnectedness of the different indicators and strive for a comprehensive understanding of the whole ecosystem. Determining the ultimate goal, whether it is to restore the ecosystem to its original state or to compensate for past human impacts, has a significant influence on the selection of indicators and the design of monitoring strategies.

METHODS

Literature Search

Relevant literature was sorted with google scholar and the NCBI databank using the search terms from Table 2. The search for indicators for marine ecosystem services was separated from the research of information and background knowledge about Dutch coastal ecosystems and local restoration efforts and possibilities. Additionally, literature from personal conversations and peer input were used to adapt the review to the target group.

Table 2: Search terms for literature collection. Red marked fields show the finally used terms for further investigation.

Search terms used	Years included	Results Google Scholar	Results NCBI (PMC)
marine ecosystem services indicators	All	525.000	4985
marine ecosystem services indicators north sea	All	282.000	2177
marine ecosystem services indicators north sea coastal	Since 2019	17.300	1750
marine ecosystem services, indicators, north sea, coastal, protected areas, marine spatial planning, synergy and succession, abundance	Since 2019	1.690	4
marine ecosystem services, indicators, north sea, coastal, protected areas, marine spatial planning, synergy and succession, abundance, ecosystem-based management	Since 2019	312	2
marine-ecosystem-services, indicators, north-sea, coastal, wetlands, salt marshes	Since 2019	61	11
marine-ecosystem-services, indicators, validation, valuation, north-sea, coastal,	Since 2019	190	17

Selection Criteria

Feasible literature was chosen by relevance for the Dutch coastal area and the use of indicators to monitor ecosystem health. Several papers were used to create background knowledge about marine ecosystem services and specific papers for detailed information about restoration approaches or specific indication methods were searched and chosen outside of the search terms.

Data Extraction and Analysis

Literature was used in two different ways: General information about marine ecosystem services and the use of indicators was collected and checked in multiple papers, to create a consensus of the terminology and the boundaries of the review. Papers that included specific indicators were skimmed and sorted to filter out relevant indicators for coastal ecosystem services, focusing on the Dutch north sea. Relevant indicators were grouped to fit the logical use for monitoring and easier separation. To make connections and complexity of indicators to different factors of marine ecosystem understandable, an indicator matrix was created, evaluating each indicator by the feasibility to monitor each ecosystem factor.

REFERENCES

Apitz, S. E. (2012). Conceptualizing the role of sediment in sustaining ecosystem services: Sediment-ecosystem regional assessment (SEcoRA). *Science of The Total Environment*, *415*, 9–30. https://doi.org/https://doi.org/10.1016/j.scitotenv.2011.05.060

Atkins, J. P., Burdon, D., & Elliott, M. (2015). *Identification of a Practicable Set of Ecosystem Indicators for Coastal and Marine Ecosystem Services* (pp. 79–102). https://doi.org/10.1007/978-3-319-17214-9_5

Barbier, E. B. (2017). Marine ecosystem services. *Current Biology*, *27*(11), R507–R510. https://doi.org/https://doi.org/10.1016/j.cub.2017.03.020

Belgrano, A., Novaglio, C., Svedäng, H., Villasante, S., Melián, C. J., Blenckner, T., Bergström, U., Bryhn, A., Bergström, L., Bartolino, V., Sköld, M., Tomczak, M., Wikström, S. A., Hansen, A. S., Linke, S., Emmerson, R., Morf, A., & Tönnesson, K. (2021). Mapping and Evaluating Marine Protected Areas and Ecosystem Services: A Transdisciplinary Delphi Forecasting Process Framework. *Frontiers in Ecology and Evolution*, *9*. https://doi.org/10.3389/fevo.2021.652492

Bossier, S., Palacz, A. P., Nielsen, J. R., Christensen, A., Hoff, A., Maar, M., Gislason, H., Bastardie, F., Gorton, R., & Fulton, E. A. (2018). The Baltic sea Atlantis: An integrated end-to-end modelling framework evaluating ecosystem-wide effects of human-induced pressures. *PLoS ONE*, *13*(7). https://doi.org/10.1371/journal.pone.0199168

Cobacho, S. P., Wanke, S., Konstantinou, Z., & El Serafy, G. (2020). Impacts of shellfish reef management on the provision of ecosystem services resulting from climate change in the Dutch Wadden Sea. *Marine Policy*, *119*, 104058. https://doi.org/https://doi.org/10.1016/j.marpol.2020.104058

Grizzetti, B., Liquete, C., Pistocchi, A., Vigiak, O., Zulian, G., Bouraoui, F., De Roo, A., & Cardoso, A. C. (2019). Relationship between ecological condition and ecosystem services in European rivers, lakes and coastal waters. *Science of the Total Environment*, *671*, 452–465. https://doi.org/10.1016/j.scitotenv.2019.03.155

Guerra-García, J. M., Navarro-Barranco, C., Ros, M., Sedano, F., Espinar, R., Fernández-Romero, A., Martínez-Laiz, G., Cuesta, J. A., Giráldez, I., Morales, E., Florido, M., & Moreira, J. (2021). Ecological quality assesement of marinas: An integrative approach combining biological and environmental data. *Journal of Environmental Management*, *286*. https://doi.org/10.1016/j.jenvman.2021.112237

Hattam, C., Atkins, J. P., Beaumont, N., Börger, T., Böhnke-Henrichs, A., Burdon, D., Groot, R. de, Hoefnagel, E., Nunes, P. A. L. D., Piwowarczyk, J., Sastre, S., & Austen, M. C. (2015). Marine ecosystem services: Linking indicators to their classification. *Ecological Indicators*, *49*, 61–75. https://doi.org/https://doi.org/10.1016/j.ecolind.2014.09.026

Hornborg, S., van Putten, I., Novaglio, C., Fulton, E. A., Blanchard, J. L., Plagányi, É., Bulman, C., & Sainsbury, K. (2019). Ecosystem-based fisheries management requires broader performance indicators for the human dimension. *Marine Policy*, *108*. https://doi.org/10.1016/j.marpol.2019.103639

Jickells, T. D., Andrews, J. E., & Parkes, D. J. (2016). Direct and Indirect Effects of Estuarine Reclamation on Nutrient and Metal Fluxes in the Global Coastal Zone. *Aquatic Geochemistry*, *22*(4), 337–348. https://doi.org/10.1007/s10498-015-9278-7

Karydis, M., & Kitsiou, D. (2013). Marine water quality monitoring: A review. *Marine Pollution Bulletin*, *77*(1), 23–36. https://doi.org/https://doi.org/10.1016/j.marpolbul.2013.09.012

Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G., Nel, J. L., Mac Nally, R., Gregr, E. J., Watermeyer, K. E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C. E. R., Etter, A., Roux, D. J., Stark, J. S., Rowland, J. A., … Kingsford, R. T. (2022). A function-based typology for Earth's ecosystems. *Nature*, *610*(7932), 513–518. https://doi.org/10.1038/s41586-022-05318-4

Luisetti, T., Turner, R. K., Jickells, T., Andrews, J., Elliott, M., Schaafsma, M., Beaumont, N., Malcolm, S., Burdon, D., Adams, C., & Watts, W. (2014). Coastal zone ecosystem services: From science to values and decision making; a case study. *Science of the Total Environment*, *493*, 682–693. https://doi.org/10.1016/j.scitotenv.2014.05.099

Schumacher, J., Lange, S., Müller, F., & Schernewski, G. (2021). Assessment of ecosystem services across the land–sea interface in baltic case studies. *Applied Sciences (Switzerland)*, *11*(24). https://doi.org/10.3390/app112411799

Selim, S. A., Blanchard, J. L., Bedford, J., & Webb, T. J. (2016). Direct and indirect effects of climate and fishing on changes in coastal ecosystem services: a historical perspective from the North Sea. *Regional Environmental Change*, *16*(2), 341–351. https://doi.org/10.1007/s10113-014-0635-7

Stebbings, E., Hooper, T., Austen, M. C., Papathanasopoulou, E., & Yan, X. (2021). Accounting for benefits from natural capital: Applying a novel composite indicator framework to the marine environment. *Ecosystem Services*, *50*, 101308. https://doi.org/https://doi.org/10.1016/j.ecoser.2021.101308

Stithou, M., Kourantidou, M., & Vassilopoulou, V. (2023). Sociocultural ecosystem services of small-scale fisheries: challenges, insights and perspectives for marine resource management and planning. *Aquatic Ecosystem Health & Management*, *25*(3), 22–33. https://doi.org/10.14321/aehm.025.03.22

Vogel, C., Ripken, M., & Klenke, T. (2018). Linking marine ecosystem services to the north sea's energy fields in transnational marine spatial planning. *Environments - MDPI*, *5*(6), 1–14. https://doi.org/10.3390/environments5060067