



Inventory of ecosystem components and functions relevant for upscaling low trophic marine (LTM) production in the Dutch part of the North Sea

With a case study on the effect of mussel farming on fish for food production

Author(s): L. Tonk, N. Mavraki, J. Schotanus, J.J. Capelle & M. Poelman

Wageningen Marine Research
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Attn.: Directie SKI
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Summary

Incorporating low trophic marine (LTM) production (seaweed, bivalves) into the food system is considered to contribute to a climate-smart and circular society. In this report the potential role and function of ecosystem-based mussel production systems is addressed by reviewing the ecosystem components and functions of a hypothetical offshore mussel farm in the North Sea with the aim to increase production and ecosystem robustness. In this context 'ecosystem-based' refers to an approach that integrates mussel farming with the entire marine ecosystem, considering the interactions and relationships within it. After reviewing how an offshore mussel farm in the North Sea can affect ecosystem components and functions, the upscaling potential of this mussel production system and how this may affect ecosystem functioning are considered in a case study for a subset of functions.

In total, eleven biotic ecosystem components and fourteen ecosystem functions were identified in a hypothetical offshore mussel farm. From this list the ecosystem functions of mussel cultivation that relate to the effect on fish for food production were selected as a methodological case study for the ecosystem-based potential of offshore mussel cultivation. Fish for food production is significant for both food security and economic benefits in the North Sea. The four functions involved are: (a) fish aggregation devices (FADs), (b) nursery area, (c) feeding grounds, and (d) breeding/production area. Currently, no commercial offshore mussel production exists in the Dutch part of the North Sea. To increase knowledge on the potential implications of upscaling offshore mussel cultivation and indicators, available methods and data were inventoried conducting literature research on the selected functions. Several knowledge gaps were identified. For instance, lack of information on the potential of mussel cultivation to function as FADs in offshore systems and the mechanisms behind the FAD effect of mussel farms. Although fish are thought to use shellfish and seaweed farms as nursery areas, none of the abiotic conditions in the (few) studies available could be compared to the North Sea.

Additionally, the potential function as a nursery for juvenile macro-invertebrates is unknown. On the other hand, the feeding function of mussel cultures for fish has been investigated, however long-term and cumulative effects are unknown. Limited research exists on the potential role of offshore mussel farms as breeding or reproduction areas for marine organisms.

Generally, there is limited information on the long-term impacts of offshore suspended mussel cultures in highly dynamic environments, such as the North Sea and other open waters. Effects of mussel cultures on the environment are site-specific and data on how ecosystem components are affected in the Dutch part of the North Sea is not available. Due to this lack of knowledge of the effects of mussel cultivation on the North Sea ecosystem, the limits of upscaling potential for mussel farms are uncertain. Based on the current information available, potential implications linked to the four functions that are reviewed in this report are mainly identified as "positive" (more food, more habitat) and could potentially lead to increased fish production in the area. However, there may be risks involved which are, due to knowledge gaps, unforeseen at this point. To monitor the effects of mussel farming on the four selected functions several suggestions are made in this report and summarized per function. An important follow-up step in the process towards a robust and resilient approach for upscaling low trophic marine production lies in terms of understanding connectivity between multiple intermediate-scale mussel farms. To facilitate informed decision making when upscaling offshore mussel production the potential implications for the broader ecosystem need to be investigated in further detail, including cumulative effects and implications such as exceeding the carrying capacity or the potential shifts in species composition.

1 Introduction

1.1 Low trophic marine (LTM) production

Low trophic marine (LTM) production is the production of species that naturally feed or depend on energy from low trophic levels such as shellfish and seaweed. The energy source at a low trophic production level can be primary producers (microalgae and seaweed) and/or waste from other animals. LTM production (such as bivalves and seaweed) is considered to contribute to a climate-smart and circular society. This is due to the nutrient efficiency and suitability for further development of this currently extensive and traditional industry.

Inclusion of LTM production in the food system is in line with the food transition of the North Sea: achieving profitable and sustainable fishing that is adapted, in terms of nature and size to wind energy developments in the North Sea driven by climate objectives (OFL, 2018). Increasing food production from sustainable aquaculture is also stimulated by EU policy such as the Blue growth Strategy (EC, 2019). Consequently, the Dutch government has designated large areas in the North Sea for marine food production (National Climate Agreement; Rijksoverheid, 2019).

In the Netherlands LTM production mainly consists of mussels and oysters (and a limited proportion of seaweed production) situated in the Oosterschelde, Lake Grevelingen and Wadden Sea. Currently no offshore aquaculture takes place in the Dutch part of the North Sea, except for some small-scale mussel farming pilots. However, LTM production is expected to expand or relocate to more exposed areas in the Dutch part of the North Sea, though the extent remains uncertain. Estimates for maximum seaweed production in the North Sea are likely limited to several hundred km². Shellfish production capacity has not yet been defined (Jansen et al 2023).

The ministry of Agriculture, Nature and Food Quality (LNV) published a vision on shellfish as a sustainable protein source from the North Sea (Ministerie van LNV, 2023), with the ambition to test, develop and diversify different forms of shellfish production in the coastal North Sea and in offshore wind parks.

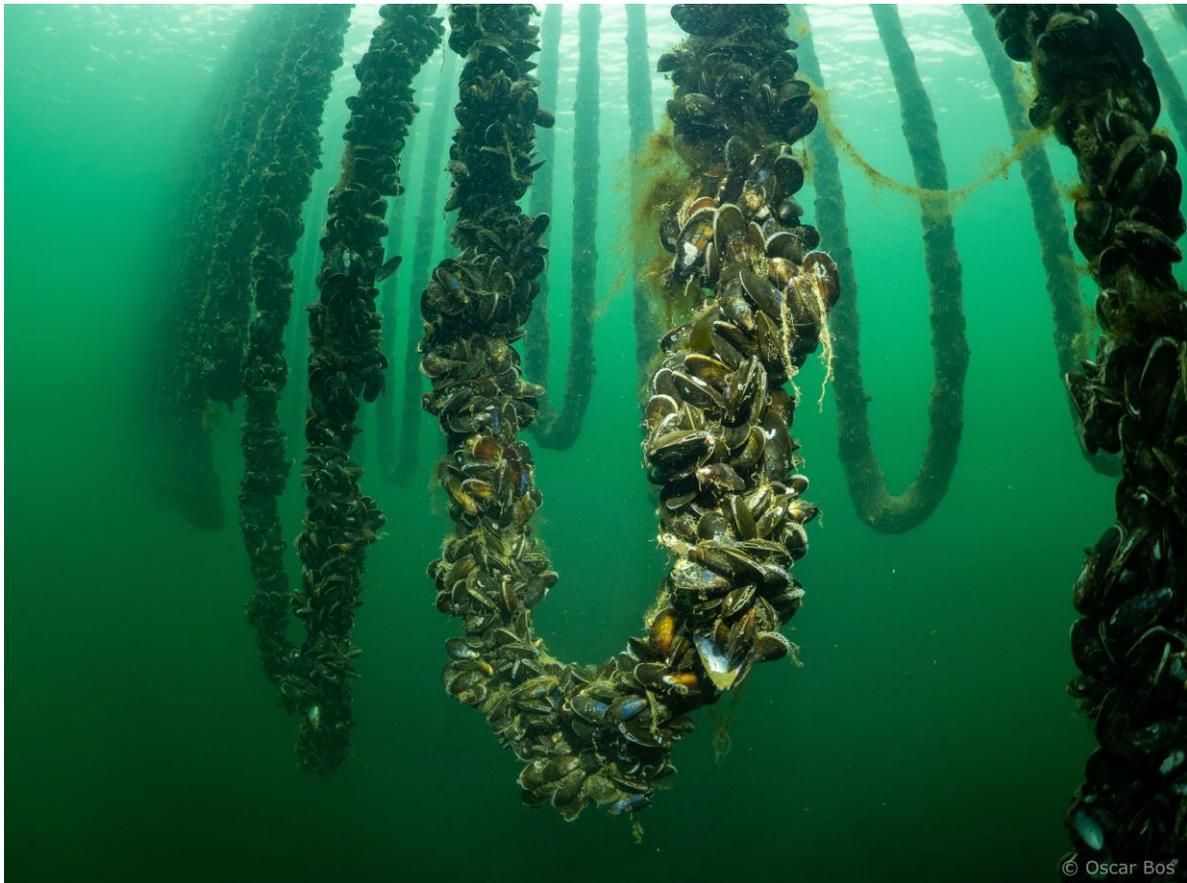


Figure 1.1 Mussel farm in Bruinisse, Eastern Scheldt, The Netherlands (photo Oscar Bos, Wageningen Marine Research).

1.2 Sustainable aquaculture & ecosystem interactions

The potential for offshore seaweed or mussel cultivation in the North Sea has been investigated in several studies (Jansen et al., 2016; Kamermans et al., 2011; Lagerveld et al., 2014). A review of global offshore cultivation experiences published by Kamermans et al. (2016) indicated that, in theory, offshore mussel production in the Dutch part of the North Sea is biologically and technically feasible. At the moment, small scale pilot projects occur or are planned, such as the OOS pilot mussel farm in offshore windfarm Borssele. It is recognized that the ecological boundaries of sustainable exploitation define the limits for large-scale aquaculture, and these cannot be set *a priori*. This implies that upscaling aquaculture activities should go hand in hand with evaluation of ecosystem interactions using data provided in those pilot experiments (Jansen et al 2023).

As our understanding of the impacts that human economic activity has on the environment increases, concepts such as ecosystem-based management (EBM) are developed and implemented in order to maintain ecosystems in a healthy, productive, and resilient condition. EBM is an environmental management approach that recognizes the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation. This approach considers the various components and functions of the ecosystem, and how a LTM production system can interact with, benefit from, and contribute to the overall health and sustainability of the marine environment.

Nature-inclusive design (NID) is a different term that is often used in Dutch policy documents. Nature-inclusive design means that the objective of the plan or project includes nature protection or restoration measures. The concept of nature-inclusive has been introduced by the Dutch government around 2014 to describe how sectors such as urban design and agriculture could take a more ecological perspective (Ministerie van Economische Zaken, 2014; Runhaar, 2017). The definition for nature-inclusive aquaculture systems is often connected with mitigation or reduction of impact. In aquaculture, a nature-inclusive concept often focuses on the enhancement of the biodiversity in and around aquaculture production sites.

Our current focus is an ecosystem-based production system. An ecosystem-based production approach extends beyond nature-inclusive design by considering the broader ecosystem as a boundary such as the effect on fish production. While nature-inclusive design often emphasizes local biodiversity enhancement, ecosystem-based production seeks to add value to the entire ecosystem. This approach includes natural values, synergies, and trade-offs (goods and services), ensuring a comprehensive and sustainable integration of aquaculture within the marine environment. To better understand the ecosystem-based potential of mussel cultivation and its impact on the broader ecosystem the functions related to mussel farming and their effect on fish production are discussed in chapter 3.

1.3 Link to Living lab Voordelta

Worldwide, offshore aquaculture is still limited due to high costs, location suitability and the need for extensive planning and infrastructure (Mascorda Cabre et al. 2021). In the Netherlands, an analysis of technical, economic and ecological boundaries indicated that offshore mussel culture currently holds the highest potential for successful application in the Dutch part of the North Sea (Jansen et al., 2016). However, practical field experience is still lacking.

The Living Lab Voordelta test site (**Figure 1.2**) provides an opportunity to experiment with mussel farming under more exposed conditions and study the potential for upscaling. This site features an experimental suspended mussel culture. The work described in this report is part of the KB34 project Marine low Trophic Production in the Living Lab Voordelta (also see Box 1).



Figure 1.2 Map indicating the location of the Living Lab (red dot) and suspended rope culture in the Voordelta (green area), november 2023 (photo Jacob Capelle, Wageningen Marine Research).

BOX 1. Living Lab Voordelta. To test the practical and technical potential of mussel production under dynamic conditions, an industry-research pilot experimental mussel culture (using suspended ropes) was initiated in autumn 2023 in the Voordelta (RVO finance: Pilot project Hangcultuur Voordelta). The Living Lab Voordelta is a collaborative project between farmers, government and scientists that aims to expand mussel farming into the offshore North Sea by integrating mussel production into the existing ecosystem. This pilot offers multiple opportunities for research to acquire on the ecological, socio-economical and food-safety aspects of offshore mussel farming and the potential for scaling up.

The focus in this report will be on mussel production, while other low trophic systems, such as seaweed, will be considered in other parts of the overarching project "KB34 Marine low Trophic Production in the Living Lab Voordelta" (see below).

1.4 Aim and research questions

The KB43 project 'Marine low Trophic Production in the Living Lab Voordelta' aims to explore how incorporating an ecosystem-based approach affects the scale-up potential of low trophic marine (LTM) production systems. It seeks to understand the implications for production efficiency, socio-economic robustness, performance, productivity, and overall acceptance within future food systems.

The 5 aims of the larger KB43 project that are tightly connected to ecosystem-based production systems are: (1) Evaluation of the role, function and reality of ecosystem-based production systems in climate-resilient production systems; (2) Assessment of socio-economic impacts; (3) Investigation of carrying capacity related to nature-inclusion and mussel production; (4) Development of a food safety by design approach to optimize and generate insights for future applications; 5) Connect to the international community for shared validation.

This report specifically examines the potential role and function of ecosystem-based LTM production systems, focusing on mussel cultivation. The goal is to enhance production and ecosystem robustness while facilitating the expansion of offshore food production in the Dutch part of the North Sea. It includes a description of ecosystem components and functions relevant to scaling up LTM production, with a special focus on the functions related to mussel farming and their effect on fish production. The primary objective is to provide insights into ecosystem-based aquaculture principles and their integration into production designs.

1.4.1 Aim

The aim of this report is: Evaluation of the role, function and reality of ecosystem-based mussel production systems in climate-resilient production systems in the Netherlands.

1.4.2 Research questions

- 1) What are the ecosystem components and functions that are affected by the introduction of mussel cultures in the Dutch part of the North Sea?
- 2) How are functions of mussel farming linked to fish production?
- 3) What are the implications of scaling up mussel farming?
- 4) What are the current knowledge gaps regarding offshore suspended mussel aquaculture in the Dutch part of the North Sea?

1.5 Reading guide

In chapter 2 background information is given about the North Sea. In addition, information on the relevant ecosystem components, the functions involved with mussel production and the linkages between components and functions is provided. In chapter 3 four of these functions that relate to fish production are selected and described in more detail to create insight in the ecosystem-based potential of offshore mussel cultivation. In addition, available methods for data collection relevant to these functions were inventoried by means of literature research. In chapter 4 the implications of upscaling offshore mussel production are investigated. In chapter 5 the conclusions and recommendations are provided.

2 Background

The Dutch part of the North Sea is the largest nature reserve in the Netherlands but is also intensively used as a source of food, energy, sand and other natural resources. It is therefore a challenge to find a balance between the conservation of biodiversity in the North Sea and the use of the area. To provide insights on ecosystem wide impacts a description of the North Sea, the ecosystem components and functions relevant to mussel cultivation are provided in this chapter.

2.1 Description of the North Sea area

The Dutch part of the North Sea (approx. 575.000 km²) encompasses approx. 58,000 km², roughly one tenth of the North Sea's entire area. The average depth of the Dutch Exclusive Economic Zone is 35 m and increases in depth to about 60 m in a northerly direction. The North Sea is a highly complex and open marine ecosystem. The seabed in the Dutch part of the North Sea, mainly consists of a mixture of soft sand and mud substrate, sometimes mixed with gravel. The vast areas with sandy substrate are mostly not flat but organized in waves, which may have lengths longer than 1000 m and heights up to 10 m and the resulting topography is highly influential on species distribution (Damveld et al., 2018). Salinity of the North Sea decreases towards land, where fresh water run off increases annual variability (Janssen et al., 1999). Average salinity is up to 35 ppt, with little annual variation (+/- 0.1 ppt) in areas where coastal effects are small. Annual mean sea surface temperature (over the period 1900-1996) ranges from 9.5-11 °C with larger annual fluctuations closer to the coastal areas. The North Sea is a windy area where calm conditions occur only 1-3% of the time (Quante et al., 2016). In the Dutch part of the North Sea dominant wind direction is southwest, with wind speeds above 7-8 Bft being quite common (**Annex 1**).

Primary production (PP) in the Dutch North Sea varies with highest PP in near shore coastal zones (~400 g C m⁻³, Cadée (1992)). PP decreases at offshore locations (375 g C m⁻³, Bot and Colijn (1996)), and from the southern part (150-200 g C m⁻³, Heip et al. (1992); Joint and Pomroy (1993); Reid et al. (1990)) to the northern part of the North Sea (70-90 g C m⁻³, Steele (1974)). Chlorophyll-a and SPM show strong spatial patterns (**Annex 2**). Secondary and higher production for different functional groups the North Sea were estimated in the 1990s to be around 2.4 g C m⁻³ for macrobenthos (Heip et al., 1992), 1.8 g C m⁻³ for fish (Daan et al., 1990), 10 g C m⁻³ for Meiofauna (Heip & Craeymeersch, 1995), negligible for phytobenthos (Josefson et al., 1993) and with an overall secondary production of 2-20 g C m⁻³ (Fransz et al., 1991).

Economic activities on the North Sea are increasing in the last decades due to the implementation of offshore wind farms. Other large-scale human activities are oil and gas extraction and sand mining, there are also extensive areas reserved for ship routes, anchor locations, and cable trajectories (**Figure 2.1**). In the Dutch North Sea, there are six designated Natura 2000 areas: Dogger Bank, Frisian Front, North Sea Coastal Zone, Voordelta, Vlakte van de Raan and 4 areas that are, or will be protected areas under the Marine Strategy Framework Directive (MSFD): Frisian Front, Central Oyster Grounds, Borkum Reef Grounds and Dogger Bank South.

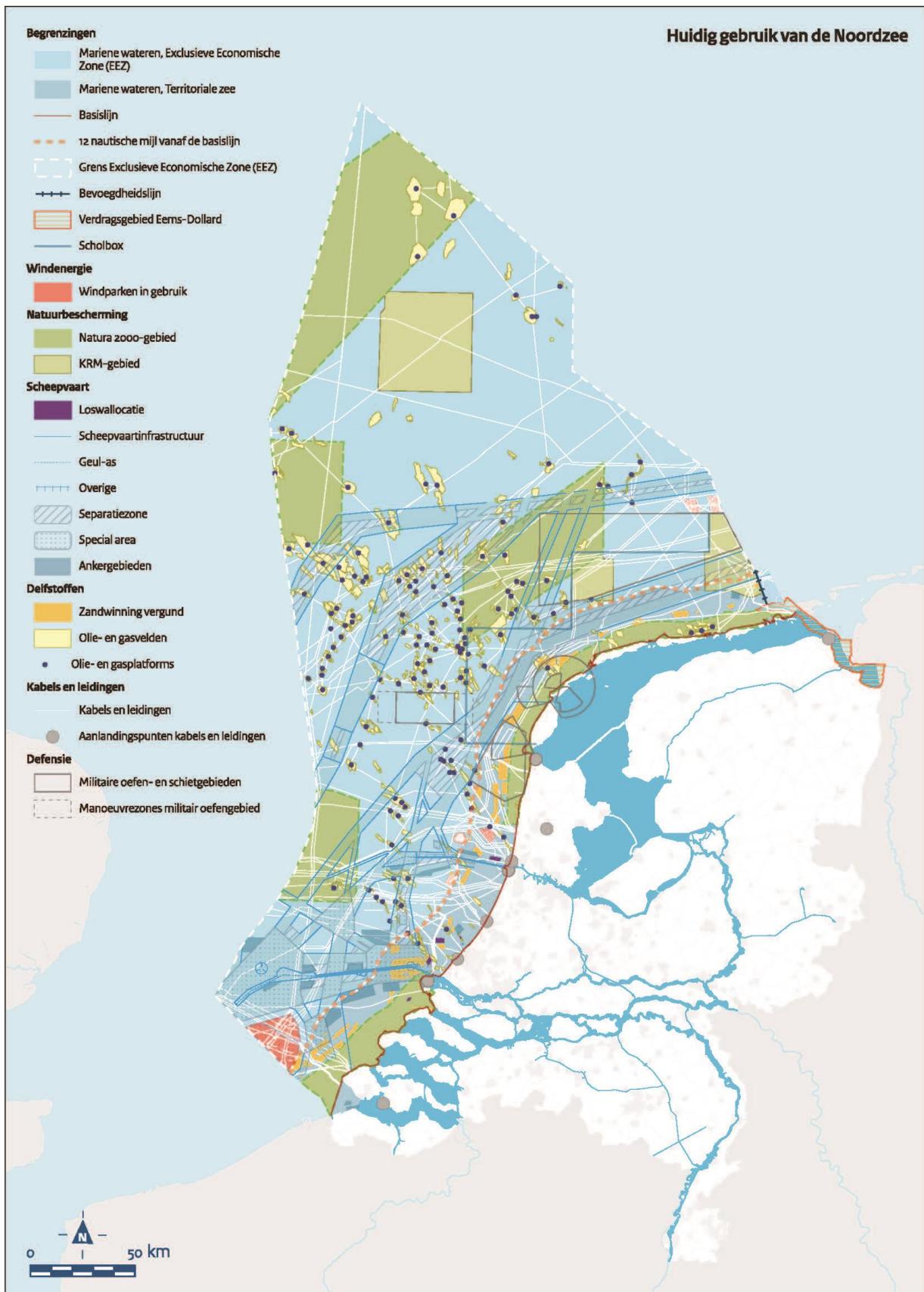


Figure 2.1 Map of economic activities, Natura 2000 areas and MSFD areas in the Dutch part of the North Sea (source: xxx).

2.2 Ecosystem components linked to mussel farming

The marine ecosystem in the North Sea area, where mussel aquaculture takes place, comprises of complexes of organisms within the marine environment. This ecosystem can be divided into various ecological components, which include groups of fauna and flora. These components are identified to assist in gaining a coherent and integrated assessment on interaction within the ecosystem **Table 2.1** details the key biotic components of the ecosystem that require consideration when analysing interactions in mussel cultivation (adapted from Tonk et al. 2021).

Table 2.1: Overview of the ecosystem components that are linked to mussel cultivation and their description (adapted from Tonk et al. 2021).

Ecological component	Subcomponent	Description
Phytoplankton		Photosynthesizing microscopic protists and bacteria
Zooplankton		Heterotrophic (sometimes detritivorous) plankton (unable to swim effectively against currents)
Fouling organisms		Organisms that live on the production structures, such as the ropes and buoys
Seaweed & seagrass		Seaweeds or macroalgae, refers to thousands of species of macroscopic, multicellular, marine algae Seagrasses are the only flowering plants which grow in marine environments
Epiphytes & epibionts		Organisms that live on the mussels in a non-parasitic manner (without extracting nutrients)
Benthos	Endobenthos	Small animals that live buried in the sediment (eg, worms)
	Epibenthos	Small animals that live on top of the sediment (eg, sea urchins, mussels, sea stars)
Pelagic fish	Adult	Adult fish in the pelagic zone
	Juvenile	Juvenile fish
	Larvae	Fish larvae
Dermersal fish	Adult	Adult fish that live and feed on or near the bottom
	Juvenile	Juvenile fish
	Larvae	Fish larvae
Mobile macro-invertebrates		Larger mobile animals without a vertebral column (eg, crabs, lobsters, squid)
Avial animals	Seabirds	Birds that live near the sea and get their food from the marine environment
	Migratory birds	Birds that travel (seasonally) to a different place
Marine mammals		E.g., harbour seals, grey seals, dolphins, harbour porpoises and minke whales

2.3 Ecosystem functions of mussel farming

Ecosystem functions refer to the processes and activities carried out by living organisms within an ecosystem and the effects these activities have on the physical and chemical conditions of their environment (Naeem et al. 1999). These functions are essential for the maintenance and sustainability of the ecosystem. Ecosystem functions can include processes such as photosynthesis, nutrient cycling, decomposition, and the regulation of populations through predation and competition. However, it is important to note that "functioning" means "showing activity" and does not imply that organisms perform purposeful roles in ecosystem-level processes (Naeem et al. 1999). Understanding ecosystem functions is crucial for assessing the impact of environmental changes, human activities, or the introduction of new elements, such as mussel farms, on the broader ecological system. Ecosystem functions also include the set of functions that are linked to benefit human well-being, commonly referred to as ecosystem services (Kremen, 2005). Rather than solely concentrating on ecosystem

services, our approach involves examining the functioning of the entire ecosystem, thereby considering the implementation of offshore mussel farming as an inclusive production system integrated into the ecosystem. Fourteen different functions that could be provided by the introduction of an offshore mussel farm were identified (**Table 2.2** using the systematics of the ODEMM (options for delivering ecosystem-based management) risk assessment framework (Knights et al. 2015) and Aquacross, a project which aims to support EU efforts to protect aquatic biodiversity and ensure the provision of aquatic ecosystem services (Borgwardt et al. 2019).

Table 2.2: Overview of ecosystems functions associated to mussel cultivation.

Ecosystem function	Description
Substrate provisioning by the artificial structures	Attraction of species towards artificial structures linked to the cultures (e.g., anchors)
Substrate provisioning by the mussel introduction	Attraction of species towards the biotic parts of the cultures (I.e., mussels)
Feeding grounds	Offshore mussel cultures acting as food source for other species (e.g., fish)
Nursery areas	Potentially more juvenile individuals underneath the suspended mussel cultures than adult ones
Refuge	Shelter between the anchors, mussel lines and other parts of the structure against predators
Breeding/Reproduction areas	Potentially some species could use these structures to reproduce
Biofiltration	Active filtration/Clearance of the water column by mussels, feeding on particles, like phyto- and zooplankton
Production/Release of organic matter	Release of organic matter in the water column (incl. nutrients).
Fish aggregation device	Provisioning of artificial structures that attract marine life due to the thigmotactic response, where fish move towards structured rather than bare areas
Sediment enrichment	Due to the biodeposition activities, sediment is enriched with faeces, pseudo faeces and shells
Sediment stabilization	Sediment underneath the cultures may become coarser, which increases stability
CO₂ release	Net release of CO ₂ from seawater to atmosphere
Stepping stones for non-indigenous species	Habitat provisioning and translocation possibility for non-indigenous species

2.4 Links between ecosystem components and functions of mussel farming

The linkages or interactions between the different ecosystem components described in section 2.2 and the ecological functions of mussel cultivation described in section 2.3 are visualized in **Figure 2.2**. A total of 46 interactions (impact-chains) were identified. The function “feeding grounds” resulted in highest number of links to ecosystem components (8 out of 13 ecosystem components). Other ecosystem functions with 6 or more links to ecosystem components include “refuge”, “biofiltration” and “production/release of organic matter”. In contrast, “sediment enrichment” and “sediment stabilization” are both linked to only one ecosystem component, namely benthos. In addition, the ecosystem component benthos had the most extensive links the different ecosystem functions.

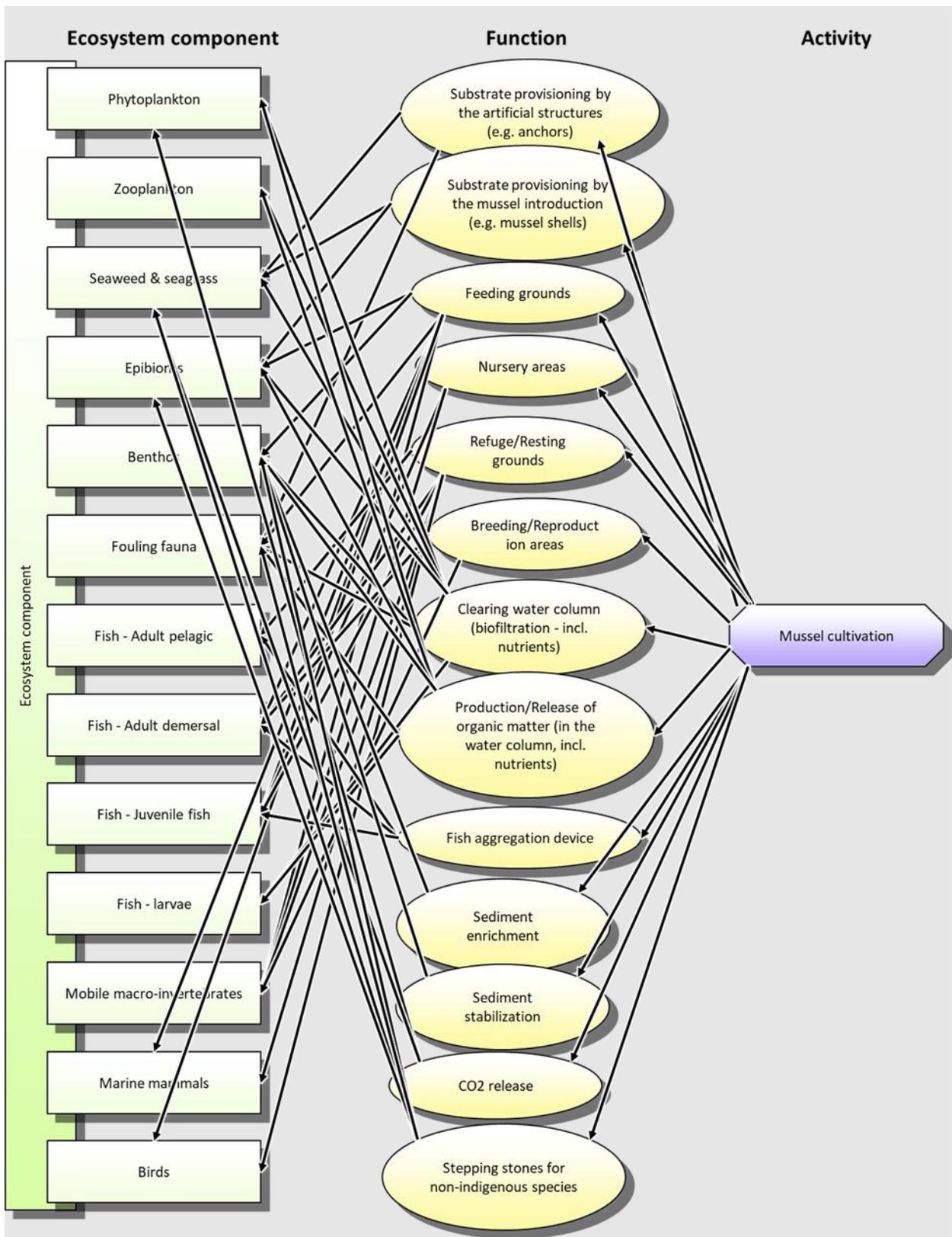


Figure 2.2 Framework representing the interactions between ecosystem components, functions and activity. The interactions are indicated in arrows. This figure has been constructed using the WMR scoping tool (De Vries et al., 2013).

3 Functions of mussel farming linked to fish production

3.1 Approach

To better understand the ecosystem-based potential of mussel cultivation and its impact on the broader ecosystem, we have selected specific functions from the list in **Table 2.2** for a more detailed analysis. Our focus is on functions related to fish production due to its significance for both food security and economic benefits in the North Sea. Sustainable fish production in the North Sea is an important source of food and income. The total landing (live weight) of the Dutch fleet was 34 million kg in 2023. This is 29% lower than in the previous year (48 million kg), mainly due to a lower fishing effort as a result of the fleet reduction (Agrimatie, 20224). Offshore wind farms (OWFs) occupy significant space, which can negatively impact traditional fisheries, such as trawling, while also presenting opportunities for low trophic marine (LTM) production, including mussel cultivation, and new or adapted fishing techniques. This multifaceted use of space underscores the need to explore how mussel cultivation might affect fish production and the broader ecosystem. In this report, we have chosen to examine four ecosystem functions directly related to fish production to provide insights into how mussel cultivation could influence food production within the broader ecosystem. The selected functions are:

1. Fish Aggregation Device (FAD)
2. Nursery Area
3. Feeding Grounds
4. Reproduction Area

These functions were selected because they have significant potential to affect food production (fish production) and have not been thoroughly studied in relation to mussel cultivation in the Dutch part of the North Sea. They offer a different perspective compared to traditional biodiversity-focused studies and highlight the broader impacts of mussel cultivation on food systems. These four functions and their interactions with different ecosystem components that are affected are visualized in **Figure 3.1**. To provide insight into the implications of mussel cultivation to the broader ecosystem the functions and linkages have been described in further detail in paragraph 3.2. Available methods for data collection relevant to these functions were inventoried by means of a literature research. A recommendation of suitable methods or methods that need to be developed to measure the effect of mussel cultivation on ecosystem functions was also provided.

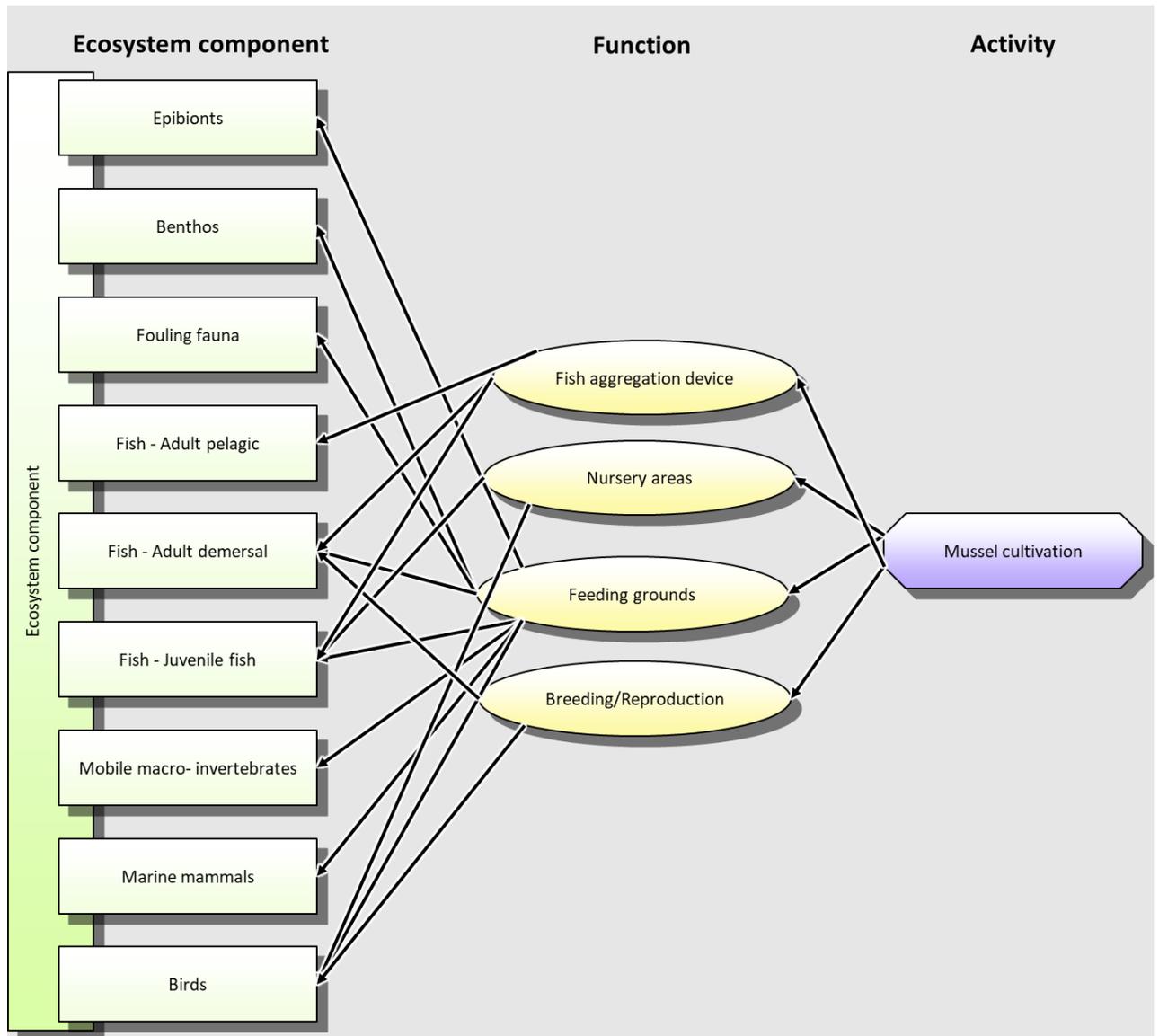


Figure 3.1 Framework representing the interactions between ecosystem components, four selected functions and activity. The interactions are indicated in arrows. This figure has been constructed using the WMR scoping tool (de Vries et al., 2013).

3.2 Selected functions of mussel farming with a focus on fish production

3.2.1 Fish aggregation device (FAD)

Description

Suspended mussel cultures may function as fish aggregating devices (FADs). FADs are artificial structures in the natural marine environment that attract marine life due to a phenomenon known as a thigmotactic response, where fish tend to “move towards structured rather than bare, featureless habitats (Brickhill et al., 2005)”. Apart from simple thigmotaxis, mechanisms behind attraction may include (a) increased feeding opportunities and (b) increased shelter from predators, which are provided by the increased structural complexity of the marine environment (Brickhill et al., 2005). The physical three-dimensional structures of suspended mussel cultures may act as fish aggregation devices attracting multiple fish species and sizes, including pelagic and demersal species as well as juveniles (Clavelle et al., 2019; McKindsey et al., 2011; Morrisey et al., 2006; Underwood & Jeffs, 2023).

Available knowledge and data

For the relevant ecosystem components (adult-pelagic, adult-demersal and juvenile) there is no data available on the potential function of offshore mussel cultivation systems as FADs in the North Sea. In a study in a New Zealand mussel farm, some pelagic species were observed to pass through the farms. However, no evidence was provided that these fish make regular use of the farms (Morrisey et al., 2006). The same study showed that mussel lines were mainly occupied by small local demersal fish species (Morrisey et al., 2006). In a review of ecological interactions of offshore mussel farms by Mascorda Cabre et al. (2021) offshore farm observations in France and New Zealand report how the introduction of mussels to the area was followed by an increase in dominant fish species densities. Although offshore mussel farms are thought to act as FAD's, the mechanisms behind the FAD effect of mussel farms are still uncertain. It is not known whether it is due to the fish being attracted or enhanced by the added physical structure, the shift to a more complex hard substrate, the farmed product itself, the associated organisms, the refuge given by the mussel matrix or a combination of these (Mascorda Cabre et al., 2021). In conclusion, a knowledge gap exists of the potential of mussel cultivation systems as FADs in offshore systems.

Potential research methods

To assess whether mussel cultivations may act as FADs, fish diversity and abundance should be measured both underneath/near the mussel culture and at control areas. The ecosystem components that are potentially affected by this function are pelagic and demersal fish species as well as juvenile fish. There are several ways to measure fish assemblage and abundance, such as diver visual census, netting and the use of camera techniques for example the use of remote underwater video systems (RUV). Hydroacoustic methods were also successfully implemented to evaluate the ecological impact of a mussel culture on the ecosystem by monitoring fish schools as well as individual fish (Brehmer et al., 2003). In the offshore setting of the mussel farm, the use of remote underwater video systems appears to be the most promising choice. This can be combined with baited camera traps (BRUV). An unbaited midwater video system for semi-automated monitoring of mobile marine fauna proved a cost-effective remote monitoring tool for biological data acquisition at offshore mussel farms (Sheenan et al., 2020). The use of soundscapes to monitor fish communities is another potential method to investigate further (Carrico et al., 2020).

3.2.2 Nursery area

Description

Fish are thought to use shellfish and seaweed farms as nursery areas (larger numbers of juveniles compared to adults) to settle and recruit. Settlement is defined as the arrival of new individuals from the pelagic habitat, and recruitment as the number of individuals surviving arbitrary periods of time after settlement. However, there is little published evidence to support this assumption.

Available knowledge and data

In a few published studies, the use of shellfish farms as nursery habitat for fish has been investigated (in Underwood & Jeffs, 2023). Some fish species are known to settle and recruit directly into non-fed aquaculture structures, utilizing the structures as nursery habitats (Underwood & Jeffs, 2023). However, in none of these studies the abiotic conditions compare with the situation in the North Sea, where mussel farms provide habitat by adding three-dimensional structure in a soft sediment environment (as opposed to mussel farms in rocky shore habitats). Similarly, mobile macro-invertebrates may use mussel farms as a nursery area. Underwood & Jeffs (2023) observed a wide range of mobile fauna with a dominance of benthic juvenile crustaceans in the mussel farm, including many crabs. Investigations into the nursery function of mussel farms for mobile macro-invertebrates are absent. However, artificial hard substrates, such as wind turbines, shipwrecks and oil platforms are known to provide habitat and attract large crustaceans (Coolen et al., 2020; Krone et al., 2013; Page et al., 1999). The finding of high amounts of small individuals (carapax width: 10-60 mm) at wind turbines indicated that the upper construction parts of the turbines may act as nursery ground and artificial larvae collector for brown crab (*Cancer pagurus*) (Krone et al., 2013b, 2017). A knowledge gap exists of the potential of mussel farms to act as nursery habitats for juvenile fish and macro-invertebrates in offshore soft sediment environments.

Potential research methods

Methods for sampling fish settlers and recruits include light traps, towed nets and diver visual surveys. Light traps, however, are biased towards capturing fish with a strong phototaxis. Towed nets can't be used in between structures and the small size and cryptic behaviour of settlers make diver visual surveys ineffective (in Underwood & Jeffs 2023). Standard monitoring units for the recruitment of fish (SMURFs) are commonly used as a reliable method to measure temporal and spatial variability in fish settlement and recruitment, including among different habitats (Arney et al., 2017; Ben-David & Kritzer, 2005; Valles et al., 2006). SMURFs generally consist of rolled plastic mesh filled up with folded plastic sheet material, creating a habitat for small fish whilst keeping out the larger fish (**Figure 3.2**). Several studies indicate that these monitoring units for fish recruitment are less discriminatory than the above-mentioned methods as they attract the settlers and recruits of a range of fish species from within the sampled area (Ammann, 2004; Valles et al., 2006). It is important to delineate between the settlement and recruitment functions of aquaculture structures because aquaculture structures may only act as an attractive habitat for recruits that have settled elsewhere. By distinguishing between settlement and recruitment, the true extent of the contribution of aquaculture habitats to the overall production and biomass of wild fish populations can be quantified (Barrett et al., 2022; Theuerkauf et al., 2022).

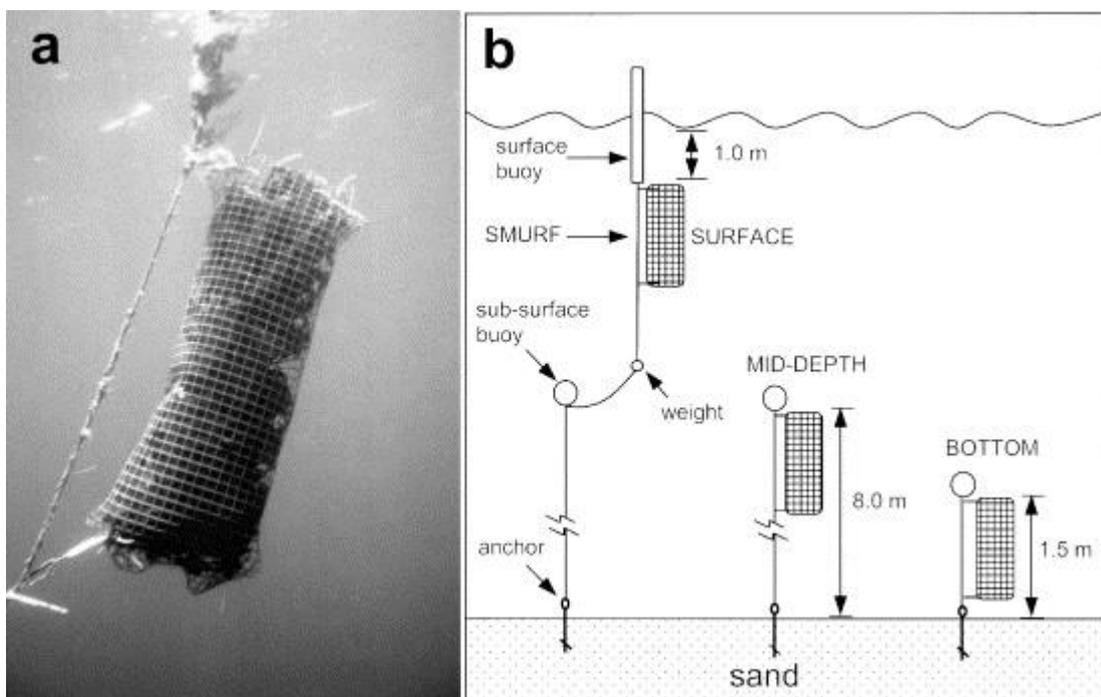




Figure 3.2: (a) Portable artificial substrate used as a standard monitoring unit for the recruitment of fish (SMURF) in Monterey Bay, CA, USA. (b) Method of deployment for SMURFs used in the depth level experiment (not to scale). (c) Different type of standard monitoring unit for the recruitment of fish (SMURF). Source: Figure a and b are taken from Ammann (2004) and figure c from Arney et al. (2017).

3.2.3 Feeding grounds

Description

Suspended mussel cultures and their products may act as feeding grounds for multiple ecosystem components, which are attracted to the structures and exploit either the suspended mussels or the fallen shells and biodeposits as food.

Available knowledge and data

The feeding function of mussel cultures has been largely investigated, still observations are brief snapshots in time and space and long-term and cumulative effects should also be studied. Adult fish individuals feed on the suspended mussels (Ackefors & Haamer, 1987; Laffaille et al., 2001; McKindsey et al., 2011), while macro-invertebrates, such as crabs and lobsters, feed on the fallen mussels and the attracted soft-sediment fauna (Freire & Gonzalez-Gurriaran 1995; Drouin et al., 2014; Inglis and Gust, 2003; Sheehan et al., 2019). Benthos and epibionts utilize the organic material that accumulates underneath the cultures (D'Amours et al., 2008), while some seabirds could directly feed on the hanging mussels and their epifauna, which may also colonize the artificial structures of the cultures, such as buoys (Roycroft et al., 2007, Scridel et al., 2020).

Potential research methods

Methods for investigating the feeding ground function of mussel cultures include abundance measurements and diet compositions nearby mussel farms compared to control areas. For example, electronic tags to track movements related to prey densities could be used as a technique for the feeding ground function (Sims, 2003). Furthermore, stomach content analysis could be used to determine diets, identify the degree of prey selection and compare this with prey availability (Patricio Ojeda & Dearborn, 1991). However, these methods are applicable only for larger individuals, such as fish, birds, macro-invertebrates. Stomach content analysis has further limitations, since it provides a snapshot of what an individual has been feeding on the last few hours, therefore already digested material cannot be identified. Stable isotope analysis and fatty acid techniques can provide an even more accurate estimation of the diets of multiple components (Puccinelli & McQuaid, 2021). These techniques may be applied to different sized individuals (from very small to large) and provide

information on the long-term (up to 6 months) diet composition of individuals. The only limitation to these advanced methods is that the entire food web should be sampled in order to get a complete picture of the diet preferences. Therefore, the combination of stable isotope and stomach content analyses has often been used as an approach that can provide a complete picture of the feeding ecology of multiple species and can improve the interpretation of aquatic food webs (Parkyn et al. 2001).

3.2.4 Breeding/Reproduction area

Description

Limited research has delved into the potential role of offshore mussel farms as breeding or reproduction areas for marine organisms. There is a plausible connection between the artificial 3D structure of mussel farm habitats and the structural complexity observed in rocky reef habitats.

Available knowledge and data

Analogous to rocky reef environments, the three-dimensional configuration of mussel farms offers refuge, hiding spots, and suitable surfaces for the attachment of eggs and juvenile organisms. This structural complexity, as suggested by Underwood & Jeffs (2023), may contribute to the reproductive success of specific fish species. Additionally, there is evidence suggesting that the presence of mussels can indirectly impact reproduction. When mussels descend to the seabed, they create a concentrated food source. This food source is believed to potentially augment the reproductive output of starfish by promoting growth and accelerating gonad maturation rates. Furthermore, the aggregation behaviour of starfish triggered by the concentrated food source is proposed to potentially enhance fertilization success, a factor influenced by the proximity of reproductive adult starfish (Inglis & Gust, 2003).

Potential research methods

Methods for investigating the breeding and reproductive function of mussel cultures include monitoring breeding behavior and the presence of early reproductive stages. Observing and documenting the breeding behavior exhibited by the ecological component within the mussel farm environment. This includes closely monitoring activities such as mating rituals, courtship displays, and other behaviors related to the reproductive process. This type of fish behavior can be monitored using high-resolution activity sensors (Burnett et al., 2023). In addition to behavioral monitoring, it is possible to assess the presence of reproductive stages such as eggs, larvae or juvenile organisms within the mussel culture area. Of the monitoring methods mentioned under 3.2.2 Nursery areas a combination of light traps and SMURF's could be used to include eggs and larvae from the water column as well as those attached to substrate in an offshore mussel farming setting. Monitoring the presence of eggs provides insight into the onset of the reproductive process, while the observation of larvae and young organisms provides valuable information about successful reproduction and survival of early life stages.

4 Upscaling scenarios (and implications) in the Dutch part of the North Sea

Some effects of offshore mussel farming may shift from positive to negative. For instance, larger-scale farms could exceed the carrying capacity of the marine ecosystem, potentially depleting primary production or obstructing migration routes for fish and mammals. Consequently, knowledge is needed on the potential implications of upscaling offshore mussel cultivation and on the relevant indicators that are involved.

In this section the implications of upscaling low trophic marine production in the Dutch part of the North Sea in a circular and climate-neutral way are investigated. Suspended culture systems are predicted to be applied for the upscaling of low trophic marine production. These systems provide hard substrate in the pelagic zone, which often does not occur naturally in the existing ecological habitat. To achieve conservation goals and to optimize production effectivity, it is essential to adopt an ecosystem-based approach to production, which optimizes large-scale marine food production. In the previous chapter we described the different ecological functions of mussel cultivation, with a focus on four functions related to fish production: 1) fish aggregation device, 2) nursery area, 3) feeding grounds, and 4) reproduction area.

In this chapter we concentrate on three hypothetical scenarios of mussel cultivation of different scales (small, intermediate, and large-scale) in the Dutch part of the North Sea and their potential impact on the forementioned four functions. Additionally, we explore how upscaling influences carrying capacity and factors related to fish production, such as habitat provision and migration.

4.1 Context

Currently no offshore mussel cultivation takes place in the Dutch part of the North Sea. The potential has been investigated in several studies (Jansen et al., 2016; Kamermans et al., 2011; Lagerveld et al., 2014). A review of global offshore cultivation experiences, published by Kamermans et al. (2016), indicated that, in theory, offshore mussel production in the Dutch part of the North Sea is biologically and technically feasible.

The mussel sector in the Netherlands has the long-term goal to double its current production (estimated at 20,000-40,000 tons, Eastern Scheldt and Wadden Sea combined) and is investigating the feasibility of locating this additional production in the offshore environment of the North Sea (Bellaart et al., 2023). Offshore mussel farming (on suspended longlines) is known to have several impacts on the environment (McKindsey et al., 2011). Commercial-scale farming of mussels interacts with the environment and may affect the ecosystem by altering the nutrient compartments, trophic structure, and energy flow (Jansen et al., 2018). Despite these potential impacts, the specific ecological effects on the North Sea ecosystem remain largely unstudied.

Given increasing concerns about the conservation objectives for marine ecosystems, it is essential that this knowledge gap is closed in order to determine whether offshore mussel production can be performed sustainably. Understanding the environmental impacts of offshore mussel production will be essential to support informed decision making and mitigate potential negative effect on the ecosystem.

4.2 Theoretical comparison between mussel cultivation scenarios of different scale

In an investigation of large-scale offshore low trophic marine production in the North Sea, a theoretical evaluation of three different scales of (ecosystem-based) mussel production was performed through an expert analysis of set of criteria (**Table 4.1**, Bellaart et al., 2023). The scenarios were:

- (a) Small scale: A system with very low density mussels in which little drop-off of shells and mussels is produced, not reaching the reef formation threshold.
- (b) Intermediate-scale: Similar to existing offshore mussel farms where sufficient drop-off is produced to allow reef formation under the lines.
- (c) Large-scale: High mussel density exceeding the carrying capacity of the North Sea ecosystem.

The main question in this evaluation was whether the different scenarios could be considered compliant with the principles according to ecosystem-based management, meaning a production system, which includes natural values in a local production setting considering a broader systematic approach to create added value for the ecosystem.

The evaluation focused on potential benefits such as biodiversity, interaction with native species, reef formation, and abiotic impacts. It did not consider broader implications such as biodeposition, biofiltration, or the creation of nursery habitats. The small-scale scenario in combination with current hydrodynamics of the North Sea and low drop-off was not expected to enhance the ecosystem or form a long-term stable environment. The latter was also not predicted for the large-scale scenario due to exceeding the carrying capacity. Most ecological benefits to the system were expected from the intermediate scenario including sufficient reef formation in this scenario to increase abundance in multiple functional groups, and increased water quality due to high filtration capacity, while staying within the limits of primary production needed in the system (**Figure 4.1**).

Although the scenarios described are highly generalized and do not include a comprehensive assessment of the various implications of upscaling mussel production, this effort does point out which criteria could be considered and that an optimum scale can be achieved based on the criteria chosen. It also shows that in theory, intermediate-scale mussel production could be considered compliant with the ecosystem-based management approach, but this will be site- and ecosystem-specific. The next step would be to determine the boundaries between intermediate and large-scale scenarios.

Table 4.1: Evaluation of different scales of mussel production. Source: Bellaart et al., 2023.

Dimension	Criteria	Small-scale	Intermediate-scale	Large-scale
System thinking	The system enhances the ecosystem structure through interactions with the native species	Yellow	Green	Red
	The system enhances the ecosystem through abiotic services	Yellow	Green	Red
	The system provides services to the surrounding areas	Yellow	Green	Red
Synergy	The system enhances the natural processes that it uses (e.g. energy flows, nutrient circulation)	Red	Green	Red
	Use of ecosystem is balanced with conservation of biodiversity	Red	Green	Red
	The system has no negative impacts to the ecosystem over different time scales (lag effects)	Green	Green	Red
Long-term	The system creates a long-term stable environment	Red	Green	Red
	The system supports conditions for different succession levels in the ecosystem	Yellow	Green	Red
Ecosystem inclusive?		No	Yes	No

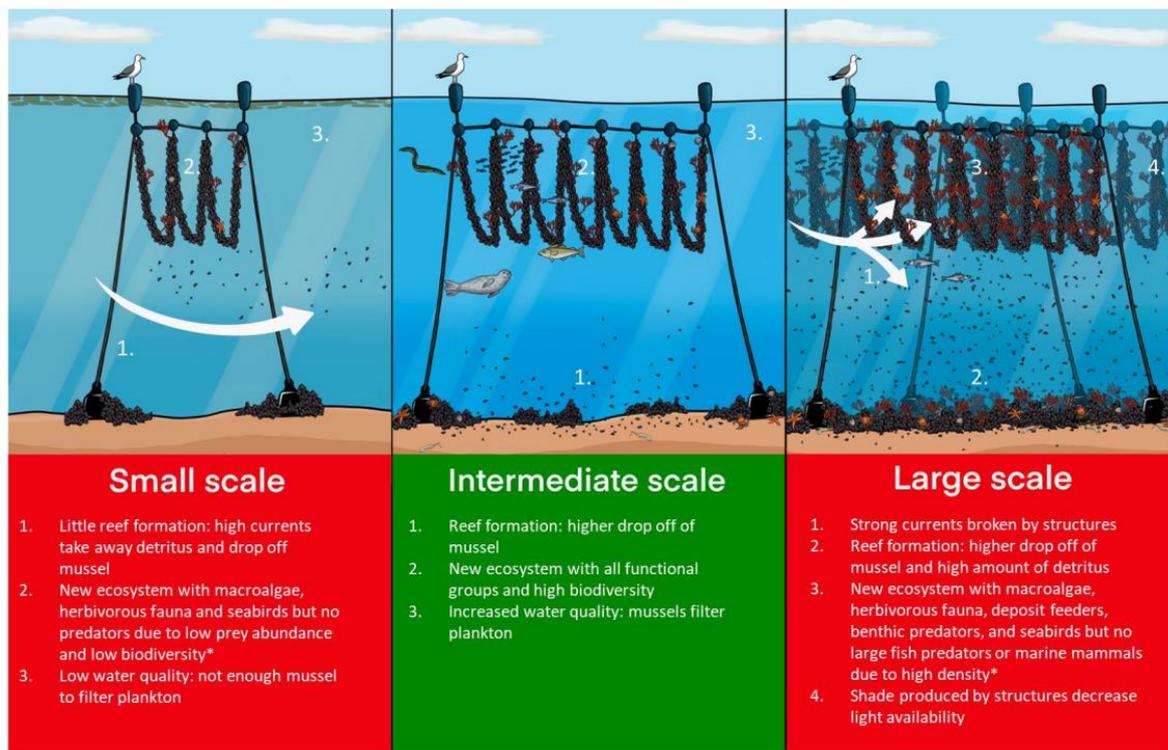


Figure 4.1: Three scenarios of mussel production that differ in scale in the Dutch North Sea (Source: Bellaart et al., 2023).

4.3 Functions related to fish production under the upscaling scenario

In chapter 3, four key functions related to fish production were described: Fish Aggregation Devices (FADs), feeding grounds, nursery areas, and breeding/reproduction habitats. These functions are crucial for understanding their direct impact on fish populations and are most likely influenced when the scale of the production system is enlarged. Other aspects that have the potential to play a significant role in fish production when considering the upscaling of mussel cultivation are habitat provision and migration patterns. In this chapter we briefly touch on these additional factors and how they are influenced by upscaling. Additionally, the concept of carrying capacity is included. Carrying capacity refers to the maximum amount of production an ecosystem can sustain without detrimental effects. Understanding how upscaling impacts carrying capacity helps in assessing the long-term viability and sustainability of enhanced fish production through mussel cultivation. Finally, potential additional methods to measure ecosystem-wide effects are shortly discussed.

4.3.1 Relevant upscaling aspects for fish production

Habitat provision

When considering the four selected functions related to fish production under the umbrella of the three scenarios of different scales, we mainly identify positive effects on (adult) fish species with increasing habitat complexity. This includes increased food availability, the development of more natural reefs suitable for nursery and breeding grounds, and the amplification of mussel cultures' FAD capabilities through the introduction of additional 3D structures. These benefits (increased feeding efficiency, provision of shelter, reproduction areas, etc.) could potentially lead to increased fish production in the area. Attraction of fish species to artificial reefs, such as mussel cultures, could lead to higher production, since they are not mutually exclusive. The scale of production depends on the surrounding habitat and the environmental carrying capacity (Brickhill et al., 2005). Artificial habitats have been previously linked to increased benthic fish production due to the increased food availability and low

fishing mortality (Cresson et al., 2019). Fish production can only be supported when the artificial habitats contribute to an increased biomass and/or abundance of fish.

Migration

Offshore fish farms have been observed to alter the migration patterns of fish by (i) preventing migration by changing the distribution of species, (ii) modifying migration patterns for migration stops at the fish farming system, and (iii) changing spawning migratory behaviour of such species (Callier et al., 2017). Mussel cultures may potentially influence migration patterns by attracting migrating fish that could temporarily feed on the organisms growing on the structures, something that could alter the distribution of these species or act as physical barriers for larger pelagic fish species or marine mammals. Therefore, there might be risks involved if migratory patterns of certain fish species are affected. The habitat provisioning by aquaculture structures could attract migratory fish species and could indirectly contribute to small-scale fisheries (Skelton et al., 2021). Coastal mussel cultures may provide the same function as these structures however there is no evidence for this. The role of offshore reef systems as a migratory stop is even less known. We do know that hard substrate species can make use of the habitat provided by Offshore Wind Farms (OWFs) in the North Sea and use it as a steppingstone to expand northwards (Glasby et al., 2007; De Mesel et al., 2015 in Degraer et al., 2020). The Atlantic cod is highly attracted to OWFs, where it shows increased site-fidelity (Reubens et al., 2013) and feeds on the fouling fauna attached on the monopile foundations for a long-period of time (Mavraki et al., 2021). This demersal fish species migrates to northern locations when it reaches the breeding age.

Carrying capacity

With the upscaling of mussel cultivation and implications for the ecosystem, exceeding the carrying capacity is usually the first aspect that raises concerns. Here we define the ecological carrying capacity for shellfish production in the North Sea as the quantity of shellfish that can be farmed in the Dutch Continental Shelf (NCP) without noticeable (negative) consequences for the ecosystem. Mussels are filter feeders and depend on phyto- and zooplankton as a food source. Phytoplankton is the basis of the marine food web and is consumed by both wild and cultured shellfish but also by other organisms, such as zooplankton, which serves as food for benthic animals and fish. Due to this extensive filter-feeding, mussels influence the carrying capacity of the ecosystem, since they control the “top-down” abundance of the planktonic community (Alonso-Pérez et al., 2010; Lehane and Davenport, 2002). The carrying capacity of the ecosystem is mainly determined by the amount of food (mainly phytoplankton but also zooplankton) available. Therefore, cultivated stocks compete with naturally occurring shellfish and other filter feeders for the available food and directly influence the low trophic levels. Above a certain grazing pressure (too many mussels), the number of phytoplankton is too low to sustain primary production despite the availability of sufficient nutrients. In this situation, the carrying capacity has been reached or exceeded resulting into little food for growth of shellfish and other organisms that depend on it with cascading effects to higher trophic levels such as the fish community (**Figure 4.2**). Before carrying capacity is reached a positive feedback mechanism may occur, through the excretion of ammonia by mussels, which is a food source for algae (Jansen et al., 2018).

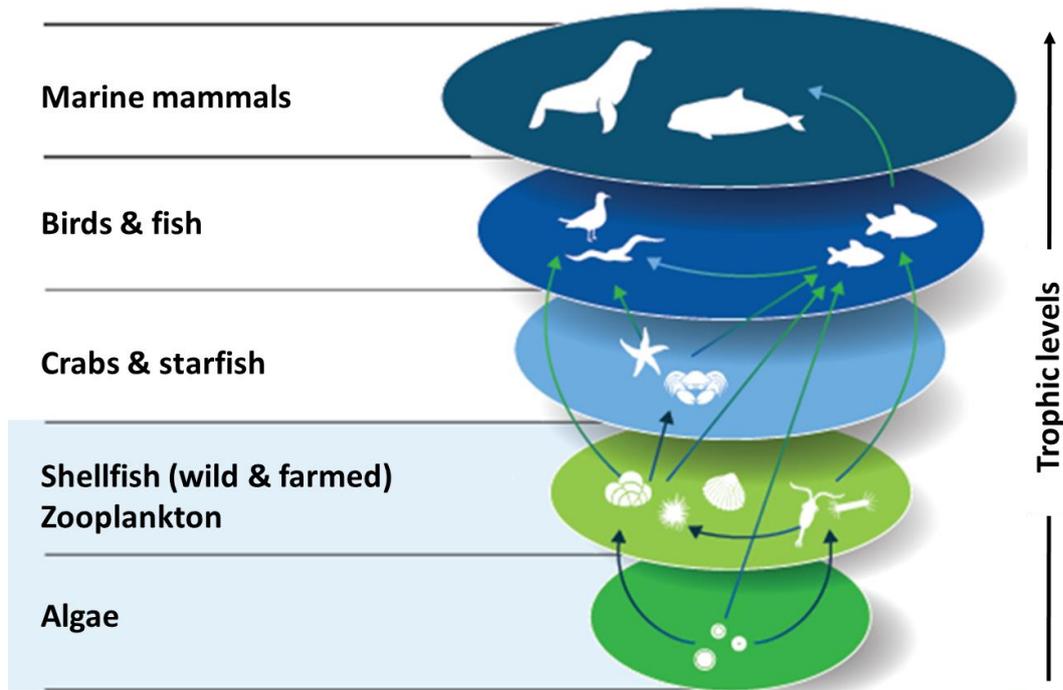


Figure 4.2: Schematic presentation of the marine food web starting from the lowest trophic level at the bottom to higher trophic levels upwards. Interactions within and between levels are indicated by arrows. This figure is adapted from Wijsman and Jansen (2019).

A production capacity of up to 400,000 – 600,000 tons was estimated feasible at cultivation sites in the Dutch North Sea taking into account space availability and ecological constraints of mussels (Foekema et al., 2024). This is approximately 10-15 times more than current shellfish production in the Netherlands but is calculated for the total production volumes (including mussels on other habitats such as wind parks). It needs to be underlined that these numbers should only be regarded as an initial indication and extensive (model) calculations are necessary for a better estimate of this maximum production capacity, as well as the effects of the size of cultivation sites (small, intermediate or large scale) on local conditions. The further implications of such large-scale mussel production, aside carrying capacity, need thorough consideration to avoid large-scale negative impacts on the ecosystem. In particular, the nutrient supply that fluctuates during the year is an important uncertainty as well as the pressure on the nutrient supply from the naturally occurring filter feeders. Moreover, the increase in hard substrate (filter feeding) species abundance on structures adds to the naturally occurring organisms and should also be taken into account. Mussels are considered prominent colonizers of such structures. The reduction in regional annual primary productivity in the North Sea is estimated at 8%, based on a model incorporating mussel colonisation on wind turbine foundations in OWFs in the southern North Sea (Slavik et al., 2019).

4.3.2 Methods to measure ecosystem-wide effects

Assessing the ecological status of an area, by means of species richness, diversity and abundance and certain species characteristics does not provide the complete overview of ecosystem services and how these are impacted by human activities such as aquaculture. When biodiversity is affected by aquaculture this may result in functional shifts when species with certain traits are replaced by other species with different traits and thereby affecting the ecosystem. There is a need for clearer impact assessments and guidance on what needs to be monitored to evaluate environmental impacts (Mascorda-Cabre et al., 2023). Biological traits analysis (BTA) can be a valuable tool for measuring ecosystem functioning in which a series of life-history, morphological and behavioural characteristics of species present is used to indicate aspects of their ecological functioning (Naeem et al., 1999). BTA provides a link between species, environments and ecosystem processes, and can be useful for the investigation of anthropogenic impacts on ecological functioning (Bremner et al., 2006). BTA has been widely applied to understand the functional response of biological communities to environmental and

pressure gradients (reviewed in Smit et al., 2021). Outcomes of a functional diversity analysis and long-term complete taxa biological trait-based analysis of infauna changes in response to the operation of an offshore long-line mussel farm support the use of functional diversity and BTA analysis to perform ecosystem assessment, supporting decision-makers implement policy and management (Mascorda-Cabre et al., 2023).

5 Conclusions & recommendations

5.1 Conclusions

5.1.1 Ecosystem components and functions related to mussel farming

The ecosystem components that are affected by the introduction of suspended mussel cultivation in the Dutch part of the North Sea range from plankton and epiphytes at the base of the foodweb to birds and marine mammals at the top. Eleven components and several subcomponents (for example adult, juvenile and larvae of pelagic fish) are listed in **Table 2.1**. Fourteen different ecosystem functions of offshore mussel cultivation have been identified with linkages to the ecosystem (see **Table 2.2**). Depending on the function, interaction of 1 up to 8 different ecosystem components have been found per function. Upscaling of mussel cultivation may benefit or impair these interactions, depending on the ecosystem component-function link, the scale and the location of the mussel farm.

5.1.2 Knowledge gaps

During this study, several knowledge gaps were identified. In general, the ecological effects of offshore mussel cultivation on the North Sea ecosystem are largely unknown. Understanding these gaps is crucial for evaluating the sustainability of offshore mussel production. The specific gaps identified for each of the four functions investigated are as follows:

Fish Aggregation Devices (FADs):

- 1) A knowledge gap exists of the potential of mussel cultivation systems as FADs in offshore systems.
- 2) Although offshore mussel farms are thought to act as FAD's, the mechanisms behind the FAD effect of mussel farms are still uncertain.
- 3) For the relevant ecosystem components (adult-pelagic, adult-demersal and juvenile) there is no data available on the potential function of offshore mussel cultivation systems as FADs in the North Sea.

Nursery areas:

- 1) Fish are thought to use shellfish and seaweed farms as nursery areas, however none of the abiotic conditions in the (few) studies available compare to the North Sea
- 2) A knowledge gap exists of the potential of mussel farms to act as nursery habitats for juvenile fish and macro-invertebrates in offshore soft sediment environments.

Feeding function

- 1) The feeding function of mussel cultures has been largely investigated. However, an assessment of which species will be affected in the North Sea and more insight in long-term and cumulative effects is needed.

Breeding/reproduction area

- 1) Limited research exists on the potential role of offshore mussel farms as breeding or reproduction areas for marine organisms.

5.1.3 Implications

There is currently limited information on the long-term impacts of offshore suspended mussel cultures in highly dynamic environments, such as the North Sea and other open waters. Effects of mussel cultures on the environment are site-specific and data on how ecosystem components are affected in

the Dutch part of the North Sea is not available. Consequently, the potential impacts of scaling up mussel farming, particularly regarding ecosystem sustainability, remain unclear.

To address these knowledge gaps, it is crucial to gather empirical data from the North Sea. Potential implications linked to the four functions selected are mainly identified as positive (more food, more habitat) and could potentially lead to increased fish production in the area. However, there might be risks involved when migratory patterns of fish species are affected. Exceeding the carrying capacity of the ecosystem is also discussed as a potential implication of upscaling. Other potential implications that are not taken into account in this study are the effect of biodeposition, releasing organic matter back to the marine environment through excretion, which might significantly affect the resilience of the ecosystem when different upscaling scenarios are applied and the introduction of non-indigenous species or shifts in species composition through the introduction of cultivation structures that may act as stepping stones by creating new dispersal pathways and facilitating species migrations (Mavraki et al., 2020; Coolen et al. 2020; Adams et al. 2014).

To facilitate informed decision making when upscaling offshore mussel production, the potential implications mentioned above need to be investigated in further detail. The use of functional diversity and BTA analysis as well as modelling studies combined with data from monitoring studies at the potential areas of interest can assist to provide information needed to prevent or mitigate negative impacts of offshore mussel production to the ecosystem, enhance ecosystem resilience and optimize local production.

5.2 Recommendations

Low trophic marine production has upscaling potential to either single farm or sector relevant volumes. Habitat provided by the suspended cultures are not native for the offshore environment (although in the field hard substrates are present in the pelagic zone). A scale-up of suspended culture production should strive to contribute to the positive state of the ecosystem. This may also require a transition pathway to include ecosystem-based considerations in a robust, resilient and effective low trophic marine production.

- With the ongoing development of artificial structures (OWFs and potentially mussel cultivation systems) in the North Sea there is an urgency to understand the effects of these developments on the ecosystem. Several recommendations are provided to that extent: Collection of samples, monitoring, development of different scale models and model validation are highly recommended to facilitate our understanding of the changes induced to the environment because of the introduction of mussel cultures. In section 3.2 several suggestions have been made for monitoring the effects of mussel cultivation on the functions fish aggregation devices (FADs), nursery area, feeding ground and breeding/production area.
 - 1) FAD: measuring fish diversity and abundance by means of remote underwater video systems
 - 2) Nursery area: the use of standard monitoring units for the recruitment of fish (SMURFs) to measure temporal and spatial variability in fish settlement and recruitment
 - 3) Feeding ground: abundance measurements and diet compositions using a combination of stable isotope and stomach content to provide insight in the feeding ecology of multiple species
 - 4) Breeding/reproduction area: monitoring breeding behaviour using high-resolution activity sensors and the presence of early reproductive stages (eggs and larvae) detected in SMURF's or light traps. An important follow-up step in the process towards a robust and resilient approach for upscaling low trophic marine production lies in terms of understanding cumulative effects and connectivity between multiple intermediate-scale mussel farms.
- A method to assess ecosystem-wide effects is the application of functional diversity and biological traits analysis to perform ecosystem assessments (described in section 4.3).

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- An important follow-up step in the process towards a robust and resilient approach for upscaling low trophic marine production lies in terms of understanding connectivity between systems. How are multiple intermediate-scale mussel farms connected, through which processes and how may this assist, or create synergy in enhancing ecosystem aspects or how may connectivity contribute to negative impacts?
 - Empirical studies that quantify the effects of the added structures are needed to understand how connectivity changes and provide insight in the underlying mechanisms of connectivity. This information is essential to minimize impacts when it comes to making choices in scale and location of mussel cultivation.
 - Management interventions to achieve an effective ecosystem-based production should be taken by low trophic producers. However, the extent to which production management, and ecosystem-based valorisation (social and economic) can influence the ecosystem is unknown. Considerations based on ecosystem benefits should be incorporated early in the design of the production system and production species.
 - Finally, these interactions and potential impacts should be placed in the context of other activities in the North Sea (shipping, offshore wind farms and fisheries) and considered from a perspective of cumulative impacts.

6 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

References

- Ackefors, H., & Haamer, J. 1987. A new Swedish technique for culturing blue mussel. *International Council for the Exploration of the Sea* 36, 1-7.
- Alonso-Pérez, F., Ysebaert, T., & Castro, C. G. 2010. Effects of suspended mussel culture on benthic-pelagic coupling in a coastal upwelling system (Ría de Vigo, NW Iberian Peninsula). *Journal of Experimental Marine Biology and Ecology*, 382(2).
- Ammann, A. J. (2004). SMURFs: Standard monitoring units for the recruitment of temperate reef fishes. *Journal of Experimental Marine Biology and Ecology*, 299(2).
<https://doi.org/10.1016/j.jembe.2003.08.014>
- Arney, R. N., Froehlich, C. Y. M., & Kline, R. J. 2017. Recruitment patterns of Juvenile fish at an artificial reef area in the gulf of Mexico. *Marine and Coastal Fisheries*, 9(1).
- Barrett, L. T., Theuerkauf, S. J., Rose, J. M., Alleway, H. K., Bricker, S. B., Parker, M., Petrolia, D. R., & Jones, R. C. 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. In *Ecosystem Services* (Vol. 53).
- Bellaart, S., Holdt, A., Ginel, S., Liu, Y., Kroezen, A., Niessen, S., & van den Akker, D. 2023. Started from the mussel, now we're here. Report p. 1-89.
- Ben-David, J., & Kritzer, J. P. 2005. Early life history and settlement of the slender filefish, *Monacanthus tuckeri* (Monacanthidae), at Calabash Caye, Turneffe Atoll, Belize. *Environmental Biology of Fishes*, 73(3).
- Borgwardt, F., Robinson, L., Trauner, D., Teixeira, H., Nogueira, A. J. A., Lillebø, A. I., Piet, G., Kuemmerlen, M., O'Higgins, T., McDonald, H., Arevalo-Torres, J., Barbosa, A. L., Iglesias-Campos, A., Hein, T., & Culhane, F. 2019. Exploring variability in environmental impact risk from human activities across aquatic ecosystems. *Science of the Total Environment*, 652.
<https://doi.org/10.1016/j.scitotenv.2018.10.339>
- Bot, P. V., & Colijn, F. 1996. A method for estimating primary production from chlorophyll concentrations with results showing trends in the Irish Sea and the Dutch coastal zone. *ICES Journal of Marine Science*, 53(6), 945-950.
- Brehmer, P., Gerlotto, F., Guillard, J., Sanguinède, F., Guénnegan, Y., & Buestel, D. 2003. New applications of hydroacoustic methods for monitoring shallow water aquatic ecosystems: The case of mussel culture grounds. *Aquatic Living Resources*, 16(3).
- Bremner, J., Rogers, S. I., & Frid, C. L. J. 2006. Methods for describing ecological functioning of marine benthic assemblages using biological traits analysis (BTA). *Ecological Indicators*, 6(3).
<https://doi.org/10.1016/j.ecolind.2005.08.026>
- Brickhill, M.J., Lee, S.Y., and Connolly, R.M. 2005. Fishes associated with artificial reefs: attributing changes to attraction or production using novel approaches. *Journal of Fish Biology* 67, 53-71.
- Burnett, M. J., Süßle, V., Saayman, T., Jewitt, G., O'Brien, G. C., & Downs, C. T. 2024. Detecting changes in fish behaviour in real time to alert managers to thresholds of potential concern. *River Research and Applications*, 40(1), 129-147. <https://doi.org/10.1002/rra.4214>
- Cadée, G. 1992. Trends in Marsdiep phytoplankton. *Proc. 7th Int. Wadden Sea Conf. Ameland. Public. Ser. Neth. Inst. Sea Res.*, 20: 143-149.
- Callier, M. D., Byron, C. J., Bengtson, D. A., Cranford, P. J., Cross, S. F., Focken, U., Jansen, H. M., Kamermans, P., Kiessling, A., Landry, T., O'Beirn, F., Petersson, E., Rheault, R. B., Strand, Ø., Sundell, K., Svåsand, T., Wikfors, G. H., & McKindsey, C. W. 2018. Attraction and repulsion of mobile wild organisms to finfish and shellfish aquaculture: a review. In *Reviews in Aquaculture* (Vol. 10, Issue 4).
- Carriço, R., Silva, M. A., Vieira, M., Afonso, P., Menezes, G. M., Fonseca, P. J., & Amorim, M. C. P. 2020. The Use of Soundscapes to Monitor Fish Communities: Meaningful Graphical Representations Differ with Acoustic Environment. *Acoustics*, 2(2).
- Cheng, C. H., Soetaert, K., & Borsje, B. W. 2020. Sediment Characteristics over Asymmetrical Tidal Sand Waves in the Dutch North Sea. *Journal of Marine Science and Engineering*, 8(6), 409.
- Clavelle, T., Lester, S. E., Gentry, R., & Froehlich, H. E. 2019. Interactions and management for the future of marine aquaculture and capture fisheries. *Fish and Fisheries*, 20(2).

-
- Coolen, J. W. P., Van Der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G. W. N. M., Faasse, M. A., Bos, O. G., Degraer, S., & Lindeboom, H. J. 2020. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. *ICES Journal of Marine Science*, 77(3).
- Coolen, J.W., Boon, A.R., Crooijmans, R., Van Pelt, H., Kleissen, F., Gerla, D., Beermann, J., Birchenough, S.N., Becking, L.E. and Luttikhuisen, P.C. 2020. Marine stepping-stones: Connectivity of *Mytilus edulis* populations between offshore energy installations. *Molecular Ecology*, 29(4), 686-703.
- Cresson, P., Le Direach, L., Rouanet, E., Goberville, E., Astruch, P., Ourgaud, M., and Harmelin-Vivien, M. 2019. Functional traits unravel temporal changes in fish biomass production on artificial reefs. *Marine Environmental Research* 145, 137-146.
- Daan, N., Bromley, P., Hislop, J., & Nielsen, N. 1990. Ecology of North sea fish. *Netherlands Journal of Sea Research*, 26(2-4), 343-386.
- Damveld, J. H., van der Reijden, K. J., Cheng, C., Koop, L., Haaksma, L. R., Walsh, C. A. J., Soetaert, K., Borsje, B. W., Govers, L. L., Roos, P. C., Olf, H., & Hulscher, S. J. M. H. 2018. Video Transects Reveal That Tidal Sand Waves Affect the Spatial Distribution of Benthic Organisms and Sand Ripples. *Geophysical Research Letters*, 45(21).
- D'Amours, O., Archambault, P., McKindsey, C., and Johnson, L. 2008. Local enhancement of epibenthic macrofauna by aquaculture. *Marine Ecology Progress Series* 371, 73-84.
- De Graaf, L. 2012. "Communication about medications for better patient transition. Needed: Format for switching." *Pharmaceutisch Weekblad* no. 147 (8):14-15.
- Drouin, A., Archambault, P., Clynick, B., Richer, K, and McKindsey, C. 2014. Influence of mussel aquaculture on the distribution of vagile benthic macrofauna in îles de la Madeleine, eastern Canada. *Aquaculture Environment Interactions* 6, 175-183.
- De Vries, P., Tamis, J. E., Foekema, E. M., Klok, C. & Murk, A. J. 2013. Towards quantitative ecological risk assessment of elevated carbon dioxide levels in the marine environment. *Marine pollution bulletin*, 73, 516-23.
- Fernandes, Alvaro A. A., Alasdair J. G. Gray, and Khalid Belhajjame. 2011. *Advances in Databases: 28th British National Conference on Databases, BNCOD 28, Manchester, UK, July 12-14, 2011, Revised Selected Papers*. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Foekema, E., Poiesz, S., Poelman, M., Kootstra, M., & Geerdink, P. (2024). *Mariene bouwstenen : Een verkenning van de mogelijkheden van benutting van schelpen in cement- en betonproductie*. Wageningen Marine Research rapport No. C002/24. Wageningen Marine Research. <https://doi.org/10.18174/645912>
- Fransz, H., Colebrook, J., Gamble, J., & Krause, M. 1991. The zooplankton of the North Sea. *Netherlands Journal of Sea Research*, 28(1-2), 1-52.
- Freire, J., and Gonzalez-Gurriaran, E. 1995. Feeding ecology of the velvet swimming crab *Necora puber* in mussel raft areas of the Ria de Arousa (Galicia, NW Spain). *Marine Ecology Progress Series* 119, 139-154.
- Heip, C., Basford, D., Craeymeersch, J., Dewarumez, J., Dörjes, J. d., De Wilde, P., Duineveld, G., Eleftheriou, A., Herman, P., & Niermann, U. 1992. Trends in biomass, density and diversity of North Sea macrofauna. *ICES Journal of Marine Science*, 49(1), 13-22.
- Heip, C., & Craeymeersch, J. 1995. Benthic community structures in the North Sea. *Helgoländer Meeresuntersuchungen*, 49, 313-328.
- Inglis, G. & Gust, N. 2003. Potential indirect effects of shellfish culture on the reproductive success of benthic predators. *Journal of Applied Ecology* 40, 1077-1089.
- Jansen, H., van den Burg, S., Bolman, B., Jak, R., Kamermans, P., Poelman, M., Stuver, M. 2016. The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. *Aquaculture International* 24, 735-756.
- Jansen, H. M., Strand, Ø., van Broekhoven, W., Strohmeier, T., Verdegem, M. C., & Smaal, A. C. 2018. Feedbacks from filter feeders: Review on the role of mussels in cycling and storage of nutrients in oligo- meso- and eutrophic cultivation areas. In *Goods and Services of Marine Bivalves*.
- Jansen, H. M., van der Burg, S. W. K., van Duren, L. A., Kamermans, P., Poelman, M., Steins, N. A., & Timmermans, K. R. 2023. Food for thought: A realistic perspective on the potential for offshore aquaculture in the Dutch North Sea. *Journal of Sea Research*, 191.
- Janssen, F., Schrum, C., & Backhaus, J. 1999. A climatological dataset of temperature and salinity for the North Sea and the Baltic Sea. *Deutsche Hydrographische Zeitschrift*, 9, 1999.

-
- Joint, I., & Pomroy, A. 1993. Phytoplankton biomass and production in the southern North Sea. *Marine Ecology-Progress Series*, 99, 169-169.
- Josefson, A., Jensen, J., & Ærtebjerg, G. 1993. The benthos community structure anomaly in the late 1970s and early 1980s—a result of a major food pulse? *Journal of Experimental Marine Biology and Ecology*, 172(1-2), 31-45.
- Kamermans, P., Ter Hofstede, R., Williams, G., & Van Koningsveld, M. 2023. The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster (*Ostrea edulis*) reef development in the southern North Sea. *Aquatic Living Resources*, 36.
- Kamermans, P., Walles, B., Kraan, M., van Duren, L. A., Kleissen, F., van der Have, T. M., Smaal, A. C., & Poelman, M. 2018. Offshore wind farms as potential locations for flat oyster (*Ostrea edulis*) restoration in the Dutch North Sea. *Sustainability (Switzerland)*, 10(11).
- Kamermans, P., Soma, K., & van den Burg, S. 2016. Haalbaarheid mosselteelt binnen offshore windparken in de Nederlandse kustzone. Wageningen, IMARES Wageningen UR (University & Research centre), IMARES rapport C075/16; 1-47.
- Kamermans, P., Schellekens, T., & Beukers, R. 2011. Verkenning van mogelijkheden voor mosselteelt op Noordzee. Wageningen, IMARES Wageningen UR (University & Research centre), IMARES rapport C021/11
- Knights, A. M., Piet, G. J., Jongbloed, R. H., Tamis, J. E., White, L., Akoglu, E., Boicenco, L., Churilova, T., Kryvenko, O., Fleming-Lehtinen, V., Leppanen, J. M., Galil, B. S., Goodsir, F., Goren, M., Margonski, P., Moncheva, S., Oguz, T., Papadopoulou, K. N., Setälä, O., ... Robinson, L. A. 2015. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. *ICES Journal of Marine Science*, 72(3). <https://doi.org/10.1093/icesjms/fsu245>
- Kremen, C. 2005. Managing ecosystem services: What do we need to know about their ecology? *Ecology Letters*, 8(5), 468-479.
- Krone, R., Gutow, L., Brey, T., Dannheim, J., & Schröder, A. 2013. Mobile demersal megafauna at artificial structures in the German Bight - Likely effects of offshore wind farm development. *Estuarine, Coastal and Shelf Science*, 125.
- Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., & Schmalenbach, I. 2017. Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of *Cancer pagurus*. *Marine Environmental Research* 123, 53-61.
- Laffaille, P., Lefeuvre, J., Thorin, S., and Feunteun, E. 2001. Are young sea bass, *Dicentrarchus labrax* L. (Teleostei: Pisces) adapted to mussel cultures? *Journal of the Marine Biological Association of the UK* 81, 363-364.
- Lehane, C., & Davenport, J. 2002. Ingestion of mesozooplankton by three species of bivalve; *Mytilus edulis*, *Cerastoderma edule* and *Aequipecten opercularis*. *Journal of the Marine Biological Association of the United Kingdom*, 82(4).
- Mascorda Cabre, L., Hosegood, P., Attrill, M. J., Bridger, D., & Sheehan, E. V. 2021. Offshore longline mussel farms: a review of oceanographic and ecological interactions to inform future research needs, policy and management. *Reviews in Aquaculture*, 13(4), 1864-1887. doi: 10.1111/raq.12549
- Mascorda-Cabre, L. M., Hosegood, P., Attrill, M., Bridger, D., Mascorda-Cabre, L., Attrill, M. J., & Sheehan, E. V. 2023. Detecting Sediment Recovery Below an Offshore Longline Mussel Farm: A Biological Trait Analysis (BTA) of Macrobenthic Organisms Detecting sediment recovery below an offshore longline mussel farm: A macrobenthic Biological Trait Analysis (BTA). <https://doi.org/10.2139/ssrn.4384899>
- Mavraki, N., Degraer, S., Moens, T., and Vanaverbeke, J. 2020. Functional differences in trophic structure of offshore wind farm communities: A stable isotope study. *Marine Environmental Research* 157, 104868.
- Mavraki, N., Degraer, S., and Vanaverbeke, J. 2021. Offshore wind farms and the attraction-production hypothesis: insights from a combination of stomach content and stable isotope analyses. *Hydrobiologia* 848, 1639-1657.
- McKindsey, C., Archambault, P., Callier, M., and Olivier, F. 2011. Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: A review. *Canadian Journal of Zoology* 89, 622-646.
- Ministerie van Economische Zaken. 2014. Natuurlijk verder. Rijkswaarnaturvisie 2014. In Rijksoverheid. <https://open.overheid.nl/documenten/ronl-archief-ac5895ba-9266-4629-90bc-5108e8c1c801/pdf>

-
- Ministerie van Landbouw, Natuur en Voedselkwaliteit. 2023. Duurzame eiwitten uit Nederlandse schelpdieren Actualisatie Schelpdierbeleid 2023 – 2033.
<https://www.rijksoverheid.nl/documenten/rapporten/2023/05/31/Inv-bijlage-actualisatie-schelpdierbeleid-2023-2033>
- Morrisey, D. J., Cole, R. G., Davey, N. K., Handley, S. J., Bradley, A., Brown, S. N., & Madarasz, A. L. 2006. Abundance and diversity of fish on mussel farms. *Aquaculture*, 252(2–4), 277–288.
<https://doi.org/10.1016/j.aquaculture.2005.06.047>
- Naeem, S., Chapin Iii, F. S., Costanza, R., Ehrlich, P. R., Golley, F. B., Hooper, D. U. and Tilman, D. 1999. Biodiversity and ecosystem functioning: maintaining natural life support processes. *Issues in ecology*, 4(11).
- Page, H. M., Dugan, J. E., Dugan, D. S., Richards, J. B., & Hubbard, D. M. 1999. Effects of an offshore oil platform on the distribution and abundance of commercially important crab species. *Marine Ecology Progress Series*, 185, 47–57.
- Parkyn, S.M., Collier, K.J., and Hicks, B.J. 2001. New Zealand stream crayfish: Functional omnivores but trophic predators? *Freshwater Biology* 46, 641–652.
- Patricio Ojeda, F., & Dearborn, J. H. 1991. Feeding ecology of benthic mobile predators: experimental analyses of their influence in rocky subtidal communities of the Gulf of Maine. *Journal of Experimental Marine Biology and Ecology*, 149(1), 13–44.
- Puccinelli, E., & McQuaid, C. D. 2021. Commensalism, antagonism or mutualism? Effects of epibiosis on the trophic relationships of mussels and epibiotic barnacles. *Journal of Experimental Marine Biology and Ecology*, 540, 151549.
- Quante, M., Colijn, F., Bakker, J. P., Härdtle, W., Heinrich, H., Lefebvre, C., Nöhren, I., Olesen, J. E., Pohlmann, T., Sterr, H., Sündermann, J., & Tölle, M. H. 2016. Introduction to the Assessment—Characteristics of the Region. In M. Quante & F. Colijn (Eds.), *North Sea Region Climate Change Assessment* (pp. 1–52). Springer International Publishing.
- Reid, P., Lancelot, C., Gieskes, W., Hagmeier, E., & Weichart, G. 1990. Phytoplankton of the North Sea and its dynamics: a review. *Netherlands Journal of Sea Research*, 26(2–4), 295–331.
- Reubens, J.T., Pasotti, F., Degraer, S., and Vincx, M. 2013. Residency, site fidelity and habitat use of Atlantic cod (*Gadus morhua*) at an offshore wind farm using acoustic telemetry. *Marine Environmental Research* 90, 128–135.
- Roycroft, D., Kelly, T.C., and Lewis, L.J. 2007. Behavioural interactions of seabirds with suspended mussel longlines. *Aquaculture International*, 15, 25–36.
- Runhaar, H. 2017. Governing the transformation towards 'nature-inclusive' agriculture: insights from the Netherlands. *International Journal of Agricultural Sustainability*, 15(4), 340–349.
- Scridel, D., Utmar, P., Franzosini, C., Segarich, M., Menon, S., Burca, M., Diviacco, P., Ciriaco, S., del Negro, P., and Spoto, M. 2020. Sink or swim? Modernization of mussel farming methods may negatively impact established seabird communities. *Biological Conservation*, 243, 108458.
- Sheehan, E., Bridger, D., Mascorda Cabre, L., Cartwright, A., Cox, D., Rees, S., Holmes, L., and Pittman, S. 2019. Bivalves boost biodiversity. *Food Science and Technology* 33, 18–21.
- Sheehan, E. V., Bridger, D., Nancollas, S. J., & Pittman, S. J. 2020. PelagiCam: a novel underwater imaging system with computer vision for semi-automated monitoring of mobile marine fauna at offshore structures. *Environmental Monitoring and Assessment*, 192(1).
<https://doi.org/10.1007/s10661-019-7980-4>
- Skelton, B. M., McKay, W. J. G., & Jeffs, A. G. 2021. Evaluation of a floating upwelling system for nursery culture of the Greenshell™ mussel (*Perna canaliculus*). *Aquaculture Research*, 52(8).
- Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., & Wirtz, K. W. 2019. The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia*, 845(1).
- Smit, K. P., Bernard, A. T. F., Lombard, A. T., & Sink, K. J. 2021. Assessing marine ecosystem condition: A review to support indicator choice and framework development. *Ecological Indicators*, 121, 107148. <https://doi.org/10.1016/j.ecolind.2020.107148>
- Steele, J. H. 1974. *The structure of marine ecosystems*. Harvard University Press.
- Theuerkauf, S. J., Barrett, L. T., Alleway, H. K., Costa-Pierce, B. A., St. Gelais, A., & Jones, R. C. 2022. Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Reviews in Aquaculture*, 14(1).

-
- Tonk, L., Jansen, H. M., Poelman, M., Nauta, R. W., Jak, R. G., Tamis, J. E., & Jongbloed, R. H. 2021. Development of a framework and toolbox for measuring and evaluating ecosystem interactions of seaweed aquaculture. <https://doi.org/10.18174/553741>
- Underwood, L., & Jeffs, A. 2023. Settlement and recruitment of fish in mussel farms. *Aquaculture Environment Interactions*, 15, 85–100.
- Valles, H., Kramer, D. L., & Hunte, W. 2006. A standard unit for monitoring recruitment of fishes to coral reef rubble. *Journal of Experimental Marine Biology and Ecology*, 336(2).
- Sims, D. W. 2003. Tractable models for testing theories about natural strategies: Foraging behaviour and habitat selection of free-ranging sharks. *Journal of Fish Biology*, 63(SUPPL. A), 53–73.
- van den Burg, S. W. K., Kamermans, P., Blanch, M., Pletsas, D., Poelman, M., Soma, K., & Dalton, G. 2017. Business case for mussel aquaculture in offshore wind farms in the North Sea. *Marine Policy*, 85.

Justification

Report: C038/25

Project Number: 4318300175

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. O.G. Bos
function

Signature:  Signed by:
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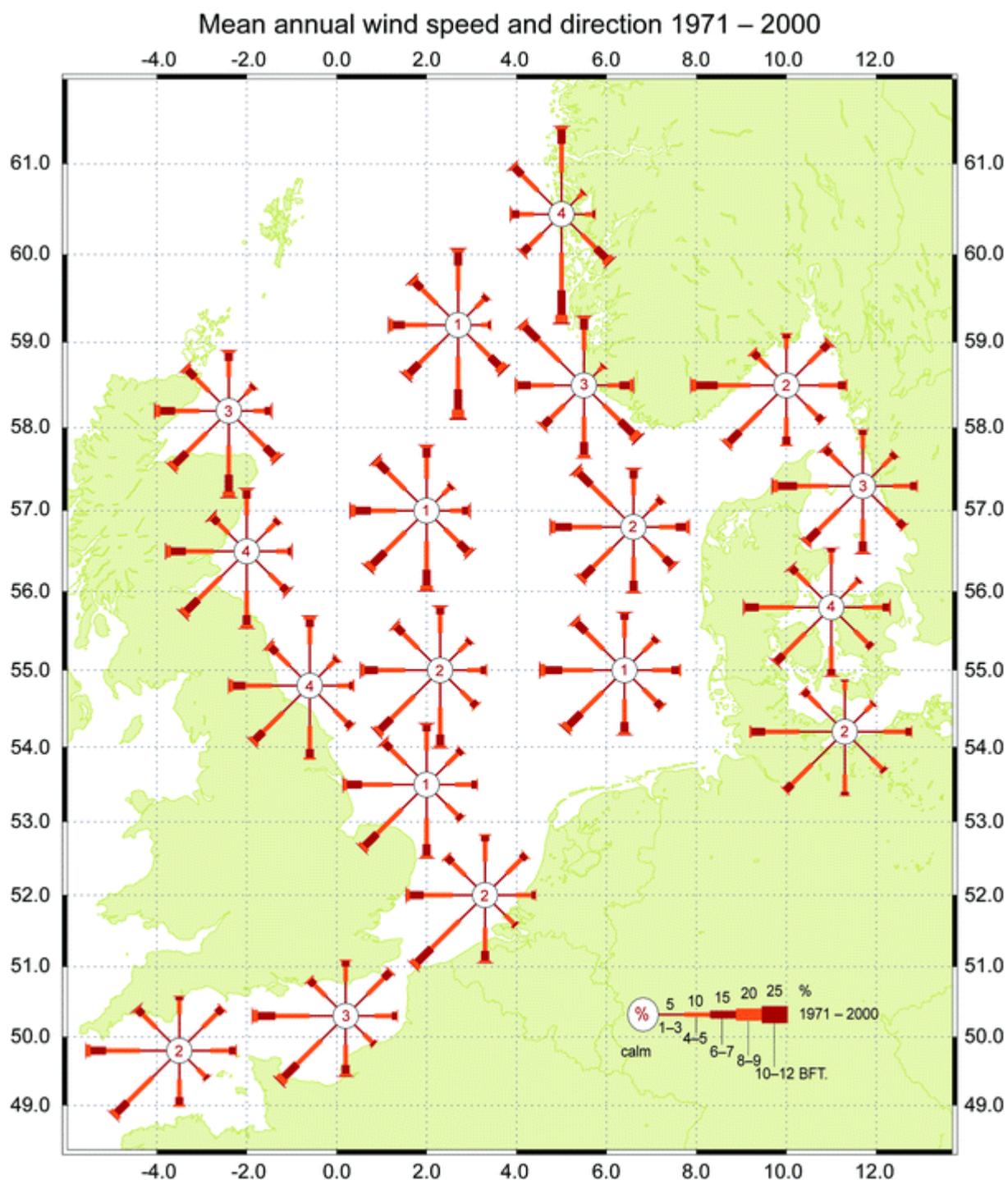
Date: 11 June 2025

Approved: Dr. ir T.P. Bult
Director

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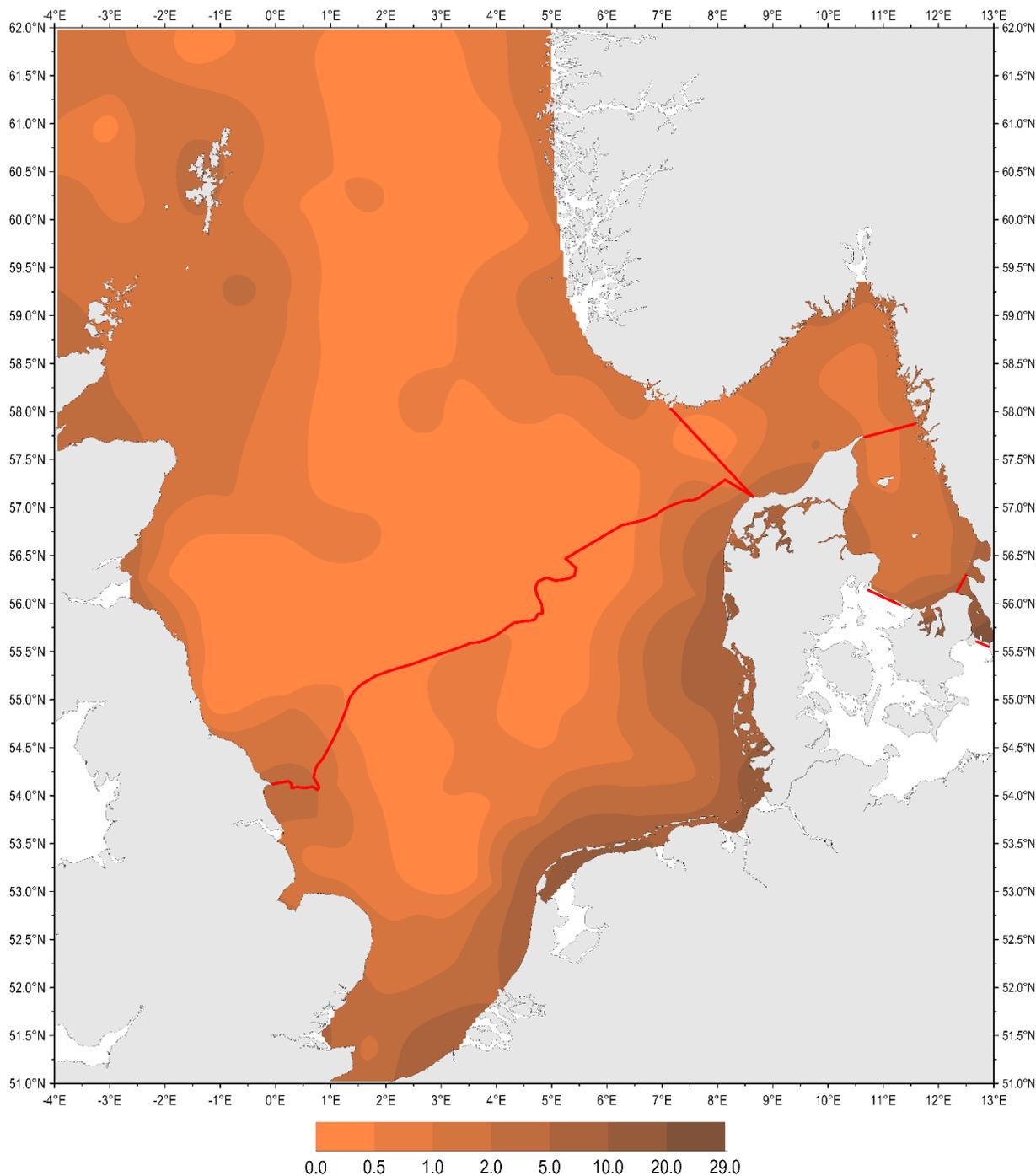
Date: 11 June 2025

Annex 1 Annual distribution of wind forces



Annual distribution of wind forces in Beaufort (Bft) derived from ship observations for different sea areas of the North Sea in the period 1971–2000. The length of each branch is proportional to the percentage frequency of the respective wind direction and wind force class. Numbers in circles denote the frequency of calm conditions. Source: (Quante et al., 2016).

Annex 2 Mean chlorophyll-a in the surface waters of the Greater North Sea, Skagerrak, Kattegat and Sound



Mean chlorophyll-a in the surface waters of the Greater North Sea, Skagerrak, Kattegat and Sound during the growing season (March-September) for the period 2006-2014. Red lines delineate boundaries for the northern and southern North Sea, Skagerrak, and Kattegat and the Sound Source: OSPAR Assessment Portal, <https://oap.ospar.org/en/>

Wageningen Marine Research
T +31 (0)317 48 70 00
E imares@wur.nl
www.wur.nl/marine-research

Visitors'adress

- Ankerpark 27 1781 AG Den Helder
- Korringaweg 7, 4401 NT Yerseke
- Haringkade 1, 1976 CP IJmuiden



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