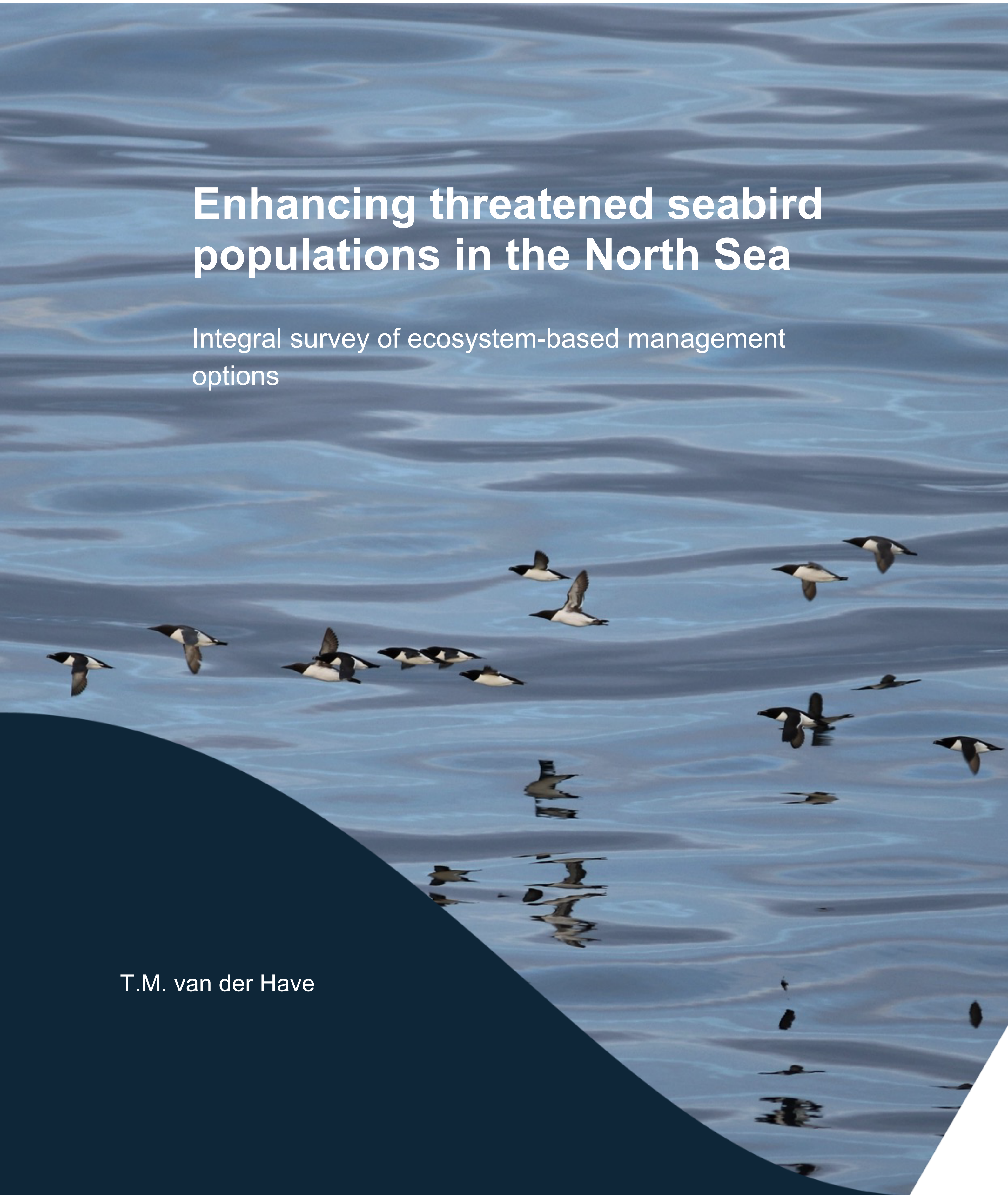

Enhancing threatened seabird populations in the North Sea

Integral survey of ecosystem-based management options

T.M. van der Have

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Nature regeneration NORTH SEA

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Preface

The programme Nature Enhancement North Sea aims for a healthy, resilient and biodiverse North Sea with attention for natural processes and sustainable use. This will be realized by practical experiments, learning-by-doing, scaling-up and increasing public awareness. The focus is on enhancement of the underwater nature as a fundament for the North Sea ecosystem. This approach includes attention to seabird populations.

As part of this programme the Ministry of LVVN commissioned Waardenburg Ecology to review enhancement measures for threatened seabirds in the North Sea with views on an ecosystem-based approach and implementation of potential measures.

The project team of Waardenburg Ecology included Tom van der Have (author) and Ineke Roëll (infographics).

The project was guided by Sam Hidskes, LVVN. Suzanne Vink and Yvette Graat provided comments on previous versions of this manuscript.

The author thanks everyone who has contributed to this report.

Summary

Aims

The programme Nature Enhancement North Sea (Natuurversterking Noordzee – NN) aims for a healthy, resilient and biodiverse North Sea with attention for natural processes and sustainable use. The focus is on enhancement of the underwater nature as a fundament for the North Sea ecosystem and vulnerable seabird populations. This group is at risk due to the increase of offshore wind in the North Sea that will have a large impact on critical seabird populations in addition to other pressure factors.

This study explores effective measures and solutions to enhance threatened seabird population in the North Sea in addition to current conservation actions for seabird populations. Special attention is given to align these measures with the ecosystem-based approach of the programme Nature Enhancement North Sea.

Ecosystem-based Management

Ecosystem-based management (EBM) is the integrative approach of management actions which considers (as much as possible) the positive interactions between complex marine habitats formed by ecosystem engineers and associated ecological groups which interact within the larger food web, such as invertebrates, fish, seabirds and marine mammals. The principles and objectives of EBM are briefly reviewed with respect to EU-Directives and current national policies. The overall comparison of EBM principles and objectives shows that the North Sea Agreement is an important link between the EU directives and the fisheries sector. On the other hand, the Nature Enhancement North Sea programme can be improved by considering social/cultural factors, applying the precautionary principle more explicitly, and to consider also economic factors, such as fisheries. The challenge is to search for common objectives with the fisheries sector within the energy transition to realise the implementation of all principles and objectives of EBM.

North Sea ecosystem

A comprehensive overview is given of the North Sea ecosystem with a focus on habitats (other than soft sediments) which are important for small fish, forage fish and their position in the food web as food for seabirds. In this report we define ‘forage fish’ as “species that occupy an intermediary trophic position and retain that ecological role throughout their life”. The species in this category are herring, sprat, anchovy, pilchard (sardine), and sandeel.

Specific areas in the North Sea form biodiversity hotspots and are of particular importance to seabirds, because they provide the birds with direct or indirect access to food (fish and marine invertebrates). These areas are often occupied by ecosystem engineers. Ecosystem engineers are those species that “directly or indirectly modulate the availability of resources to other species by causing physical state changes in biotic or abiotic

materials. In doing so they modify, maintain, and create habitats". These include marine habitats which provide high habitat complexity by 3D-structures, such as seagrass meadows, kelp forests and biogenic reefs formed by shellfish or polychaete worms.

These habitats typically function as nurseries for many fish species and may additionally act as their feeding grounds, spawning areas or migration routes. These fish species depend on these essential habitats for survival., Other species may benefit indirectly from these habitats as they forage on the organisms associated with these habitats and these include piscivorous fish, seabirds and marine mammals.

Pressure factors

The factors that affect seabird populations through demographic factors such as reproduction (e.g. breeding success) and survival are briefly reviewed. These pressure factors can be grouped into eight categories: diseases, fisheries, human activity offshore, climate change, invasive species, pollution, ecosystem effects, and persecution. Factors that negatively impact both reproduction and survival, such as disease, reduced food availability and habitat loss will have the highest impact. Most pressure factors are directly or indirectly related to human activities such as fisheries, offshore infrastructure, invasive species, climate change and pollution. The impact of diseases, climate change, food availability, fisheries and predation are discussed. In addition, the pressure factors related to offshore wind farms separately, including collision risk, habitat loss and barrier effects are reviewed.

Enhancement measures

The negative impacts of offshore wind farms on seabirds, including collisions, habitat loss and barrier effect can obstruct the large-scale rollout of offshore wind farms in the North Sea. Various mitigation measures are currently implemented or under development, such as marine spatial planning, increased turbine visibility and smart curtailment. A range of conservation measures have been recently proposed or taken as compensation to the negative ecological effects of offshore wind farms. In most cases these compensatory measures were proposed for planned offshore wind farms relatively close to large seabird breeding colonies in the UK. Compensatory measures should mitigate mortality at least equal to the losses of birds caused by the offshore wind farms.

Compensation can be achieved by (1) acting on factors that influence the bird population and with this enhance the population (e.g. food abundance and predation) or (2) minimize negative impacts caused by other human factors, such as fisheries and pollution. This report presents examples of compensatory measures, including vegetation control, invasive species removal, and minimizing disturbance at breeding sites and increasing food abundance by regulating fisheries (e.g. food reservation for seabirds), decreasing mortality because of bycatch in fisheries, hunting and pollution. Ecosystem-based management is presented as a complementary approach, which includes enhancement of structured habitats formed by seagrass beds, kelp forest, biogenic reefs such as worm reefs, mussel beds and oyster reefs. These biogenic reefs function as spawning sites for forage fish, nursery sites for demersal fish and habitat for small fish species.

Forage fish

Forage fish ecology and their management are crucial: they have a key role in the North Sea food web by transferring the primary production and zooplankton to higher trophic levels including large fish of both commercial and conservation concern, as well as threatened seabirds and marine mammals. This implies that the EBM of forage fish will contribute both to commercial fisheries and the conservation of threatened large fish species, seabirds and marine mammals.

Innovation and actions

Several suggestions for innovation are presented, including artificial nesting sites for seabirds, spatial planning of seaweed farms providing nest material for seabirds and highly selective fishing gear to increase fish stocks. A list of actions for Nature Enhancement Programme to enhance threatened seabirds is presented together with a set of ranking criteria to prioritize actions and a comparison of benefits and drawbacks. An overview is presented of national and international research projects with respect to the developments of offshore wind farms in the North Sea, including the MONS/WOZEP research programme.

International cooperation

An overview is presented of recent international research programmes in the North Sea area that are related to the impact of offshore wind farms on seabirds and biodiversity enhancement and compensation measures. Cooperation and alignment of research and monitoring of compensatory measures in the Dutch part of the North Sea with these programmes would strengthen the knowledge base of compensatory measures for seabirds in the North Sea area. Several possibilities of international cooperation are presented including the Joint Working Group on Seabirds and Regional Action Plan Seabirds of the OSPAR Convention, and the Greater North Sea Basin Initiative (GNBSI).

Knowledge gaps and recommendation

Several knowledge gaps were identified, including what stock size of forage fish is necessary to restore threatened seabird populations to a favourable conservation status, what impact increasing water temperatures will have on the ecosystem, food and seabirds, and how enhancement measures will impact reproduction and survival of threatened seabirds. It is recommended to organise an international expert meeting on food availability, strengthening reproduction and protecting marine habitats for threatened seabirds in the North Sea area.

Nederlandse samenvatting

Doelstelling

Het programma Natuurversterking Noordzee streeft naar een gezonde, veerkrachtige en biodiverse Noordzee met aandacht voor natuurlijke processen en duurzaam gebruik. De focus is op versterking van onderwaternatuur als basis voor Het Noordzee ecosysteem inclusief kwetsbare zeevogel populaties. Deze groep is kwetsbaar voor de toename van offshore windenergie in de Noordzee, dat een grote impact zal hebben op kritische zeevogel populaties in aanvulling op andere drukfactoren.

Ecosystem-based management

Ecosystem-based management (EBM) is de integrale benadering van het Beheer van mariene resources. Deze benadering gaat zoveel mogelijk uit van de positieve interacties tussen complexe mariene habitats die gevormd worden door ecosysteem engineers en geassocieerde ecologische groepen die interacties aangaan met het grotere voedselweb, inclusief ongewervelden, vissen, zeevogels en mariene zoogdieren. De principes en doelen van EBM worden kort besproken in relatie tot EU-wetgeving en het huidige nationale beleid. Een analyse van EBM-principes en doelstellingen laat zien dat het Noordzeeakkoord en belangrijke link is tussen de EU-wetgeving en de visserijsector. Anderzijds, het NN-programma kan versterkt worden door ook sociaal-culturele en economische factoren, zoals visserij, te beschouwen, en het voorzorgsbeginsel expliciet toe te passen. De uitdaging is om te zoeken naar gemeenschappelijke doelen met de visserijsector binnen de energietransitie om alle principes en doelen van EBM te realiseren.

Noordzee ecosysteem

Een samenvattend overzicht wordt gegeven van het Noordzee ecosysteem met een focus op habitats (anders dan zacht sediment) die belangrijk zijn voor Kleine vis, prooivis en hun positie in het voedselweb als voedsel voor zeevogels. In dit rapport definiëren wij prooivis als “vissoorten die een intermediaire trofische positie innemen en deze rol behouden gedurende hun hele leven”. De soorten in deze categorie zijn haring, sprot, ansjovis, sardines en zandspiering.

Specifieke gebieden in de Noordzee vormen biodiversiteit hotspots en zijn van belang voor zeevogels omdat ze direct of indirect voedsel leveren, zoals vis en ongewervelden. In deze gebieden komen vaak biobouwers (ecosystem engineers) voor. Dit zijn soorten die “direct of indirect de beschikbaarheid van resources voor andere soorten moduleren door in biotische en abiotische materialen fysieke veranderingen te veroorzaken”. Dit betreffen mariene habitats die een hoge habitat complexiteit hebben door 3D-structuren, zoals zeegrasbedden, kelpvelden en biogene riffen gevormd door schelpdieren of wormen.

Deze biotopen functioneren als opgroeigebieden, foerageergebied, paaigebied en migratieroutes voor vele vissoorten. Deze habitats vormen essentiële schakel in de levenscyclus van deze vissoorten. Andere soorten kunnen indirect van biogene riffen profiteren omdat zij foerageren op de soorten die geassocieerd zijn met deze habitats zoals visetende vissen, zeevogels en mariene zoogdieren.

Drukfactoren

De factoren die zeevogel populaties beïnvloeden door demografische factoren zoals reproductie (e.g. broedsucces) en overleving worden kort gereviewed. Deze drukfactoren bestaan uit acht categorieën: ziektes, visserij, menselijke offshore activiteiten, klimaatverandering, invasieve soorten, vervuiling, ecosysteem effecten en vervolging. Factoren die zowel reproductie als overleving beïnvloeden, zoals ziektes, verminderde voedselbeschikbaarheid en habitatverlies hebben de grootste negatieve impact. De impact wordt besproken van drukfactoren, die direct of indirect veroorzaakt worden door menselijke activiteiten, zoals visserij, offshore infrastructuur (e.g. aanvaringen, habitatverlies en barrière-effect), invasieve soorten, klimaatverandering en vervuiling.

Maatregelen voor natuurversterking

De bovengenoemde negatieve impact van offshore windparken op zeevogels kan de grootschalige uitrol van windenergie in de Noordzee belemmeren. Verschillende mitigatie maatregelen worden momenteel geïmplementeerd of ontwikkeld, zoals de planning van maritiem ruimtegebruik, vergrootte zichtbaarheid van turbines en slimme stilstandsvoorzieningen. Een range aan beschermingsmaatregelen zijn recentelijk voorgesteld of uitgevoerd als compensatie voor de negatieve ecologische impact van offshore windparken die in de nabijheid van zeevogelkolonies zijn gepland in het VK. Compensatiemaatregelen hebben als doel om minimaal het verlies aan vogels door specifieke offshore windparken te compenseren.

Compensatie kan gerealiseerd worden door (1) acties gericht op factoren die de grootte van de zeevogelpopulaties beïnvloeden en hierdoor de populatie te versterken (e.g. voedselaanbod en predatie) of (2) de negatieve impact veroorzaakt door andere menselijke activiteiten, zoals visserij en vervuiling, te minimaliseren. Dit rapport presenteert voorbeelden van compensatiemaatregelen, zoals vegetatiebeheer, verwijderen van invasieve soorten en het verminderen van verstoring in broedgebieden en broedkolonies en het vergroten van voedselbeschikbaarheid door het reguleren van visserij (e.g. een voedselreservering voor zeevogels), verminderen van sterfte door bijvangst in visserij, jacht en vervuiling. Ecosystem-based management wordt gepresenteerd als een aanvullende werkwijze, die versterking van structuurrijke habitats omvat, die gevormd worden door zeegrasvelden, kelpwouden, en biogene riffen, zoals kokerwormriffen, mosselbedden en oesterriffen. Deze biogene riffen functioneren als paaigebieden voor prooivissen, kraamkamers voor bodemvissen en habitat voor kleine vissoorten.

Prooivissen

De ecologie van prooivissen en het beheer van prooivisbestanden is cruciaal: deze groep heeft een sleutelrol in het Noordzee-voedsel web door fyto- en zoöplankton om te zetten naar hogere trofische niveaus, inclusief grotere vissen met een commercieel en natuurbeschermingsbelang, bedreigde zeevogels en mariene zoogdieren. Dit impliceert dat EBM van prooivisbestanden zowel bijdraagt aan visserij als de bescherming van bedreigde vissoorten, kwetsbare zeevogels en mariene zoogdieren.

Innovaties, maatregelen en onderzoek

Een aantal suggesties voor innovatie worden gepresenteerd, zoals kunstmatige nestgelegenheid voor zeevogels, ruimtelijke planning van zeewierfarms die indirect nestmateriaal kunnen leveren voor zeevogels, en selectieve vismethoden die visbestanden kunnen versterken. Dit rapport presenteert een lijst van concrete maatregelen om populaties van kwetsbaren zeevogelsoorten te versterken samen met een set van rangschikkingscriteria om acties te prioriteren en een vergelijking van voor- en nadelen. Een overzicht wordt gegeven van nationale onderzoeksprojecten naar de gevolgen van de aanleg van offshore windparken in de Noordzee, zoals het MONS/WOZEP onderzoeksprogramma.

Internationale samenwerking

Een overzicht wordt gegeven van recente internationale onderzoeksprogramma's naar de impact van offshore windparken en compensatiemaatregelen. Samenwerking en afstemming van onderzoek en monitoring van natuurversterkende maatregelen in het Nederlandse deel van de Noordzee kunnen de kennisbasis van natuurversterking in de Noordzee vergroten. Een aantal mogelijkheden voor internationale samenwerking worden gegeven, zoals met de Joint Working Group on Seabirds en het Regional Action Plan Seabirds van de OSPAR Conventie en het Greater North Sea Basin Initiative (GNBSI).

Kennishiaten en aanbevelingen

Een aantal kennishiaten worden geïdentificeerd, zoals welke bestandsgroottes prooivissen zijn nodig voor het herstel van bedreigde zeevogelpopulaties tot een gunstige beschermingsstatus, wat is de impact van toenemende watertemperatuur op het ecosysteem, voedsel voor zeevogels en hun populaties, en hoe natuurversterkingsmaatregelen de reproductie en overleving van bedreigde zeevogelsoorten zal beïnvloeden. Het wordt aanbevolen om een internationale expert bijeenkomst te organiseren over de voedselbeschikbaarheid, het versterken van reproductie en de bescherming van mariene habitats voor bedreigde zeevogelpopulaties in het Noordzeegebied.

Contents

1 Introduction

1.1 Background

The programme Nature enhancement North Sea (NN; Natuurversterking Noordzee – NN) aims for a healthy, resilient and biodiverse North Sea with attention for natural processes and sustainable use. This will be realized by practical experiments, learning-by-doing, scaling-up and increasing public awareness. The focus is on enhancement of the underwater nature as a fundament for the North Sea ecosystem. This approach includes attention to seabird populations. More specifically, the increase of offshore wind in the North Sea has a large impact on several critical seabird populations (KEC5.0; Potiek *et al.*, 2022; IJntema *et al.*, 2025). Developing and implementing meaningful enhancement measures for this group is notoriously difficult, but not impossible (Furness *et al.*, 2013). This study aims to support the quest for effective measures and solution to enhance threatened seabird population in the North Sea (Levrel *et al.*, 20212) in addition to current conservation measured for seabird populations.

1.2 Aim of the study

The aim of this study is to give an overview of possible enhancement measures which are aligned with the ecosystem-based approach of the programme Nature Enhancement North Sea. In addition, this study will give insight how the implementation of measures can be combined with other initiatives.

These aims have been detailed in the following research questions:

- What are the possibilities for enhancement measures for threatened seabirds in the Dutch part of the North Sea outside offshore wind farms at sea and on land?
  - What are the pressure factors?
  - How to balance compensatory measures with negative impacts?
  - How to prioritize enhancement measures?
  - What are potential areas for innovation?
  - What are the most important knowledge gaps?

- What are the possibilities for international cooperation and joint action with other countries around the North Sea?

1.3 Approach

Complementary to species protection plans

The North Sea Agreement initiated the Monitoring, Research, Nature Enhancement and Species Protection programme (MONS) and the development of several species' protection plans (Bos et al., 2023 a,b; some are still in preparation) for most of the focal seabird species in this report (Table 2.1). These plans are essentially focused on individual species and propose measures for individual species. In this study we aim to complement the species protection plans by analysing the requirements for ecosystem-based management.

Ecosystem-based management

The ecological requirements of the focal threatened seabird species overlap in time, space and food choice. These species occur year-round in large parts of the North Sea and select the same forage fish species, including herring, sprat and sand eel species (Clausen *et al.*, 2018; Croll *et al.*, 2022; Dickey-Collas *et al.*, 2014; Erisman *et al.*, 2017; Furness *et al.*, 2013; Wanless *et al.*, 2005, 2007). Locally, the interaction can become more intense when they forage in Multi-species Feeding Associations (MFSA's) together with marine mammals on shoals of forage fish (Veit & Harrison, 2017; Camphuysen *et al.*, 2007). These forage fish are also important as prey for large fish of which many species are also commercially exploited. Therefore, ecosystem-based management is essential for sustainable fisheries and effective conservation of threatened species. During the breeding season there is less overlap in the use of the North Sea between species, but an ecosystem-based management is equally important as well, including habitat management of breeding sites and enhancement of forage fish stocks near the breeding sites.

International cooperation

This study reviews relevant information from scientific sources and grey literature:

- Enhancement and compensation measures proposed for seabirds which are negatively impacted by the construction of offshore windfarms, such as in the UK e.g. Furness *et al.,* (2013); Skeate *et al.,* (2022). The proposed measures include species- and ecosystem-based conservation measures, which also can be implemented in the Dutch part of the North Sea (DPNS).
- Consulting international seabird experts in international conferences and workshops (Seabird Group conference, 2-6 sept 2024; BOU conference Birds and Net Zero, York, October 2024).
- Exploring opportunities for international cooperation within the framework of OSPAR and the Greater North Sea Basin Initiative (GNSBI), with countries around the North Sea with seabird colonies and the Joint Working Group Seabirds (OSPAR, HELCOM; ICES, 2023).

1.4 Overview

This report will work out the requirements for effective ecosystem-based management of the North Sea to realise a favourable status of all threatened seabirds. This has been worked out in the following sections and chapters.

Chapter 1 Introduction
Includes background, aims and approaches.

Chapter 2. Materials and methods

Chapter 3 Ecosystem-Based Management

- The principles and objectives of Ecosystem-based management are briefly reviewed with respect to EU-Directives and national policies.

Chapter 4 Ecosystem

- Review important habitats other than soft sediments, the key position of forage fish in the North Sea ecosystem with a focus on the food web, and overview ecology of seabirds.

Chapter 5 Pressures of seabirds in the North Sea

- Review fishing pressure on forage fish populations and identify knowledge gaps with respect to monitoring forage fish and the link with seabird populations.

Chapter 6 Enhancement measure for seabirds in the North Sea area

- Review terrestrial habitats: enhancement of colonies
- Review impact of restoration of important benthic habitats on fish populations, including seagrass beds, kelp forest, biogenic reefs such as worm reefs, mussel beds and oyster reefs.
- Explore measures and innovations to enhance forage fish stocks by other measures than quota, such as conservation of spawning sites and spawning populations.
- Explore innovations to enhance forage fish populations outside offshore wind farms.
- Review measures to enhance forage fish stocks, including protection and restoration of spawning sites, to improve the food availability of fish for seabirds.
- list of actions for NN-programme to enhance threatened seabirds.

Chapter 7 Research programmes, knowledge gaps & recommendations

- An overview is presented of national and international research projects with respect to the developments of offshore wind farms in the North Sea.
- The possibilities of international cooperation are explored.
- The latest version of the Regional Action Plan Seabirds (RAPS) of the Oslo Paris Convention (OSPAR) is reviewed.

Chapter 8 Conclusions, knowledge gaps and recommendations

- Major conclusions are given, relevant knowledge gaps are reviewed and recommendations for follow-up actions are given.

2 Materials and methods

2.1 Species selection

Over 30 species of seabirds regularly occur in the North Sea (Furness *et al.,* 2013) of which 17 were considered for inclusion in this report and 12 were finally selected (Table1). This selection was based on the numbers present and conservation status in the Dutch part of the North Sea, their inclusion in cumulative effect studies (KEC5.0; Potiek *et al.,* 2022; IJntema *et al.*, 2025) and species protection plans (Bos *et al.,* 2024a,b), their sensitivity to impact of offshore wind farms and the availability of compensatory measures developed in the UK. Although migrating land birds are included in the KEC5.0 study, these species do not forage in the marine habitat.

2.2 Conservation status and species protection plans

An overview of the conservation status is presented in Appendix I. For which species a species protection plan is published or planned is included in Table 2.1.

2.3 Ecosystem-based approach

In the management of marine areas and including spatial planning of human activities, several concepts have been developed and used to ensure that marine ecosystems remain healthy and productive. This approach implies that, natural resource management respects and base decision-making on the ecological limits and spatial boundaries of ecosystems (Kirkfeldt, 2019). These concepts are briefly discussed in Chapter 3, and ecosystem-based management is chosen as being most appropriate for the implementation of enhancement measures in the intensively used North Sea.

2.4 International cooperation

International cooperation for the implementation of enhancement measures can be established at (1) the governmental level, for example, the implementation of EU Directives (Marine Strategy, Bird Directive, Restoration Directive), and conventions such as OSPAR and (2) at the level of research institutes (universities and gouvernmental research institutes Deltares and Wageningen Marine Research).

The Northeast Atlantic region is the “working range” of several conventions including OSPAR (focus on general marine biodiversity), ICES (focus on sustainable use, including fish stocks) and HELCOM (focus on marine biodiversity in the Baltic). Within the EU, their aims generally overlap with the EU Marine Strategy Framework Directive (Good Environmental Status) and spatially overlap with the Marine Protected Areas of the EU Natura 2000 network.

Table 2.1. Overview of relevant seabird species considered for inclusion in this report based on designation of N2000-areas Brown Bank, Frisian Front, inclusion in KEC5.0, sensitivity to habitat loss, collision risk, and barrier effect, and for which measures are implemented in the UK to compensate for impact of offshore wind farms. Grey: seabird species not included in this report.

Name	Brown Bank	KEC 5.0	Species protection plan	Sensitive habitat loss	Sensitive collision risk	Sensitive barrier effect	Compensatory measures UK
Red-throated diver *Gavia stellata*		✓	✓	✓			
Northern fulmar *Fulmar glacialis*	*	✓	✓	✓			
Northern gannet *Morus bassanus*	✓	✓	✓	✓	✓	✓	✓
Cormorant *Phalacrocorax carbo*		✓					
Common scoter *Melanitta nigra*			✓				
Arctic skua *Stercorarius parasiticus*		✓			✓		
Great skua *Stercorarius skua*	✓	✓	✓		✓		
Little gull *Hydrocoloeus minutus*	✓	✓	✓		✓		
Lesser black-backed gull *Larus fuscus*	*	✓	✓		✓		✓
Herring gull *Larus argentatus*	*	✓	✓		✓		✓
Great black-backed gull *Larus marinus*	✓	✓	✓		✓		
Black-legged kittiwake *Rissa tridactyla*	*	✓	✓		✓		✓
Sandwich tern *Thalasseus sandvicensis*		✓	✓		✓	✓	✓
Common tern *Sterna hirundo*		✓	✓		✓	✓	
Guillemot *Uria aalge***	✓		✓	✓		✓	✓
Razorbill *Alca torda***	✓		✓	✓		✓	✓
Puffin *Fratercula arctica*			✓				✓

* under consideration

** Natura 2000 Frisian Front

KEC5.0 - Framework study cumulative effect offshore wind farms North Sea (IJntema *et al.*, 2025)

The rapid development of the rollout of renewable energy in the North Sea area has prompted several very recent initiatives for more cooperation: (1) the Joint Working Group on Seabirds (initiated in 2020); (2) the OSPAR Marine Bird Recovery Action Plan (initiated in 2022); (3) Intersessional Correspondence Group on Offshore Renewable Energy Development (ICG-ORED, initiated in 2023); and (4) Greater North Sea Basin Initiative (GNBSI, initiated in 2023). These developments will be further discussed in Chapter 6.

The international cooperation in research and monitoring we first describe are the national research programmes for the local impact of offshore wind farms on biodiversity in general and birds and bats in particular (WOZEP) and the ecosystem-wide impact at the level of the Dutch Continental Shelf (MONS). In addition, we highlight several very recent and ongoing research programmes on mitigation and compensation of impacts of offshore wind farms on seabirds in the UK. Finally, we give a brief overview of relevant national and international databases that are closely linked to the EU Directives and international conventions.

2.5 Literature review

To reach the research objectives a literature review was undertaken. For this review previous reports from Waardenburg Ecology were used as a starting point, after which Scopus was used (TITLE-ABS-KEY). In addition, grey literature, which includes governmental and consultancy reports, was used in this literature review. The search term used for Scopus was "(Wind farm OR OWF OR wind energy OR Offshore wind farm) AND (compens* OR "biological offset) AND bird". After using these search terms, the results were very limited (n=21).

This led to the choice of using the 'snowballing' procedure, in which additional publications are used that are in the reference list of or refer to the articles found with the search terms (Wohlin 2014). The results found with the search term were filtered on relevance and accessibility.

2.6 Glossary of terms

See Appendix II for a glossary of terms used in this report.

3 Ecosystem-based management

In the management of marine areas based on EU Directives, national policies and marine spatial planning, several ecosystem-based concepts have been developed and implemented to ensure that marine ecosystems remain healthy and productive.

The overall definition of ecosystem-based management is “the integrative or inclusive approach of management actions which considers (as much as possible) the positive interactions between complex marine habitats formed by ecosystem engineers and associated ecological groups which interact within the larger food web, such as invertebrates, fish, seabirds and marine mammals”. This approach implies that, natural resource management respects and base decision- making on the ecological limits and spatial boundaries of ecosystems (Kirkfeldt, 2019).

Three slightly different concepts are used: ecosystem-based management (EBM), ecosystem-based approach (EBA) and ecosystem approach (EA). Ecosystem-based management is in this report chosen as being most appropriate for the implementation of enhancement measures in the intensively used North Sea.

Kirkfeldt (2019) carried out a literature review of more than 100 publications and identified 11 principles, and 11 objectives linked to specific principles (Table 3.1). These principles are ranked according to the total number of publications using that principle in either EBM, EBA or EA definitions. The largest set of principles is included in EBM. Most principles are currently implemented in the international North Sea including the Dutch Continental Shelf (DCS) as part of EU Directives and national and international policy goals. For each principle and objective, the relevant legislation and policies are indicated.

These principles and objectives are briefly reviewed with respect to the North Sea ecosystem, EU Directives, marine spatial planning and policy goals, including the opportunities and challenges for the Nature Enhancement programme. Please note that these are preliminary indications and not based on an in-depth analysis of all relevant EU legislation and policies and Dutch programmes and policies.

The EU-legislation and policies and relevant Dutch policies are the Marine Strategy Directive (MSFD), the Common Fisheries Policy (CFP), Bird and Habitat Directive, Natura 2000 (N2000), the Nature Enhancement North Sea programme (NN), Nature Restoration Regulation (NRR) and the North Sea Agreement/MONS programme (NSA).

The overall comparison of EBM principles and objectives shows that the North Sea Agreement is an important link between the EU directives and the fisheries sector. In addition, it seems that the Nature Enhancement North Sea programme can be improved by including humans as part of the ecosystem, by considering social/cultural factors, applying the precautionary principle more explicitly, and to consider also economic factors, such as fisheries. Therefore, the challenge is to search for common objectives with the fisheries sector within the energy transition to realise the implementation of all principles and objectives of ecosystem-based management (EBM).

Table 3.1. *Principles and objectives of EBM-concepts, ranked according to the total number of publications using that principle in either EBM, EBA or EA definitions. 9a and 9b were cited in the same number of times (Adopted from Kirkfeldt, 2019). MSD: Marine Strategy Directive; CFP: Common Fisheries Policy; N2000: Natura 2000; NN: Nature Enhancement North Sea; NRR: Nature Restoration Regulation: NSA: North Sea Agreement/MONS. The Nature Enhancement North Sea programme is indicated in blue.*

Nr	Principles	Concepts	Objectives	MSD	N2000	NRR	NN	NSA	CFP
1	Acknowledge interlinkages	EBM, EBA, EA	Guiding actions	✓		✓	✓	✓	
2	See humans as part of the ecosystem	EBM, EBA, EA	Coexistence	✓	✓		✓	✓	✓
3	Consider cumulative impacts	EBM, EBA, EA	Impact management	✓	✓		✓		
4	Consider ecological/environmental factors	EBM, EA	Ecosystem/environmental management	✓	✓	✓	✓	✓	
5	Consider social/cultural factors	EBM, EBA, EA	Societal benefits					✓	✓
6	Balance objectives	EBM, EA	Natural resource management	✓	✓	✓	✓	✓	
7	Apply the precautionary principle	EBM, EBA, EA	Conservation		✓	✓			
8	Consider ecosystem services	EBM, EA	Sustainability			✓	✓	✓	✓
9a	Consider economic factors	EBM, EA	Economic benefits			✓		✓	✓
9b	Consider global trends	EBM, EA	Sustainability	✓		✓	✓	✓	✓
10	Base decisions on societal choice	EBM, EA	Human well-being				✓	✓	✓

Acknowledge interlinkages
This principle applies foremost to the trophic linkages within the food web and the links between ecosystem compartments such as bentho-pelagic coupling and interactions between land, including rivers, and sea (e.g. freshwater influence, nutrients among others). Other interlinkages include the impact of human activities on hydrodynamics, local climate, marine habitats, species groups and individual species. In addition, human activities are linked with other human activities, such as shipping lanes are linked with ports. The objective of this principle is to guide human activities, to respect these interlinkages, which is usually included in marine spatial planning. This principle is lacking or weakly developed in N2000 and CFP. The carbon sequestration potential in natural habitats and the possible negative effects of human activities on this potential is lacking in most legislation and policies, except for the Nature Restoration Regulation.

See humans as part of the ecosystem
The most important human activities in the North Sea include fisheries, gas and oil exploration, offshore wind farm and shipping (Figure 5.1). The impact of these activities on the ecosystem is substantial and therefore is this principle included in most if not all relevant legislation and policies (Table 3.1). The objective of this principle is to realise coexistence with other activities and the ecosystem.

Consider cumulative impacts
Although included in all three concepts, the cumulative impact of human activities and natural trends is mainly implemented in the MSFD (e.g. Kader Ecologie en Cumulatie, KEC), N2000-legislation and seems to be lacking in other legislation and policies. It is implemented in the MSP with respect to the construction of offshore wind farms. The objective of this principle is to manage the impact by mitigation and compensation.

Consider ecological/environmental factors
Ecological and environmental factors are included in most legislation and policies, except for the CFP, which mainly focuses on sustainable levels of fishing to keep the exploited stocks biologically save. The objective is to manage the ecosystem to make it more resilient to environmental variation.

Consider social/cultural factors
The attention for social and cultural factors is explicitly included in the CFP and NSA and aims for societal benefits. It is implicitly included in all other legislation and policies.

Balance objectives
The principle of balancing objectives with the aim of natural resource management is implemented in most policies and legislation except for CFP, which is mainly aimed at the regulation of fishing intensity to ensure the sustainability from the fisheries perspective.

Apply the precautionary principle
The precautionary principle with the aim of conservation of protected species and habitats is mainly implemented in the Bird and Habitat Directive and to a lesser extent in the Nature Restoration Regulation.

Consider ecosystem services
Ecosystem services are considered with the aim of sustainability in the Nature Restoration Regulation, Nature Enhancement North Sea programme, North Sea Agreement and is the central issue of the Common Fisheries Policy.

Consider economic factors
Economic factors to ensure economic benefits are included in the Nature Restoration Regulation, the North Sea Agreement and Common Fisheries Policy.

Consider global trends
Global trends with the aim of sustainability are considered in the Marine Strategy Directive (e.g. shipping, invasive species), the Nature Restoration Regulation (e.g. Carbon sequestration), the Nature Enhancement North Sea (e.g. global conservation status and migration of seabirds, marine mammals and large fishes), the North Sea Agreement and Common Fisheries Policy (global trends in fisheries and management of oceanwide fish stocks).

Base decisions on societal choice
The principle to base decisions on societal choice with the objective of human well-being is explicitly included in the North Sea Agreement and the Common Fisheries Policy and implicitly in the Nature Enhancement North Sea programme.

4 North Sea ecosystem

4.1 Introduction

This chapter give a comprehensive overview of the North Sea ecosystem with a focus on habitats (other than soft sediments) which are important for small fish, forage fish and their position in the food web as food for seabirds (Figure 4.1).

The main food of seabirds in the North Sea are forage fish (Table 4.1). In this report we define 'forage fish' as "species that occupy an intermediary trophic position and retain that ecological role throughout their life". We thus exclude from our definition species that assume this role early in life but later move into higher trophic categories as they age (e.g. Atlantic cod, pollock; Pikitch *et al.*, 2014; Engelhard *et al.*, 2014). The North Sea species in this category are herring, sprat, anchovy, pilchard (sardine), and sandeel. This group is also known as "small, pelagic fish" referring to their size and depth distribution or feeding guild. However, this category lacks the sandeel-species, which have a mixed demersal/pelagic life cycle. Furthermore, this description also lacks the important trophic position of forage fish between phyto- and zoöplankton at the lower trophic levels and the predators in the higher trophic levels.

Engelhard *et al.,* (2014) describe forage fish as: "planktivorous, pelagic species that often form the major food web component for transforming zooplankton production into food available to higher trophic levels. They are typically obligate schoolers and respond strongly to climatic changes. As they all feed mainly on zooplankton, forage fish may compete for food leading to potentially complex interactions".

4.2 Important habitats (other than soft sediments)

Some areas in the North Sea form biodiversity hotspots and are of particular importance to seabirds, because they provide the birds with direct or indirect access to food (fish and marine invertebrates). These areas are often occupied by ecosystem engineers (Meadows *et al.*, 2012; Coleman & Williams, 2002). Ecosystem engineers are defined by Jones *et al.,* (1994) as those species that "directly or indirectly modulate the availability of resources to other species by causing physical state changes in biotic or abiotic materials. In doing so they modify, maintain, and create habitats". These include marine habitats with provide high habitat complexity by 3D-structures, such as seagrass meadows, kelp forests and biogenic reefs formed by shellfish or polychaete worms.

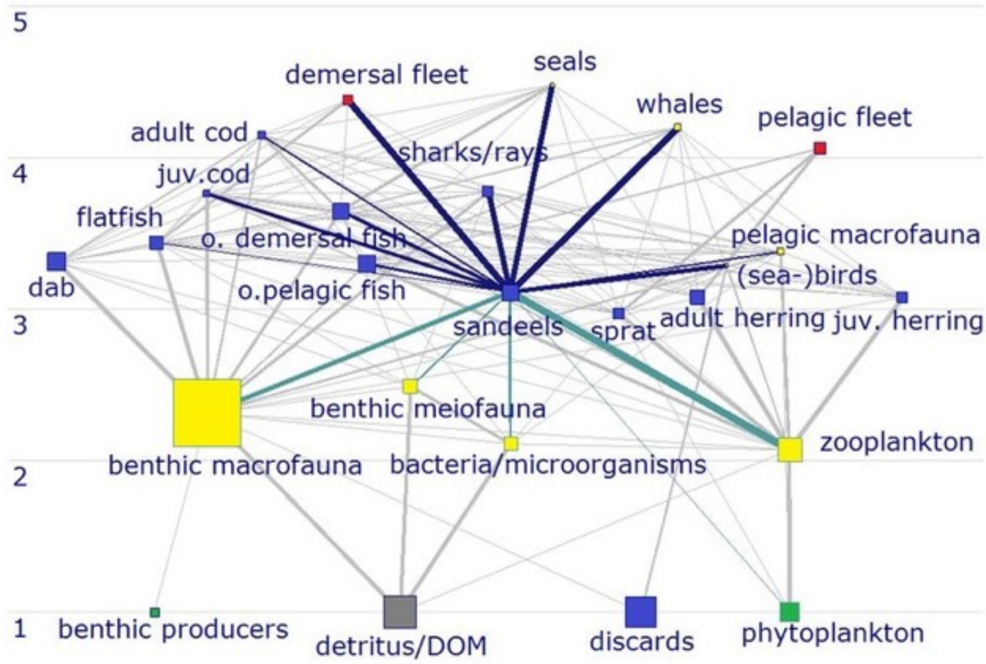

Figure 4.1. *Food web of the Southern North Sea showing the central position of sandeels, with the lines indicating the trophic flows and the numbers indicating the trophic level. The size of the squares is proportional to the biomass of a group, with grey representing detritus, green representing primary producers, blue representing fish, yellow representing marine organisms (except fish) and red representing fishing fleets (Otto et al., 2019)*

These habitats typically function (directly) as nurseries for many marine species (Dahlgren *et al.*, 2006; Lefcheck *et al.,* 2019; Joubert *et al.*, 2025; including fish and invertebrates; Figure 4.2-4.3) and may additionally act as their feeding grounds, spawning areas or migration routes (Seitz *et al.,* 2014). These species depend on these essential habitats for survival., Other species may benefit indirectly from these habitats as they forage on the organisms associated with these habitats and these include piscivorous fish, seabirds and marine mammals. Seagrass meadows, kelp forests and biogenic reefs all suffer from exploitation and other human activities (Coleman & Williams, 2002). Therefore, conservation and/or restoration of these habitats is a prerequisite to a viable North Sea ecosystem. As mentioned in chapter 3, the management of biogenic habitats and their associated ecological groups are a key issue in ecosystem-based management.

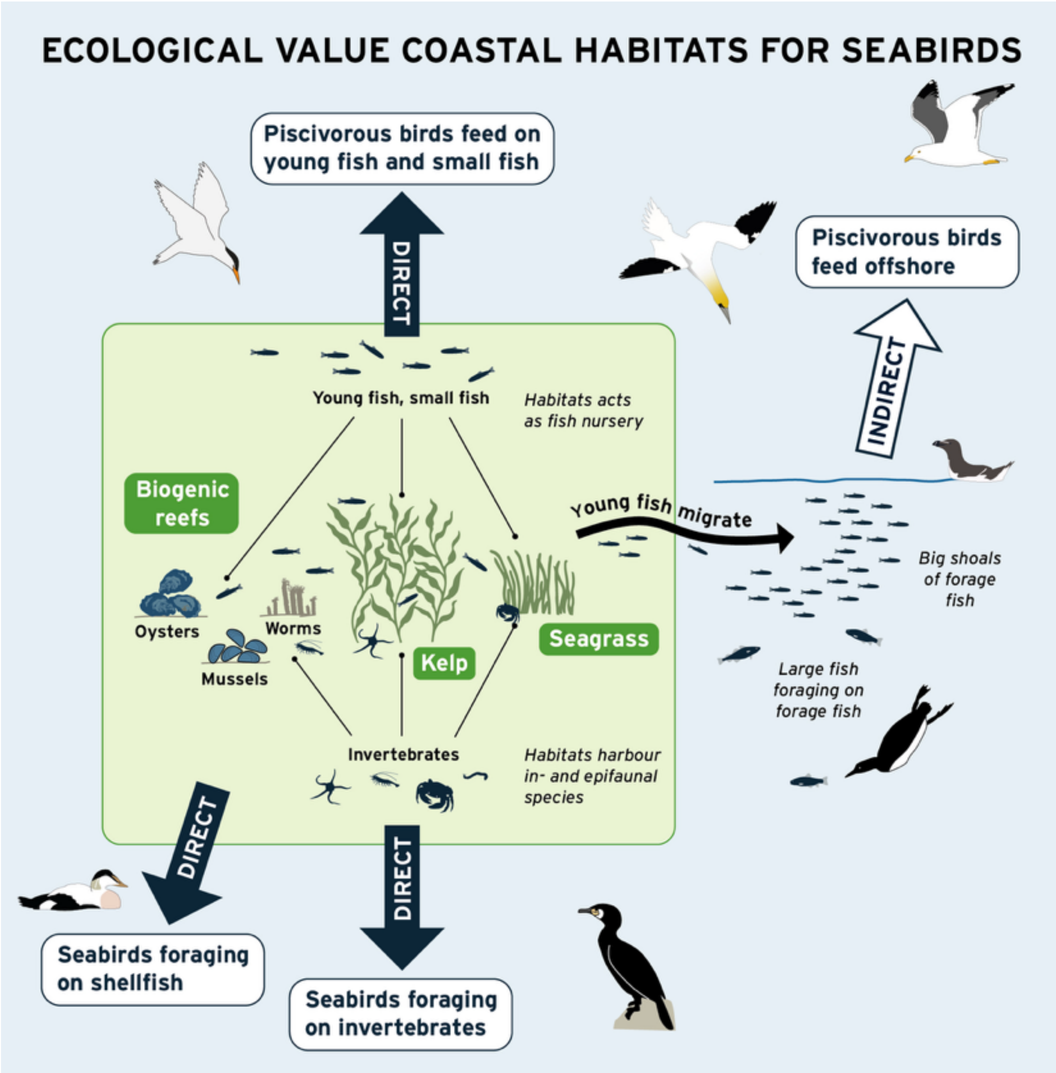

Figure 4.2. *Conceptual diagram: direct and indirect relationships between coastal marine habitats with high structural complexity and dependent or benefitting species.*

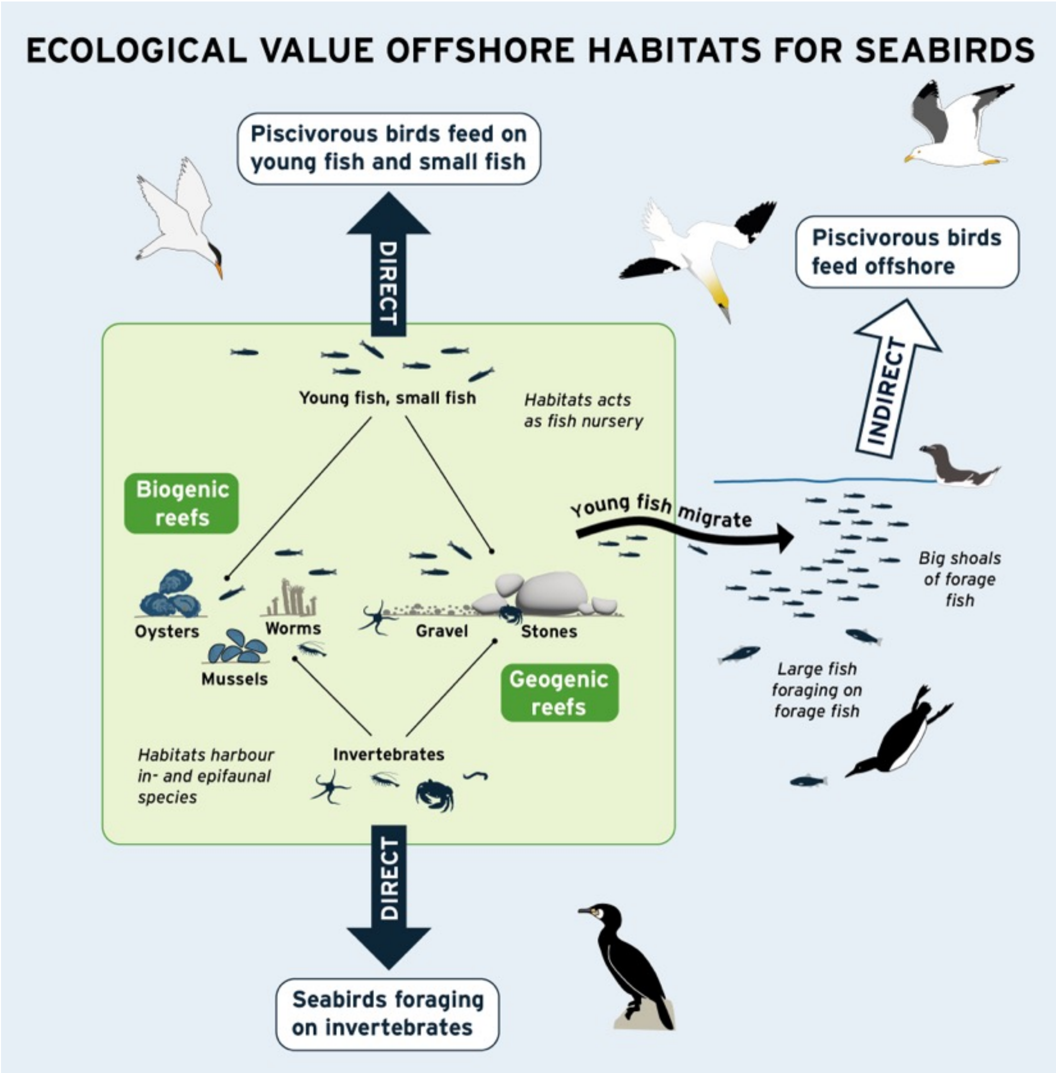

Figure 4.3. *Conceptual diagram: direct and indirect relationships between offshore marine habitats with high structural complexity and dependent or benefitting species.*

4.2.1 **Seagrass meadows**

Seagrasses, such as *Zostera marina*, are clonal, marine plants forming meadows in shallow coastal areas. In the North Sea, fish species recorded in seagrass meadows include sandeel, eel, herring, sand smelt, European sea bass, cod, whiting, salmon, and sea trout (Seitz *et al.,* 2014; Peters *et al.,* 2016). Several of these species are important forage fish for seabirds. Furness and Unsworth (2020) studied seagrass areas on the west coast of the UK and found the most prevalent fish species to be small-spotted catshark (also called lesser spotted dogfish), whiting, common dragonet and common goby. In a study in the Swedish Baltic Sea, Phil *et al.,* (2016) found that both fish numbers and fish biomass were more than two times higher in existing seagrass beds than in locations where seagrass had disappeared. Species richness was also higher in existing seagrass beds (Phil *et al.,* 2016), with abundant species belonging to the gobies and sticklebacks.

Seagrass is of great importance to birds, also to seabirds. Some species, such as geese, graze on seagrass, while others, such as waders, herons and gulls, forage on (small) fish and marine invertebrates living in the seagrass (Unsworth *et al.,* 2021). Seagrass also indirectly supports birds typically foraging miles away from this habitat. Pelagic seabirds are linked to seagrass through their fish prey, such as cod, herring and sprat, which often utilise seagrass as nursery habitats (Bertelli *et al.,* 2014; Unsworth *et al.,* 2018). Where seagrass meadows decline, there is evidence that this has negative effects on the pelagic fish stocks (Seitz *et al.,* 2014), which in turn will have negative effects on seabird populations.

4.2.2 Kelp forest

Kelp seaweeds, such as *Saccharina latissimi* and *Laminaria hyperborea*, occur in coastal areas of the North Sea up to a depth of some 30 m and can grow into large forests. Currently, data on kelp-associated fish assemblages in the North Sea are very limited, possibly due to the challenges of catching or observing fish in dense kelp forests. Seitz *et al.,* (2014) list as North Sea species: eel, cod, pollack, saithe, salmon and sea trout. Common species of kelp on the west coast of the UK are two-spotted goby, European pollack (or pollock) and ballan wrasse (Furness and Unsworth 2020).

Kelp forests directly provide food (fish) for diving seabirds, such as cormorants. In a large-scale experiment off the coast of central Norway, Loretsen *et al.,* (2010) studied the effect of kelp harvesting on the presence of gadid fish (cod, pollock, haddock, whiting) and the foraging behaviour of great cormorants (*Phalacrocorax carbo carbo*). They found that kelp harvesting dramatically reduced the number of juvenile gadid fish, and that cormorants largely ignored harvested areas when foraging. The work of Loretsen *et al.,* (2010) shows an effect of disturbance of a coastal marine habitat at a multi-trophic level, stressing that ecosystem-wide knowledge is crucial when drawing up plans to increase the resilience of the North Sea ecosystem.

Vandendriessche *et al.,* (2007) showed that in the North Sea, many seabird species associate with rafts of floating seaweed. Such floats may provide the seabirds with food in the form of small fish taking refuge in these floats, and the seaweed itself may be used as nest material (Furness and Furness 2025).

4.2.3 Blue mussel (*Mytilus edulis*)

Mussel beds occur at intertidal areas of the North Sea. These beds are relatively poor in fish, although gobies do occur (Asmus 1987) and herring use mussel beds for spawning (Seitz *et al.,* 2014). Mussel beds, however, do hold many species of polychaete (bristle) worms and crustacea (Buschbaum *et al.,* 2009). Moreover, in the North Sea, mussel beds are more species-rich than surrounding sediments without mussels (Buschbaum *et al.,* 2009).

The mussels themselves are an important food source for eider duck and oystercatcher, but also are predated on by herring gulls, a seabird species (Hilgerloh 1997). Gulls also feed on the epifauna attached to the buoys that are used in aquacultures of blue mussel (Roycroft *et al.,* 2007).

4.2.4 European flat oyster (*Ostrea edulis*)

European flat oysters, also called native oyster, grow in dense reefs from the intertidal zone to depths of some 80m. These bivalves were once very common around the coast, but they have now virtually disappeared from the intertidal and shallow sublittoral zone because of over-exploitation, habitat damage and disease. Consequently, not much is known about fish assemblages in naturally occurring native oyster reefs. A recently discovered natural reef, composed of both native and non-native (Pacific) oysters as well as blue mussels, held five-bearded rocklings and rock gunnels (Christianen *et al.,* 2018).

Many populations are now artificially laid. One such restoration project, in the German Bight, found that already after one year, a dozen or so fish species, such as dragonets and wrasses, were present at the site (Pineda-Metz *et al.,* 2023). Typical seabird forage fish were not (yet) observed.

Herring gulls have learned to feed on Pacific oysters by dropping them on hard substrate (Cadée 2008). Herring gulls are also known to feed on animals associated with Pacific oyster beds, such as crabs (Waser *et al.,* 2016). Likely, these birds would also forage on native oysters, if these would be available.

4.2.5 Ross worm (*Sabellaria spinulosa*)

S. spinulosa is a sedentary polychaete worm, constructing tubes of sand and shell fragments in the sublittoral zone. Although it typically lives solitary, it can form biogenic reefs. Video footage collected during an exploratory survey of *S. spinulosa* reefs located in the Brown Bank area revealed the presence of many different species of fish, such as dragonets and flatfishes (Van der Reijden *et al.,* 2019). Some species occurred at densities of several individuals per 100m^2 (Van der Reijden *et al.,* 2019). Van der Reijden *et al.,* (2019) also found that the long-clawed porcelain crab is massively abundant between the tubes of the *S. spinulosa* reefs, which is a very important prey item for many associated fish species. Moreover, they observed small-spotted catshark to rest in between *S. spinulosa* reefs. Although these observations show the importance of *S. spinulosa* reefs for the North Sea ecosystem, it is unknown if, and in what way, seabirds profit from these reefs.

4.2.6 Lanice-reefs

Biogenic reefs composed of the tube-building polychaete *Lanice conchilega* are important from a conservation point of view because they noticeably increase the biodiversity in otherwise species poor environments (DeSmet *et al.,* 2025). In a study of intertidal reefs, it was found that *L. conchilega* reefs positively affect several types of benthic communities

(Figure 4.3; DeSmet *et al.,* 2025). In general, *L. conchilega* reefs do not only affect abundances and diversity but they substantially steer the structure of the intertidal benthic sandy beach ecosystem. It is assumed that this effect also occurs in subtidal areas.

The structuring effect of Lanice reefs on the distribution of plaice *Pleuronectes platessa* was studied in an intertidal nursery area with an experimental design (Rabaut *et al*., 2009). The density distribution of this flatfish species is significantly explained by the presence of Lanice reefs. The importance of this reef builder has been shown before, but this study demonstrates that not only the benthic biodiversity is affected by Lanice reefs, but that the distribution pattern of plaice is structured by them as well. This structuring impact of small-scale benthic reefs creates a patchy environment in nursery areas and potentially plays an important role in other marine environments, such as subtidal and offshore areas.

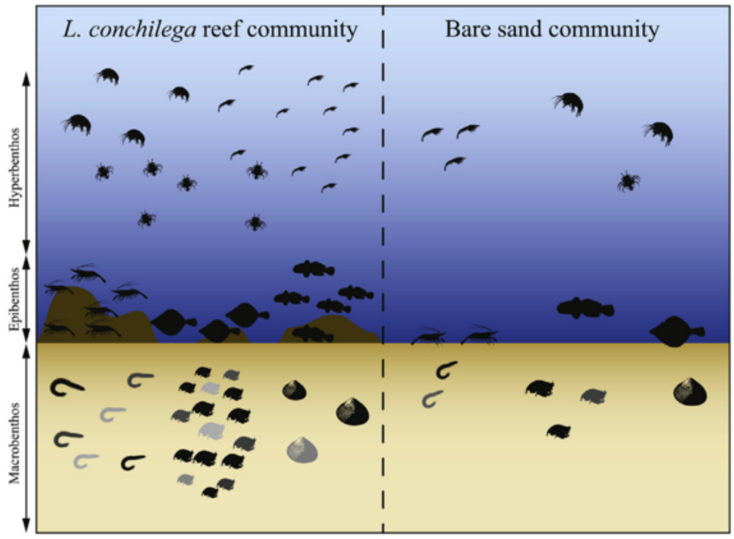

Figure 4.4. Schematic overview of the effect of the L. conchilega reef (left) and a bare sand habitat (right) on the macro-, epi-, and hyperbenthic communities of an intertidal sandy beach food-web. Differential dependency of the benthic communities to the sea floor account for differences in the extent of the structuring effect of the L. conchilega reef in terms of abundances (number of symbols) and species diversity (different shades of grey). Macrobenthos: polychaetes (e.g. Eumida sanguinea), amphipods (e.g. Urothoe poseidonis) and bivalves (e.g. Cerastoderma edule); Epibenthos: Crangon crangon, Pomatoschistus sp., flatfish sp. (Pleuronectes platessa); Hyperbenthos: mysida (Mesopodopsis slabberi), amphipoda (Nototropis swammerdamei) and decapod megalopa larvae (De Smet et al, 2015).

The importance of temperate, estuarine polychaete reef habitats for estuarine fish communities was recently studied by Schroder *et al.,* (2025) in Australia. They found positive associations with demersal gobies and juveniles of estuarine species. These categories of fish species are like those occurring in the Northern Hemisphere in the North Sea and suggests that these associations are a basic feature of polychaete reefs worldwide.

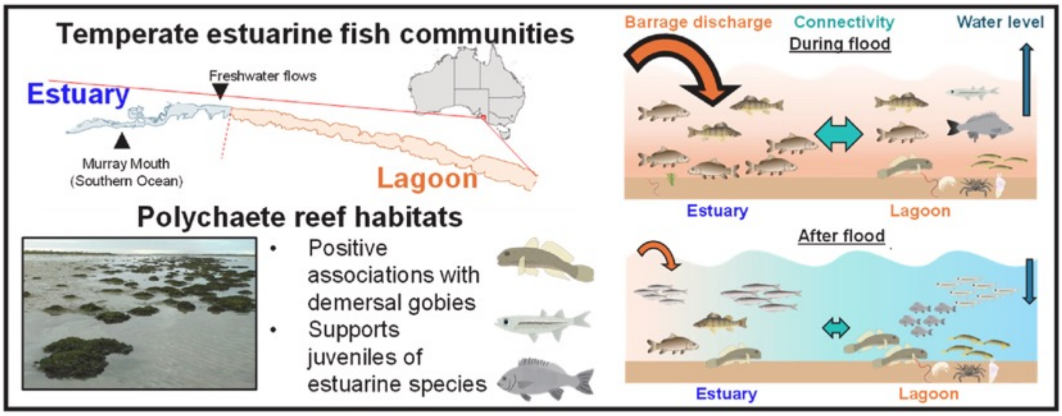

Figure 4.5. Graphical summary of the relationships between polychaete reef habitats and fish communities (Schroder et al., 2025).

4.3 Forage fish: species accounts & stock size

Four species are relevant in the southern North Sea including the DCS: herring *Clupea harengus*, sprat *Sprattus sprattus*, sandeel Ammodytes marinus and Norway pout *Trisopterus esmarkii*. Herring supports an important targeted fishery for human consumption; sandeel, sprat, and Norway pout that support a substantial industrial fishery for fishmeal and fish oil. Two other forage fish species, European sardine (or pilchard) *Sardina pilchardus* and European anchovy *Engraulis encrasicolus* have a low abundance and are not included.

Several small, pelagic species, including herring and sprat, are monitored in the international HERAS-monitoring programme in June and January (Figure 4.6-4.7). Recently, this programme has been complemented by the MONS-survey of small, pelagic fish, including herring, sprat, pilchard, anchovy in the Dutch coastal zone in June and January (Couperus *et al.*, 2024).

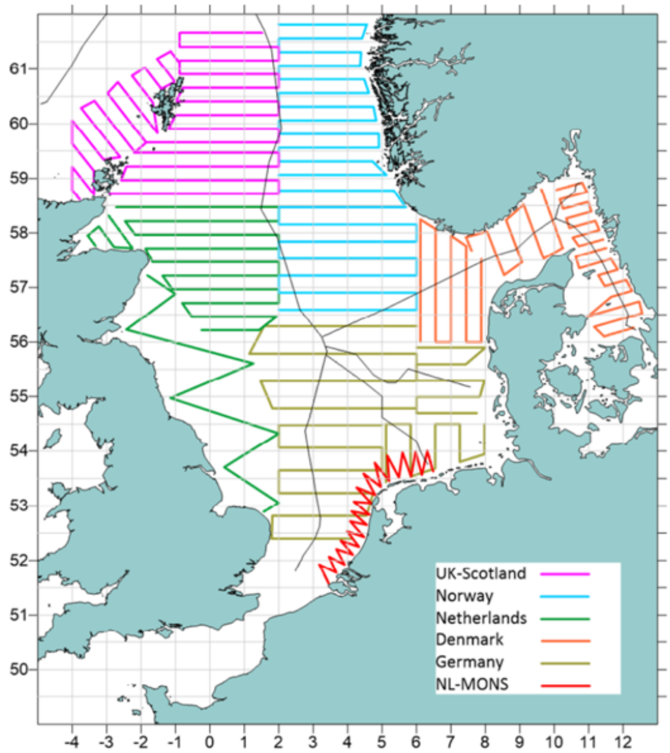

Figure 4.6. The zigzag transect of the MONS summer survey in 2023 was designed to join, and partially overlap, the international herring acoustic survey (HERAS) displayed by the transects performed yearly by each participating country (Couperus et al., 2024).

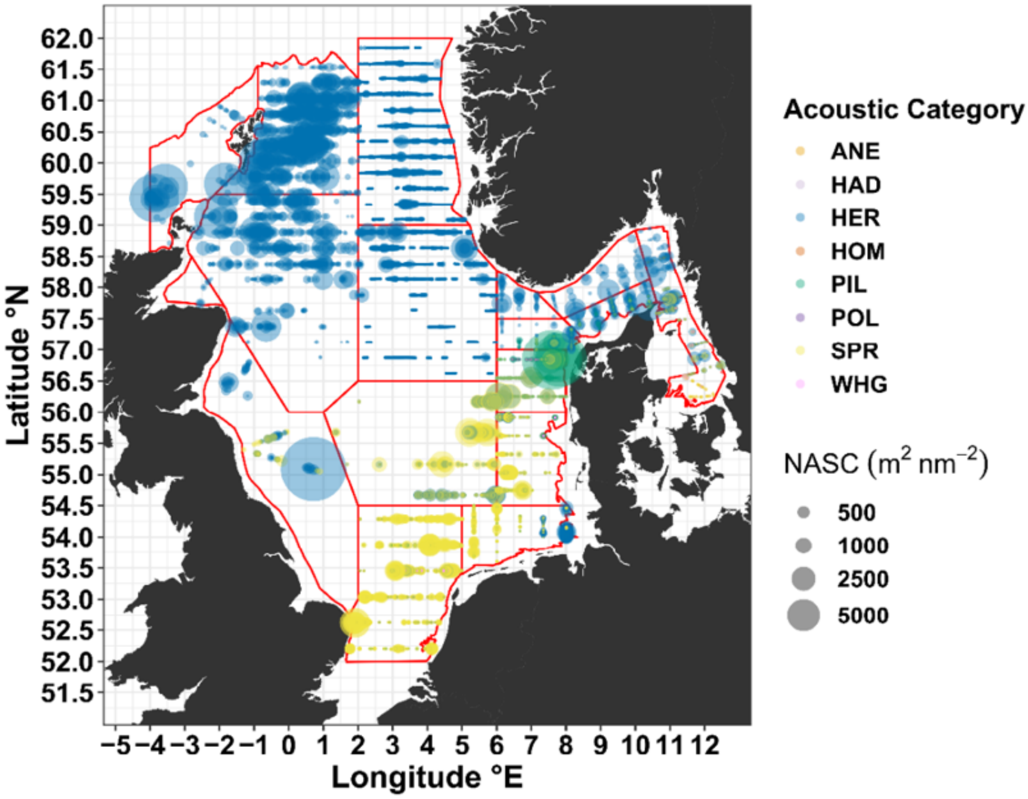

Figure 4.7. *Densities of small pelagic species (forage fish and young stages of haddock, pollock and whiting) determined by the HERAS survey, June 2023 – Disaggregated hydroacoustic categories assigned to hydroacoustic data after implementing the splitNASC-process in StoX software. Aggregated acoustic categories: CLU – Clupeids. MIX – Clupeids plus various other fish species. Disaggregated acoustic categories: ANE – anchovy. HAD – haddock; HER – herring; HOM – horse mackerel; PIL – pilchard; POL – pollock; SPR – sprat; WHG – whiting (Source: Couperus et al., 2024).*

4.3.1 Herring

Atlantic herring (*Clupea harengus*) is a small, pelagic species and one of the most abundant fish species in the world. The distribution range includes both sides of the northern Atlantic Ocean. They live in large schools and can reach a size of up to 45 cm in length. They feed on zooplankton (copepods, krill) and small fish, while their natural predators are larger fish, birds, seals and whales. Therefore, they have an important trophic position in the North Sea food web. Herrings reproduce at the age of 3 to 5 years. The life expectancy once mature is 12 to 16 years. Atlantic herring may have different spawning components within a single stock which spawn during different seasons, locations and habitats. They spawn in estuaries, coastal waters or in offshore banks.

In the North Sea the estimated spawning stock biomass (SSB) of herring declined rapidly in the fifties and sixties due to overfishing until it fell far below the biological safe limit and the fishery was closed (Figure 4.8). Stock size increased again but never reached the level of the early fifties and is in recent years just above the biological safe limit (ICES, 2023). ICES advises that no activities on spawning habitats should be allowed unless the effects of these activities have been assessed and shown not to be detrimental.

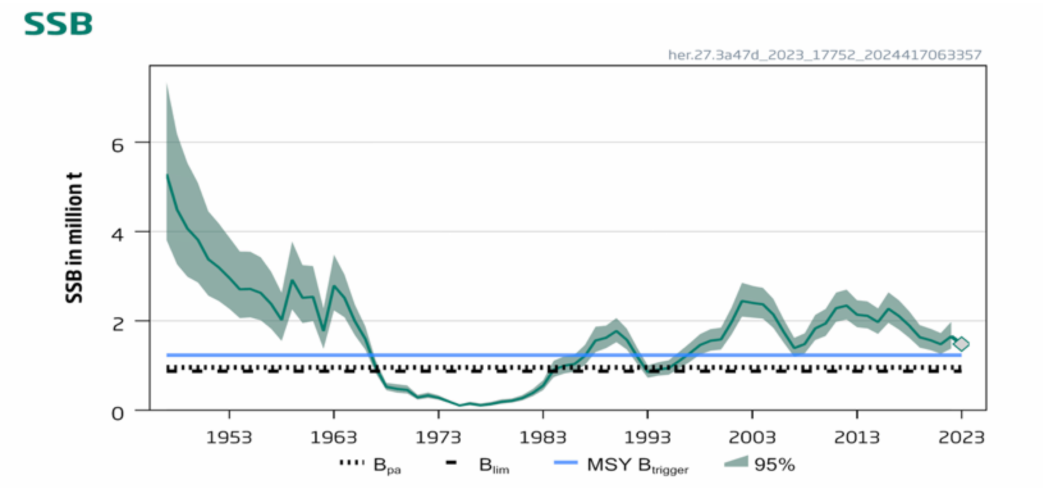

Figure 4.8. Herring spawning stock biomass (SSB) in the greater North Sea area 1950-2023 (ICES 2023).

4.3.2 Sprat

The following text is adapted from ICES 2005. Species factsheet – sprat.
Sprat is a small, pelagic species that is most abundant in relatively shallow waters, including areas of low salinity such as the Baltic (ICES, 2005). It is important food for large fish, seabirds and marine mammals. Sprat is mainly landed for industrial processing (often mixed with juvenile herring), but a small market exists for human consumption (smoked sprat and whitebait). Sprat is widely distributed in the shelf waters of Europe and North Africa, ranging from Morocco to Norway, including the Mediterranean, Black Sea and Baltic Sea, but stays largely within the 50 m depth contour and is also common in inshore waters. Sprat is most abundant south of the Dogger Bank and in the Kattegat.

Spawning occurs in both coastal and offshore waters, during spring and late summer, with peak spawning between May and June, depending on water temperature. Spawning generally takes place at night. The eggs (0.8- 1.3 mm in diameter) and larvae of sprat are pelagic. Important spawning areas are situated in the inner German Bight, off Jutland, along the English coast, and in areas west and north of Scotland. The larvae are known to be most abundant in the vicinity of tidal mixing fronts. Sprat is short-lived and rarely attains an age of more than five years or a length of >16 cm.
During winter young fish migrate towards inshore waters, though older fish are likely to remain offshore. Sprat shoals also undertake vertical migrations on a diurnal basis, with schools moving to surface waters at dusk. Larvae feed on diatoms, copepods and

crustacean larvae. Older age classes feed on larger planktonic organisms, including cladocerans, Oikopleura, bivalve larvae, mysids, and euphausids. Sprat forms an important prey for many commercially important predatory fish such as the larger gadoids, as well as seabirds.

The spawning stock biomass (SBB) of sprat declined rapidly in the early eighties (Figure 4.9) to levels below the biological safe limit and increased in the nineties up to level above or just at the biological safe limit. The current level (2024) is below the biological safe limit (ICES 2024).

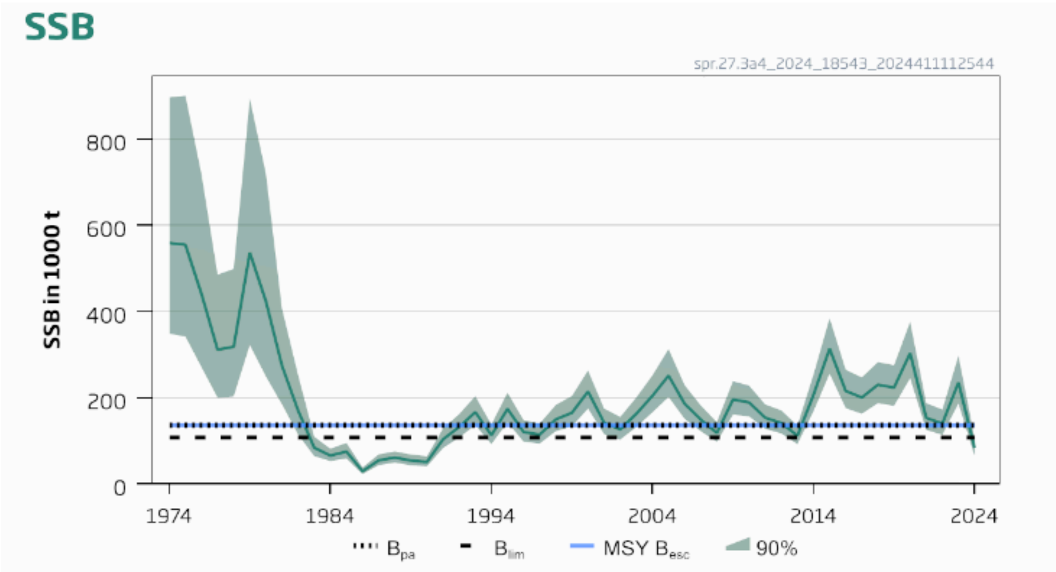

Figure 4.9. *Sprat population in Division 3.a and Subarea 4. Summary of the stock assessment. Years refer to the model year, July to June; recruitment and SSB as of 1st July. The paler shaded recruitment value for 2024 is assumed. Catches for 2023 are preliminary and only include catches up to 1st March 2024 (paler shaded bar; ICES 2024).*

4.3.3 Sandeel species

The following text is adapted from the project "FORAGE FISH", carried out by NIOZ (the Royal Netherlands institute for sea research) in collaboration with Wageningen University & Research, CEFAS and St. Andrews University and RWS Wozep. Sandeels are small, slender, semi-pelagic fish that live buried in the seabed for much of the year. In most cases, they live in a specific area on the top of the sandbanks, where they burrow tail-first into the coarse sand. They only emerge from the seabed during short spawning periods and in spring and early summer, when they forage on plankton ranging from small plankton eggs to larger energy-rich copepods.

The spawning periods vary for the three species of sand eel. The great sand eel (*Hyperoplus lanceolatus*) spawns in April-September, the lesser sand eel (*Ammodytes tobianus*) in December-January, and small sand eels (*Ammodytes marinus)* in February-April and September-November. All three species lay their eggs in the sand, where they mature for a few weeks before hatching. The larvae float on the current to other areas where they settle in the seabed again.

The following text is adapted from https://www.habitas.org.uk/priority/species.asp?item=100014

The lesser sand eel *Ammodytes marinus* is a shoaling species which alternates between lying buried in the sand at night and hunting for prey in mid water during daylight. It feeds mainly on plankton and high activity periods are associated with strong tidal currents when they leave their burrows and form large shoals. During low light intensity periods such as at night or in winter they bury themselves into the bottom. They have neither a swim bladder nor fins. *A. marinus* is of great importance as a food source.

Found widely distributed throughout the North Sea. Extremely common offshore in northern European Seas and occasionally found, mostly as juveniles, in inshore habitats. Typically found at depths greater than 30 metres in sand and fine gravel. They are an important food source for a wide range of predatory fish and seabirds and marine mammals. The main threats are overfishing, climate change and renewable energy developments

Lesser sand eels can reach a maximum length of 25 cm. It is a relatively short-lived species living up to 9 years. Spawning usually takes place in winter between November and February. The eggs are laid in sticky clumps on sandy substrates at the bottom of the sea. The hatched larvae remain in the water column before settling near the seabed approximately 2-5 months after hatching. There is little movement between spawning and feeding grounds which suggest that foraging and spawning grounds coincide. Maturity is attained mainly at the end of the second year with some maturing in the first year.

Lesser sand eels feed on plankton, worms, small crustaceans, including fish eggs and larvae. In spring lesser sand eels emerge from the seabed to feed on plankton. The availability of suitable seabed substrate is an important factor driving sand eel distribution and in addition the highest sand eel densities have been found where zooplankton concentrations are also high.

The spawning stock biomass (SSB) of sandeels in the two of the divisions of the North Sea relevant for the Netherlands (1r and 2r, Figure 4.10) is highly variable. In division 1, the SBB was variable and in recent years around or just above the precautionary reference level (Bpa, Figure 4.11-4.12). In division 2 the SSB was relatively high up to 2003 after which it declined to below the biological safe limit (Blim, Figure 4.12). Since then, SSB remained low just above Bpa. The ICES advices that no activities on spawning habitats should be allowed unless the effects of these activities have been assessed and shown not to be detrimental (ICES 2023b, 2024b)

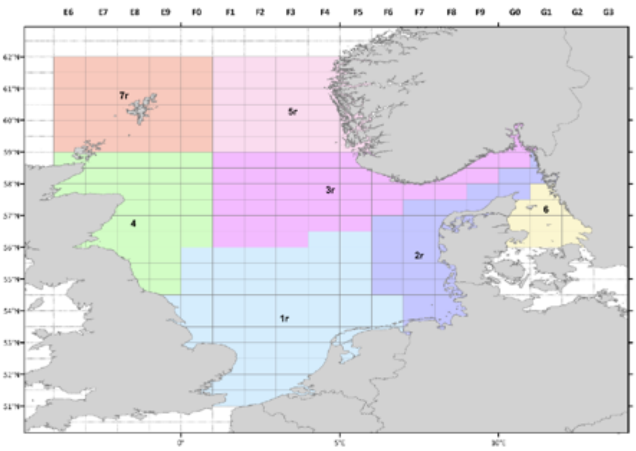

Figure 4.10. *Location of the sandeel areas (1-7r) in the North Sea (ICES 2017). Areas 1r and 2r are relevant for the Dutch EEZ.*

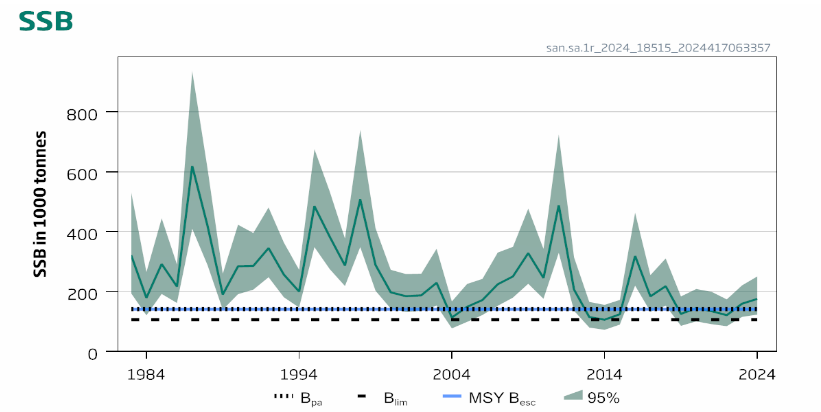

Figure 4.11. *Sandeel spawning stock biomass (SSB) in division 1 Southern North Sea 1984-2024 (ICES 2024).*

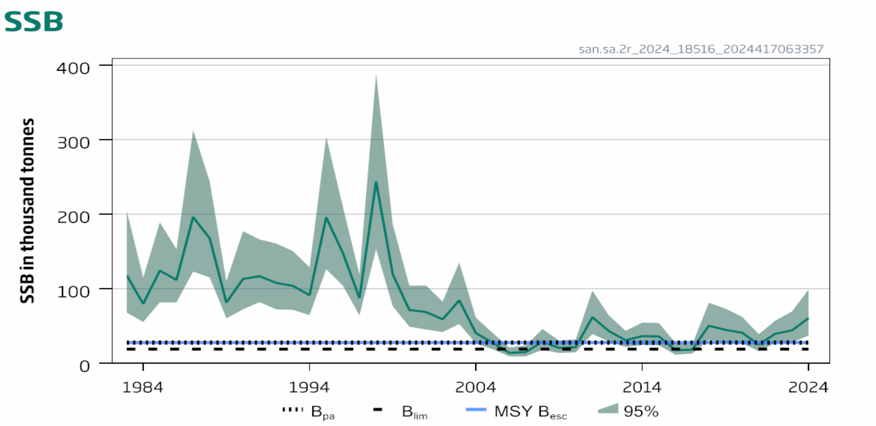

Figure 4.12. *Sandeel spawning stock biomass (SSB) in division 2 Southeastern North Sea 1984-2024 (ICES 2024).*

4.3.4 **Other species**

A recent analysis of benthic sampling surveys with the Triple-D (deep digging dredge) in the North Sea revealed that the small fish biomass in the Dutch Exclusive Economic Zone and parts of the Dogger Bank is much higher than previously estimated with bottom trawling surveys (total biomass of small fish: Figure 4.13; Parmentier *et al.*, 2025). The most common species in this survey were dab *Limanda limanda*, dragonet spp., goby spp., plaice *Pleuronectes platessa*, sandeel spp. Ammodytes sp., scaldfish *Arnoglossum luteum*, and solenette *Buglossidium luteum.* The high biomasses in the UK part of the Dogger Bank are formed by sandeel-species. This discussed in more detail in paragraph 6.4.2.

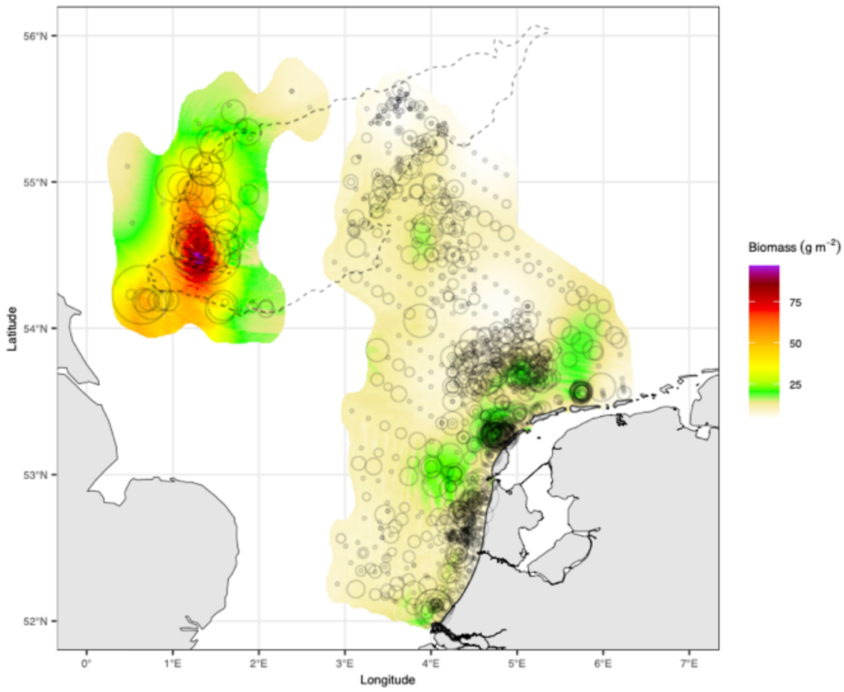

Figure 4.13. Distribution of total biomass of small fish (<30 cm) in the southern North Sea. Biomass estimates for the Dutch EEZ are a winter prediction, while estimates for the UK Dogger Bank reflect summer conditions. Size of black circles correspond with the observed biomass densities per station (corrected for haul distance and sorting fraction). The 40 m depth contour of the Dogger Bank is indicated by the black dashed line (Parmentier et al., 2025).

4.4 General ecology seabirds North Sea

The general ecology of the relevant seabird species is briefly summarized in Table 4.1. This selection of seabird species all makes use of the same area, the North Sea, but differ in the spatial and temporal occurrence of this area, food type and in the method of obtaining their preferred food. In this way competition is reduced and can they coexist in the wider North Sea area (e.g. Petalas *et al.,* 2024). On the other hand, due to the difference in ecology, pressure factors and their impact on these seabird populations will also differ substantially (e.g. Fauchald *et al.,* 2011).

4.4.1 Food

Most selected seabird species are highly specialized in locating, catching and transporting fish (except for the kleptoparasitic skuas and little gull). Forage fish species constitute the main prey for most of the selected seabird species. These include pelagic species: herring (*Clupea harengus*), sprat (*Sprattus sprattus*) and European anchovy (*Engraulis encrasicolus*) and sandeel species (lesser sandeels *Ammodytes spp*., greater sandeels *Hyperoplus spp*.), which live as adults in sandy sediments (during night and winter) or in pelagic shoals.

4.4.2 Foraging

In contrast with the high overlap in prey choice, the selected seabird species differ in the how they catch their prey (Table 4.1). The skuas, which are like gulls in their morphology, are **kleptoparasites** and usually steal their prey from seabirds. After persistent pursuits the seabird victim let their prey (usually fish) loose or regurgitate it. Northern gannets are plunge divers and feed by **deep plunging** on pelagic fish shoals of various species (up to 30 cm length) such as herring, sprat, anchovy, sandeel, mackerel, Atlantic cod, and others. The gull species are all **surface feeders** and take small (little gull) to large items (herring gull, lesser black-backed gull, great black-backed gull) including forage fish and invertebrates and occasionally steal prey items from other seabirds (kleptoparasitism). Black-legged kittiwakes are also surface feeders and take forage fish, including sandeels and small-sized herring and sprat and are more sensitive to prey availability near the surface compared to the plunge and pursuit divers. The terns, Sandwich tern and common tern, feed on small-sized forage fish (herring, sprat, sandeel) by shallow **plunge diving**. Northern gannets are also plunge divers, but practice **deep plunging** to at least 11 m and possibly to around 25 m (Ropert-Coudert *et al*., 2009). Common guillemot and razorbill are **pursuit divers** and acquire their prey by “flying” or swimming with their wings underwater. They forage on small-sized forage fish, including herring, sprat and sandeels, but also invertebrates and small-sized or juvenile demersal fish.

Table 4.1. General ecology of the selection of seabird species with scientific name, feeding type (surface feeder, surface plunging, deep plunging, pursuit diver, kleptoparasite), colony habitat, summer foraging habitat and winter foraging habitat and migration distance.

Bird species	Type of feeding	Colony habitat	Foraging habitat summer	Foraging habitat winter	Migration distance
Red-throated diver	Pursuit diver	Inland lakes	Inland lakes	North Sea	Medium
Northern fulmar	Surface feeder	Cliffs	North Sea	North Sea, North Atlantic	Medium
Northern gannet	Deep plunging/ plunge diver	Cliffs	North Sea	North Sea, North Atlantic	Medium/long
Arctic skua	Kleptoparasite	Tundra	Tundra, Barents Sea	Atlantic	Long
Great skua	Kleptoparasite	Tundra	North Sea	Atlantic	Medium
Little gull	Surface feeder	Inland lakes	Inland lakes	North Sea, North Atlantic	Medium
Lesser black- backed gull	Surface feeder	Dunes, cities	North Sea, inland	North Sea, North Atlantic	Medium/long
Herring gull	Surface feeder	Dunes, cities	North Sea, inland	North Sea	Short
Great black-backed gull	Surface feeder	Cliffs	North Sea	North Sea	Short
Black-legged kittiwake	Surface feeder	Cliffs	North Sea	North Sea, North Atlantic	Medium
Sandwich tern	Surface plunging	Islands	North Sea	Africa	Long
Common tern	Surface plunging	Islands	North Sea, inland lakes	Africa	Long
Razorbill	Pursuit diver	Cliffs	North Sea	North Sea, North Atlantic	Medium
Guillemot	Pursuit diver	Cliffs	North Sea	North Sea, North Atlantic	Medium

4.4.3 Multi-species feeding associations

Many seabird species are highly social and are often seen foraging in groups consisting of several different species, a phenomenon termed multi-species feeding associations (MSFAs). MFSAs occur in all the world’s seas and oceans (Veit and Harrison 2017), showing how important these are to seabirds as a species group. In the North Sea, MSFAs may in fact be more common than mono-species feeding groups (Camphuysen *et al.,* 2007). Although MSFAs may form around fishing trawlers (Camphuysen and Webb 1999), most MSFAs are formed ‘naturally’ around shoals of forage fish, like sandeel, herring and sprat. Groups of deep-diving seabirds, such as guillemots and razorbills (or other underwater predators, such as large fish, cetaceans or seals) drive the fish to the surface, where these then become available to surface feeding or shallow plunging seabirds (Camphuysen and Garthe 2004). MSFAs may thus increase the feeding success of (at least part of) the participants (Veit and Harrison 2017). In the North Sea, kittiwakes are typically the first to discover the dense balls of fish driven to the surface by auks or other predators. The kittiwakes' activity subsequently attracts other seabirds, such as large gulls, skuas and gannets to the feeding site. Kittiwakes seem to be especially bound to MSFAs, but each of the seabird species listed in Table 4.1 can be found in MSFAs (Camphuysen *et al.,* 2007). Next to auks, in the North Sea, predators frequently observed to drive fish to the surface are harbour porpoise, white-beaked dolphin and minke whale (Camphuysen and Webb 1999).

The dependency of surface feeding or shallow plunging seabirds on other marine animals to drive forage fish to within their reach means that any decrease in population size in the latter group will have a knock-on effect on the former group. In other words, conservation of any one species of seabird must take into consideration the status and possible conservation of those species that the focal species benefits from while foraging (Veit and Harrison 2017). This again stresses the need for an ecosystem-based approach when aiming to protect (or boost) the seabird populations of the North Sea.

Breeding

Most selected seabird species breed in large colonies on steep cliffs (northern gannet, black-legged kittiwake, razorbill, common guillemot), predator-free islands (Sandwich tern, common tern), or loose colonies in dunes, salt marshes and urban areas (herring gull, lesser black-backed gull) or tundra (Arctic skua). Exceptions are great skua (breeds dispersed on tundra and remote islands), little gull (in mixed gull colonies at inland lakes), great black-backed gull (dispersed colonies on rocky coasts) (Table 4.1). During breeding most selected colonial seabird species are dependent on the availability of forage fish stocks relatively close to the breeding colony. In addition, both intra- and inter-specific competition will determine the foraging distance and range, which can vary from tens of kilometres in alcids, gulls and terns up to hundreds of kilometres in northern gannets (e.g. Bolton *et al.,* 2019).

It should be noted that the actual number of birds breeding in a specific year is not a direct measure of the population size. Individual birds may decide not to breed depending on the food availability or other factors such as age. Non-breeding birds, including immatures, may not be present on or near the colonies and therefore difficult to estimate.

Most selected seabird species produce only one, relatively small clutch (1-3 eggs) without the possibility of relaying. Individual birds start at a late age with breeding up to six to seven years in the larger species. These life history characters are also linked with low adult mortality and a long lifespan (for example, Northern gannet has an average life span of 17 years, with individuals reaching 37 years of age; Mitchell *et al.,* 2004). These factors make the selected seabird species very sensitive for additional adult mortality and is responsible for the low resilience of seabird populations to pressure factors and ecological risks.

4.4.4 Migration

All species are highly migratory (short to long-distance), which depends on the breeding latitude, feeding behaviour and availability of preferred prey (Table 4.1). The plunge-divers Sandwich tern and common tern are long-distance migrants up to the African coasts in the South Atlantic, as their preferred prey, small-sized clupeids, are not available at the sea surface during winter. They are often followed by their kleptoparasite, the Arctic skua, which migrates to the wider South Atlantic including the South American coast (Van Bemmelen *et al.,* 2024). The pursuit divers, common guillemot and razorbill still can find their forage fish prey during winter in the North Sea and are medium distance migrants within the North Atlantic. Most of the gulls can switch to other prey items and coastal and terrestrial prey and are therefore short to medium distance migrants.

4.5 Species accounts

4.5.1 Red-throated diver *Gavia stellata* A001

Red-throated diver is a migrant and winter visitor in the Netherlands and breeds in the boreal and arctic areas from West-Greenland to Taimyr, Russia (SOVON, 2022). During winter they stay predominantly in the coastal areas of the North Sea and prefer shallow waters up to 10-20 km from the coast. Smaller numbers overwinter in the Wadden Sea and the Delta area. During autumn they stay in the deeper gulleys between the Wadden Sea islands. Red-throated divers forage and rest in loose groups in open water. They are pursuit divers and feed exclusively on relatively small-sized fish (4-25 cm) such as gobies, sticklebacks and young individuals of Atlantic cod and whiting, while diving to depths of 15 up to 25 m.

4.5.2 Northern fulmar *Fulmar glacialis* A009

The northern fulmar breeds throughout the north Atlantic and north Pacific, ranging from Japan and the United Kingdom in the south, to the high Arctic in the north. Northern populations migrate south during winter as the sea freezes over. Southern populations are more dispersive, but do not usually reach zones of warm water. Young birds may undertake transoceanic crossings and general wander further than the less mobile adults (BirdLIfe, 2018).

Northern fulmars breed on cliffs and rock faces, but also occasionally on flatter ground sometimes up to 1 km inland. It will also breed near human habitation, sometimes even on occupied houses along the seafront of towns. Its diet comprises of variable quantities of fish, squid and zooplankton (especially amphipods), and it will also feed on discards, fish offal and carrion (e.g. whale blubber). Most of its food is obtained by surface dipping but it will also plunge. During breeding they forage close to the colony, preferring the continental shelf. As chicks become older, parents forage further from the colony, eventually regularly embarking on long trips.

BirdLife International (2018). Species factsheet: Northern Fulmar Fulmarus glacialis. Downloaded from https://datazone.birdlife.org/species/factsheet/northern-fulmar-fulmarus-glacialis on 19/06/2025.

4.5.3 **Northern gannet** *Morus bassanus* **A016**

Northern gannets breed in large colonies on cliffs situated around islands in the North Sea and Northeast Atlantic (SOVON, 2022). The breeding areas range from the northern Atlantic, from Canada through Iceland, Faeroe to most countries around the North Sea (excluding the Netherlands). Adult birds remain near the breeding colonies between March – October, during which period they make foraging trips of on average 80 km. Longer trips of up to 600 km from the colony do occur during which they can reach the DCS. They overwinter in more southern areas up to the Gulf of Mexico, Northwest Africa and western Mediterranean Sea and occur year-round in the DCS. Gannets search for forage fish (herring, mackerels, sprat) while flying and capture their prey with deep plunging (usually up to 5m, occasionally up to 35 m. They also feed on discards from fishing vessels.

4.5.4 **Little gull** *Hydrocoloeus minutus* **A177**

Little gull is the smallest gull species in the world (25-30 cm) and breeds in inland lakes in Scandinavia up to Russia and east Asia (SOVON, 2022). It is a rare breeding bird in the Netherlands and the largest number occur during spring migration in April which heading for the breeding areas in Northeastern Europe. In this period, they can be found on the North Sea and the Ijsselmeer area and less frequently in inland areas. They forage on small invertebrate prey and small fish which they take from the surface. A large proportion of the flyway population occurs in the Netherlands during southward migration in the autumn.

4.5.5 **Lesser black-backed gull** *Larus fuscus* **A183**

The lesser black-backed gull breeds from Iceland and British Isles to most countries around the North Sea and Baltic Sea. The lesser black-backed gull occurs in the Netherlands locally as a breeding bird and common migrant and overwinters in small numbers (SOVON, 2022). The breeding habitat is mainly limited to coastal areas with small numbers breeding inland. Nest locations are situated in open dune areas and salt marshes, industrial areas, roof tops, ruderal areas and islands in closed sea arms. They often breed together with herring gulls. The coastal breeders forage at large distances from the colonies usually within a radius of 135 km and occasionally up to 200 km. They forage on the open sea on discards of fishing vessels (flat fish, gadids and other demersal species, but also independently on mobile species like swimming crabs, clupeids, sandeels and horse mackerel. Other foraging areas are beaches, agricultural areas and rubbish tips. The Dutch breeding birds overwinter on the Atlantic coasts from France to Morocco and in the western Mediterranean Sea.

4.5.6 **Herring gull** *Larus argentatus* **A184**

Herring gull is a large-size gull species of up to 50 cm. Herring gulls breed from Iceland, the British Isles and France through northwest Europe to northwest Russia, and northern Siberia east to the Bering Strait (BirdLife, 2021). The breeding range includes the United Kingdom, Denmark, Norway, Sweden, France, the Netherlands and Russia. Northern breeding populations are migratory southern populations are nomadic or completely non-migratory. Northern populations winter mainly in maritime northwest Europe, but as far south as northern Iberia). Herring gulls occur in coastal and near-coastal areas but may also forage inland on large lakes and reservoirs, agricultural fields and refuse rips. It breeds in a variety of habitats but may show a preference for rocky shores with cliffs, outlying stacks or, otherwise nesting on rocky and grassy islands, sandy beaches, dunes, gravel bars, saltmarshes, rocky outcrops, buildings, claypits, tundra with reeds or hummocks, swampy lowlands near lakes and on river islands. Although herring gulls exploit refuse tips and farmland extensively all year round, their breeding distribution is limited to coastal areas. The species is an opportunist and will exploit almost any superabundant source of food. It takes fish, crabs and other marine invertebrates (e.g. molluscs, starfish or marine worms), adult birds, bird eggs and young, rodents. It also scavenges at refuse dumps and frequently follows fishing boats. The feeding range has been variously reported as 35 km (for breeding herring gulls in a Dutch colony). Northern breeding populations of this species are migratory although populations in the south are nomadic or completely non-migratory.

4.5.7 **Great black-backed gull** *Larus marinus* **A187**

The great black-backed gull is the largest gull species in the world (64-79 cm). It breeds on the rocky coasts of Scandinavia, the Faeroe Islands and the British Isles and occur in autumn and winter on the North Sea and in the surrounding countries, including the DCS. The wintering birds in the Netherlands originate from Norway, with smaller numbers from the British Isles (SOVON, 2022). They arrive from July onwards until November and depart after January. They scavenge on discards from fishing vessels and take fish from the surface in the open sea and forage on mobile fauna on seashores and offshore platforms, where they also rest. During the breeding season they often breed in or near seabird colonies where they feed on birds. Breeds also in the Netherlands in small numbers.

4.5.8 **Black-legged kittiwake** *Rissa tridactyla* **A188**

The black-legged kittiwake breeds in the North Atlantic, from northern central Canada and northeastern U.S.A. east through Greenland to western and northern Europe, and on to the Taymyr Peninsula and Severnaya Zemlya (Russia) (BirdLIfe, 2018). They winter south to the Sargasso Sea and West Africa. This species is highly migratory and disperses after breeding from coastal areas to the open ocean. Breeding occurs from mid-May to mid-June in huge single- or mixed-species colonies that often exceed 100,000 pairs. Dispersal from the breeding colonies starts between July and August, often moulting in large flocks of several thousand individuals on beaches between the breeding grounds and the open sea. It nests on high, steep coastal cliffs with narrow ledges in areas with easy access to freshwater. On passage, it may concentrate at sea on continental shelves, areas of upwelling and at rich fish banks. During the winter the species is highly pelagic, usually remaining on the wing out of sight of land. They feed on forage fish (sandeel, herring, sprat) and marine invertebrates (e.g. squid and shrimps), which they take from the surface. At sea during the winter, it will also take planktonic invertebrates and discards from fishing vessels and generally forage within 50 km of the breeding colony.

4.5.9 **Sandwich tern** *Thalasseus sandvicensis* **A191**

The Sandwich tern breeds in countries around the North Sea and Baltic Sea, and around the Black and Caspian Sea (BirdLIfe, 2018). The Sandwich tern breeds in the Netherlands in large colonies of hundreds to thousands of birds often mixed with Black-headed and Mediterranean gulls (SOVON, 2022). These colonies are situated on sparsely vegetated islands, salt marshes in the Wadden Sea and Delta area. They arrive in April and depart in September to the wintering areas along the coasts fo West and Southern Africa. Individual birds often are prospecting in several colonies in early spring resulting in much exchange between colonies, which can quickly grow or disappear. They feed exclusively on forage fish, including herring, sprat and sandeels by plunge diving.

4.5.10 **Common tern** *Sterna hirundo* **A193**

The common tern breeds in northern central Canada and northeastern U.S.A., in most European countries and east from Russia to central Asia. Common terns arrive in March in the Netherlands and start breeding from the end of April (SOVON, 2022). The leave in August-September for the wintering areas along the coasts of West and Southern Africa. They breed in small to large colonies in areas in or close to open water, both fresh or salt water and prefer sparsely vegetated sand plates, salt marshes and islands. Also, artificial sites, such as floating platforms and roof tops with gravel. Common terns are plunge divers and feed on forage fish, small fish and shrimps within a range of 5-10 km from the colony.

4.5.11 **Common guillemot** *Uria aalge* **A199**

The common guillemot breeds in the North Atlantic, from eastern Canada and northeastern U.S.A. east through Greenland to the British Isles and western and northern Scandinavia (BirdLIfe, 2018). They winter in the North Atlantic and North Sea. Common guillemots breed on cliffs in large to very large colonies in countries around the North Sea. They are nearly year-round present in large parts of the North Sea (SOVON, 2022). Young birds from the colonies in Great Britain disperse in the summer to the DCS. In the Dutch part of the North Sea large concentrations of guillemots can be found nearly year-round. The numbers increase during autumn and winter up to peak numbers in February. Common guillemots are pursuit divers and specialise during breeding on forage fish, including herring, sprat and sandeels, outside the breeding season they feed on a wider range of fish species. The maximum foraging range during breeding is 25 km in small colonies and 50-200 km in very large colonies (Cleasby *et al.,* 2024).

4.5.12 **Razorbill** *Alca torda* **A200**

The razorbill breeds in the North Atlantic, from eastern Canada and northeastern U.S.A. east through Greenland to the British Isles and western and northern Scandinavia (BirdLIfe, 2018). They winter in the North Atlantic and North Sea. Razorbills breed in large to very large colonies on cliffs in countries around the North Sea, usually mixed with other species like common guillemots and black-legged kittiwakes. After a short breeding season, family groups with flightless young and moulting adults disperse to the open sea but stay closer to the colonies than common guillemots. They stay year-round in the North Sea and North Atlantic, including the DCS, where they are common in the winter period. The razorbill is a pursuit diver and feeds on forage fish (herring, sprat and sandeels), small fish (sticklebacks and gobies) and small, mobile invertebrates. They dive to depths of 35 m on average and occasionally up to 100 m.

5 Pressures of seabirds in the North Sea

5.1 Introduction

The OSPAR Quality Status Report 2023 concluded that climate change is an important cause of declines in seabirds in the North Atlantic, mainly via changes in their food supply (Chapter 4; Figure 5.1). The declines in many seabirds in the North Atlantic, including the North Sea appear to be a consequence of shortages in the prey availability, particularly those who feed on forage fish. The links between seabird breeding productivity and increasing sea temperatures strongly suggests that climate change is driving at least some of the observed declines in forage fish species (OSPAR, 2023). Over-fishing of forage fish stocks in some regions has also contributed to these declines in the past and industrial fisheries on sandeels, herring and sprat are still competing with seabirds and marine mammals. Climate change has also a direct effect on seabirds, which is evident through changes in the range and distribution in some species, for example, the disappearance of breeding colonies of black-legged kittiwake in the Bay of Biscay region. The QSR 2023 also concluded the impacts of climate change as mentioned above are being exacerbated by additional pressures from direct mortality, habitat loss and habitat degradation and disturbance by developments in shipping, tourism and renewable energy (Figure 5.1).

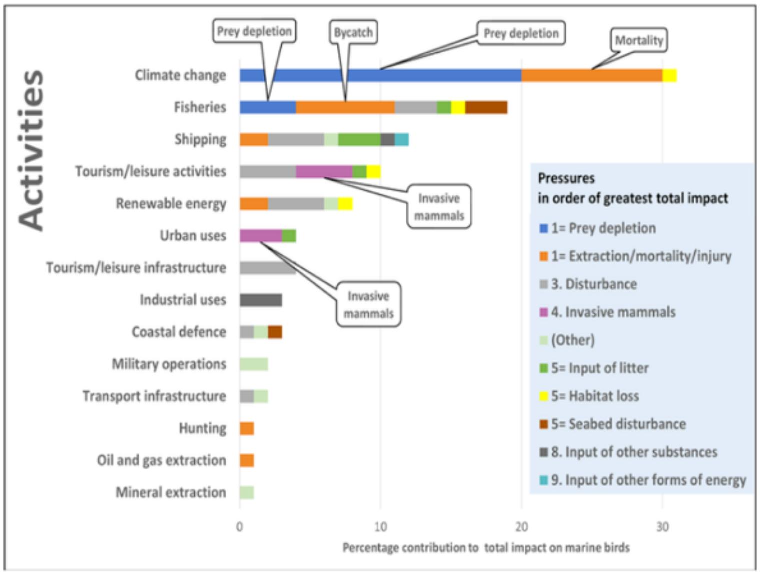

Figure 5.1. Most important human activities and pressures impacting marine birds in the OSPAR Maritime Area (OSPAR, 2024).

5.2 General pressures

Many factors that affect seabird populations through demographic factors such as reproduction (e.g. breeding success) and survival have been identified (Mitchell *et al.,* 2004; Furness *et al.,* 2013). These pressure factors can be grouped into eight categories: diseases, fisheries, human activity offshore, climate change, invasive species, pollution, ecosystem effects, and persecution (Table 5.1). In two expert meetings in relation to the development of species protection plans (Ministry of LNV; 14 January and 8 March 2023) these pressure factors were ranked together with their impact on reproduction and survival., Factors that negatively impact both reproduction and survival, such as disease, reduced food availability and habitat loss were ranked as the most important pressure factors (Table 5.1). Most pressure factors are directly or indirectly related to human activities such as fisheries, offshore infrastructure, invasive species, climate change and pollution. First, we will briefly discuss diseases, climate change, food availability, fisheries and predation. Second, we will discuss the pressure factors related to offshore wind farms separately, including collision risk, habitat loss and barrier effects.

5.3 Diseases

In 2021, Highly Pathogenic Avian Influenza (HPAI H5N1) first appeared in seabird colonies around the North Sea in the Netherlands, Belgium, UK, Norway, Denmark and Germany. This strain has had a significant impact on these globally important seabird populations. A total of 21 of our 25 regularly breeding seabird species around the North Sea have tested positive for the virus, and tens of thousands of seabirds died in the period 2021-2023. In the Netherlands, breeding colonies of Sandwich tern, common tern, herring gull, black-headed gull, black-legged gull and black-legged kittiwake were impacted (Caliendo *et al.,* 2024).

Table 5.1. General pressure factors of four seabird species (northern gannet, herring gull, great black-backed gull, black-legged kittiwake) identified and ranked by a group of seabird experts (14 January and 8 March 2023) with impact on reproduction and/or survival.

Main pressures	Pressure factor category	Repro-duction	Survival	Rank
Infection with High Pathogenic Avian Influenza (HPAI)	Diseases	✓	✓	4
Habitat loss (displacement)	Human activity offshore	✓	✓	3
Reduced food availability	Fisheries	✓	✓	3
Reduced food quality	Climate change	✓	✓	2
Reduced carrying capacity	Fisheries	✓	✓	2
Offshore wind farms (collisions)	Human activity offshore		✓	1
Extreme weather events/heat waves	Climate change	✓	✓	1
Plastic ingestion	Pollution		✓	1
Light distraction (vessels, offshore infrastructure)	Pollution		✓	1
Reduction in discards	Fisheries		✓	1
Disturbance by shipping	Human activity offshore		✓	0
Future multi-use of wind farms (solar, gillnets, aquaculture)	Human activity offshore		✓	0
Oil pollution	Pollution		✓	0
Increased nest predation	Invasive species	✓		0
Increased nest predation	Ecosystem	✓		0
Bycatch in Fisheries	Fisheries		✓	0
Entanglement in plastic	Pollution		✓	0

In the UK, where most North Sea seabird colonies are situated, a national programme of additional targeted seabird population counts were conducted in 2023 using a coordinated and collaborative approach across statutory bodies and conservation organisations (Tremlett *et al.,* 2024). Nearly half of the seabird species showed a decrease of >10% in overall counts across all UK sites that were surveyed in 2023: great skua (-76% decrease in overall count); common tern (-42%); Sandwich tern (-35%); Arctic skua (-28%); northern gannet (-25%); lesser black-backed gull (-25% of the natural-nesting population); roseate tern (-21%); great black-backed gull (-20%); and black-headed gull (-11%). The most severe decline was seen in great skua (world population 16.000 breeding pairs of which a significant part occurs in the North Sea), with counts decreasing by >50% at 79% of previously occupied sites surveyed, including important SPA populations. The scale and impact of HPAI on North Sea seabird populations is large and unprecedented and can currently be considered the most important pressure factor.

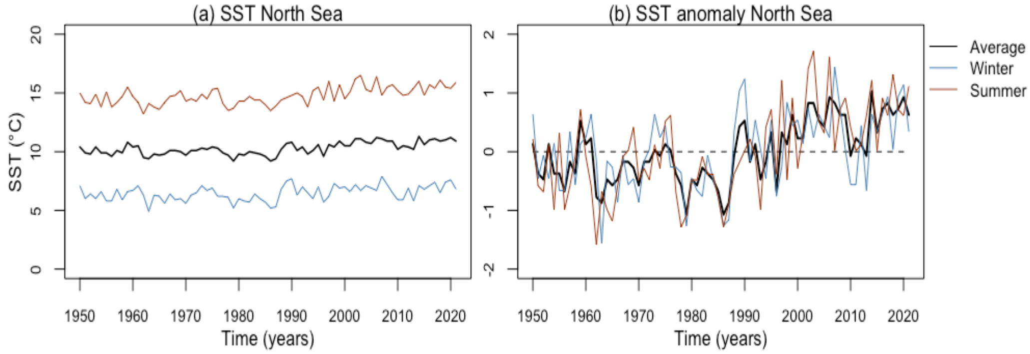

Figure 5.2. *Time series of the (**a**) yearly SST and (**b**) SST anomaly of the North Sea area (Lat. 48.5°N -61.5°N; Lon. -5.0°W -9.0°E) from 1950 until 2021 (Brekelmans 2022).*

5.4 Climate change

Sea surface temperature (SST)[1] in the North Sea has increased c. 1.0°C since 1990 (Figure 5.2), in the southern North Sea more than in the northern part of the North Sea (Brekelmans, 2022). The temperature increase has pervading effects on the North Sea food web from zooplankton and benthic macrofauna through forage fish up to seabirds (Figure 4.1).

In the period 1990-1993, a regime shift occurred in the North Sea in reaction to higher SSTs (Figure 5.3). A temperature induced decrease in biomass and shift (from large-sized to small-sized species) in zooplankton populations caused an estimated 25% reduction of forage fish spawning biomass in the North Sea (Figure 5.3; Clausen *et al.,* 2018). This estimate is based on model simulations without fishery mortality. The pelagic fisheries caused additional declines in the forage fish populations as discussed in the previous section.

As mentioned before, reproductive success is in many seabird species variable with regularly reproductive failure due to several factors, including anthropogenic disturbances, and direct and indirect effects of climate change (Furness 2016; Wanless *et al.,* 2007; Wanless *et al.,* 2005).

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[1] The SST was taken from ERA5, the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 combines historical observations to get global estimates with the data covering the Earth on a 30 km grid. Monthly averaged data from 1950 until 2021 were used to calculate the SST anomaly (Brekelmans 2022).

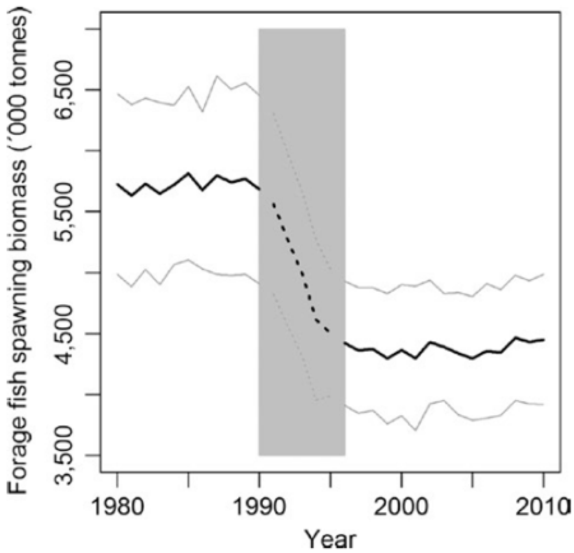

Figure 5.3. Climate change induced development of the combined forage fish (herring, sprat, sandeel, Norway pout) spawning stock biomass in the North Sea without fishing, based on model simulations with mean (black line) and SD (grey lines). The decline of c. 25% is caused by the observed changes in stock recruitment and weight at age in the stocks. The grey field defines the transition zone (1990-1993) between the high productivity period and the low productivity period (Clausen et al., 2018).

These indirect impacts may be effective at lower trophic levels of the ecosystem on which seabirds depend for their daily food demand (Furness 2016). This food demand is quite high for seabirds as they approximately need to consume 30-80% of their body mass daily (Saraux *et al.,* 2021). Additionally, during the breeding season, they gather in large colonies of thousands up to tens of thousands of individuals and depend heavily on local food sources (Carroll *et al.,* 2017; Otterå *et al.,* 2012). The breeding colonies can cause a substantial pressure on local food stocks, leading to local stock depletion (Saraux *et al.,* 2021). Depending on their foraging strategy and diet, seabird species are differently impacted.

Seabird species that use energetically high demanding foraging methods, such as plunge diving and long foraging distances, are likely to be more impacted by changes in prey abundance than species that have a low foraging cost (e.g. pursuit divers), have nearby foraging ranges and have a large amount of 'off-duty' spare time (Furness & Tasker 2000). These predictions are supported by earlier studies that show that, as mentioned before, seabird survival and productivity is often linked to forage fish abundance and availability, an important prey item for seabirds (Carroll *et al.,* 2017; Furness & Tasker 2000).

As mentioned before, forage fish are an important food source for upper trophic levels such as predatory fish, marine mammals, and seabirds (Carroll *et al.,* 2017; Otterå *et al.,* 2012).

Predatory fish consume the highest amount of forage fish (60-70%), while only a small part is consumed by seabirds (10%) (Dickey-Collas *et al.,* 2014). Forage fish species are characterized by variable but rapid somatic growth and by a short life expectance depending mostly on environmental factors (Buren *et al.,* 2019). Hence, forage fish exhibit large fluctuations in abundance and biomass. Additionally, this makes them very sensitive to climate change (Clausen *et al.,* 2018; Saraux *et al.,* 2021). As these forage fish have a central position in the food chain (Figure 4.1), lower and higher tropic levels, are impacted by these fluctuations in their abundance (Clausen *et al.,* 2018).

Bottom-up control of food webs is predominantly governed by climate related changes, such as an increased sea surface temperature (SST) (Fauchald *et al.,* 2011). But also top-down control can be influenced by higher temperatures (Piatt *et al.,* 2020).

Positive SST anomalies[1] or higher temperatures alter ectotherm[2] physiology. Through bottom-up control, warming can cause changes in zooplankton abundance and species, sometimes leading to the loss of high-lipid species (Piatt *et al.,* 2020). This will reduce the energy flow to ectothermic forage fish, while their food demand increases due to a temperature-induced increase in metabolic rate (Furness 2016; Piatt *et al.,* 2020).

Consequently, this will lead to smaller and/or leaner forage fish, reducing their abundance and their quality as prey for top predators such as predatory fish, endothermic birds and mammals (Piatt *et al.,* 2020). In turn, predators will need to consume a higher number of forage fish to meet their daily food demand (Furness 2016; Piatt *et al.,* 2020). In endothermic birds and mammals, the energy demand remains the same at a much higher level. Through top-down control, raised temperatures can lead to increases in the metabolic rate of ectothermic predatory fish (Piatt *et al.,* 2020) and thus an increase in their food intake (Piatt *et al.,* 2020). This can cause depletion of forage fish stocks and increased competition between predators (Furness 2016; Piatt *et al.,* 2020). As a result, these bottom-up and top-down impacts can cause high die-off of seabirds and marine mammals and reproductive failure if seawater temperatures increase (Piatt *et al.,* 2020).

This double-edged impact of raised temperatures on ectotherms (reduced abundance, lower quality and increased competition with predatory fish) on seabirds has been termed the 'ectothermic vise' in a conceptual, explanatory model for recent large mortality events and reproductive failures in seabirds and marine mammals in the North Pacific (Figure 5.4; Furness 2016; Piatt *et al.,* 2020). Piatt *et al.,* (2020) describes that ectotherms will normally be able to migrate vertically or horizontally to meet their habitat demands and life history traits. However, during the marine heat wave in the North Pacific, seabirds and were caught in an ectothermic vise as their ectotherm physiology was altered due to continually warm water temperatures everywhere in the area at the exact same moment (Piatt *et al.,* 2020). If we implement the ectothermic vise hypothesis to the North Sea area, we might expect a similar but more subtle impact on forage fish stocks and prey quality and consequent survival rates and reproductive success of seabirds (Brekelmans, 2022).

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[1] A warmer Sea Surface Temperature (SST) than average (Piatt *et al.,* 2020).
[2] An animal whose internal physiology is regulated by external sources (Piatt *et al.,* 2020).

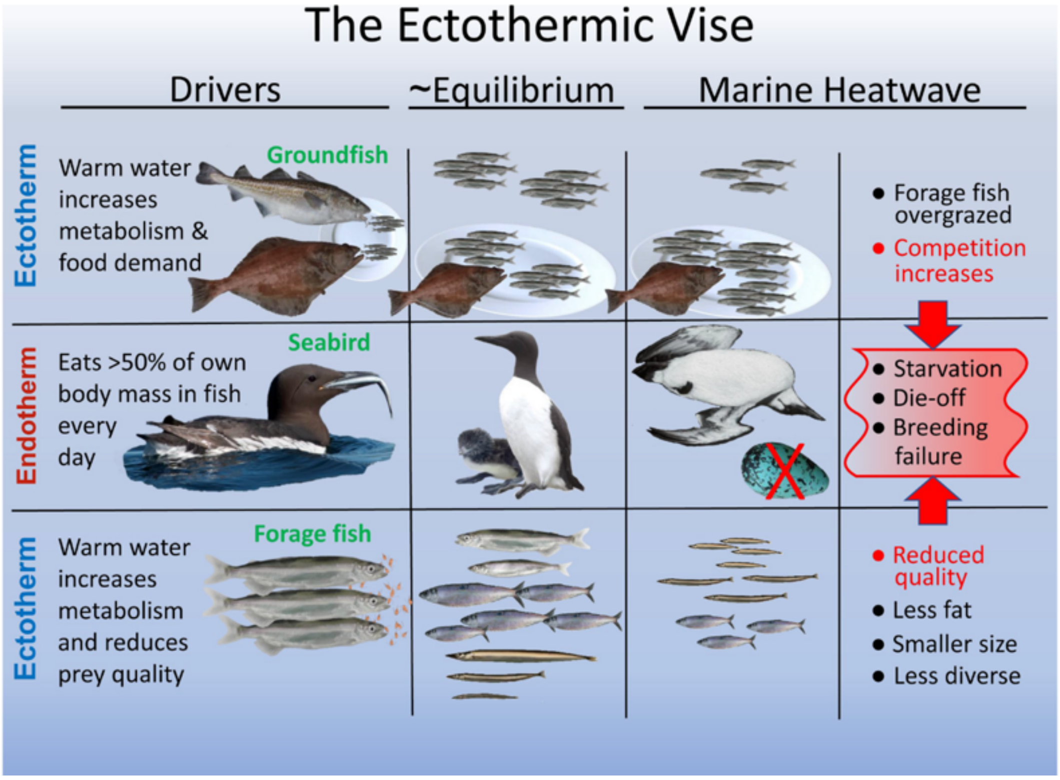

Figure 5.4. Conceptual model of the ectothermic vise hypothesis described by Piatt et al., (2020). This hypothesis describes the recent large die-off and reproductive failure event of murres during the 2014-2016 marine heatwave in the North Pacific. This heatwave affected ectothermic forage fish (decreased quality) and ectothermic groundfish (increasing food intake) leading to a strong bottom-up and top-down effect (vise-like) on guillemot (murre) survival and reproduction (Piatt et al., 2020).

5.5 Food availability

The sizes of seabird breeding populations are predominantly affected by food abundance, and this factor is the most important determinant of seabird population sizes at a regional level (Furness *et al.,* 2013). Small-sized, surface-feeding seabirds with limited foraging ranges and no alternative food sources are particularly vulnerable to variation in food abundance (Furness and Tasker 2000). Dramatic changes in breeding numbers of seabirds have been observed resulting from changes in fish abundance. Common tern breeding numbers, for example, in the Firth of Forth were reduced by 50% when sprat abundance was reduced (Furness *et al.,* 2013; Jennings *et al.,* 2012). Arctic tern and Arctic skua breeding numbers in Shetland fell by at least 50% after the decline of the Shetland sandeel stock (Furness *et al.,* 2013; Forrester *et al.,* 2007).

The demography of seabird populations in the UK, where many of the selected seabird species breed, is according to Mitchell *et al.,* (2004) 'strongly affected by the availability of food' (Furness *et al.,* 2013). Many breeding seabird species feed primarily on forage fish.

As discussed in paragraph 4.4, forage fish are small pelagic, planktivorous species, that play a key role in marine ecosystems as they are an important food source for upper trophic levels such as predatory fish, marine mammals, and seabirds (Carroll *et al.,* 2017; Otterå *et al.,* 2012). These forage fish are an important food source because they tend to be abundant, available close to the surface of the sea, have a high energy density, and are relatively small and easy to catch and swallow. As a rule, seabird populations will be stable as one third of the long-term maximum prey biomass of forage fish is available (Cury *et al.,* 2011). Below this stock biomass level many seabird species suffer from reduced reproductive success, which will to lead to population decline if sustained. Forage fish populations and thereby food availability for seabirds can be reduced by fisheries and climate change, but also through the loss of spawning grounds and increases in predatory fish populations.

5.5.1 Stock sizes of forage fish in the North Sea

The ecology and stock sizes of herring, sprat and sandeel are discussed in paragraph 4.4. The long-term ICES-monitoring shows that the stocks of herring (monitored since 1951), sprat (monitored since1974) and sandeel (monitored since 1983) have decreased substantially since the start of monitoring and are now just above (herring and sandeel) or just below the biological safe limit.

Herring
In the North Sea the estimated spawning stock biomass of herring declined rapidly in the fifties and sixties due to overfishing until it fell far below the biological safe limit and the fishery was closed (Figure 4.8) and is in recent years just above the biological safe limit (ICES, 2023).

Sprat
The spawning stock biomass of sprat declined rapidly in the early eighties (Figure 4.9) to levels below the biological safe limit and increased in the nineties up to level above or just at the biological safe limit. The current level (2024) is below the biological safe limit (ICES 2024).

Sandeel
The spawning stock biomass of sandeels in the two of the divisions of the North Sea relevant for the Netherlands (1r and 2r, Figure 4.10) is highly variable. In division 1, the SBB was variable and in recent years around or just above the precautionary reference level (Bpa, Figure 4.11-4.12). In division 2 the SSB was relatively high up to 2003 after which it declined to below the biological safe limit (Blim, Figure 4.12). Since then, SSB remained low just above Bpa.

5.5.2 Fisheries

The fisheries on pelagic species like herring, sandeel and sprat is in volume (total biomass landed) the most important fishery in the greater North Sea Area since the development of “industrial fishing” in Norway and Denmark (Figure 5.5; ICES 2022).

Pelagic fisheries

Pelagic trawl and seine fisheries operate throughout most parts of the North Sea, except in the eastern portion of the central North Sea (ICES 2022). The small-meshed (< 32 mm codend) pelagic trawl targets forage fish species including sandeel and sprat, but also Norway pout, and blue whiting for reduction purposes (fish oil and fish meal). The pelagic trawl fishery for human consumption is operated by refrigerated seawater trawlers (>40 m) and freezer trawlers (>60 m) and targets herring, mackerel, and horse mackerel (ICES 2022). The total of landings of pelagic fish was over 1 million tonnes in recent years (Figure 5.6).

Up to the nineteen-seventies, herring dominated the landings total until the population crash in the early seventies (Figure 5.7; ICES 2022). The pelagic fisheries switched to sprat, which dominated the total landings (in biomass) in the mid-seventies. After the subsequent decline of the sprat stock the pelagic fisheries switched to sandeel which dominated the landings until 2003 (Figure 5.7). In the last decade the landings of herring, sandeel and mackerel together constitute a substantial proportion of the total landings (Figure 5.7).

The spatial distribution of the annual fishing effort (Figure 5.8) shows that most pelagic fisheries on herring, sandeel, sprat and mackerel with pelagic trawls and seines occurs in the northern part of the North Sea, around the Dogger Bank (including the Dutch part of the North Sea) and in the Channel.

To conclude, industrial fisheries on forage fish species herring, sprat and sandeel in a substantial area of the North Sea forms in biomass the largest part of the total landings, responsible for a considerable reduction of forage fish populations and is, therefore, an important factor in reducing the food availability for the selected seabird species year-round. This impact was exacerbated by climate change starting in the nineties of the last century (see section 5.4 Climate change).

Fisheries bycatch

Gannets and great skuas occasionally get caught as fisheries bycatch (Furness *et al.*, 2013). Although the numbers caught are small, which probably has a limited contribution to population decline, there is the potential to minimize this threat to adult survival within European waters through the European Plan of Action for Seabirds (BirdLife International, 2009), which is specifically addressing the issue of seabird bycatch in European waters and among European fleets. Although, any reductions in adult mortality will reduce pressure on declining populations, reductions in fisheries bycatch are generally not recommended as compensatory mitigation for the impacts of OWFs because the evidence base of the effect size of this bycatch is missing.

Discards

In 2013 the revised Common Fisheries Policy (CFP) came into force, which included the 'obligation to land all catches' and thus, at least on paper, prohibit discarding to contribute to better management of fish stocks (EC, 2013). This discard ban was implemented gradually but applies to all EU fisheries as of January 1st of 2019. Before the ban, scavenging seabirds consumed large quantities of discarded fish, and offal (60-80% of round fish discards and 70-95% of offal discards) (Furness *et al.,* 2013). Great skua colonies of the northern North Sea have seen rapid population growth from early in the 20th Century up to the end of the century, and this has been correlated to increases in fishery discards from the 1940s to the 1980s (Furness *et al.*, 2013). Great skua populations around Shetland relied heavily on fishery discards as a substantial component of their diet. Dependence on fishery discards was also apparent in large colonies of great black-backed gulls and possibly in several other gull species (Furness *et al.*, 2013). This would suggest that lifting the discard ban would positively contribute to population growth of several seabird species.

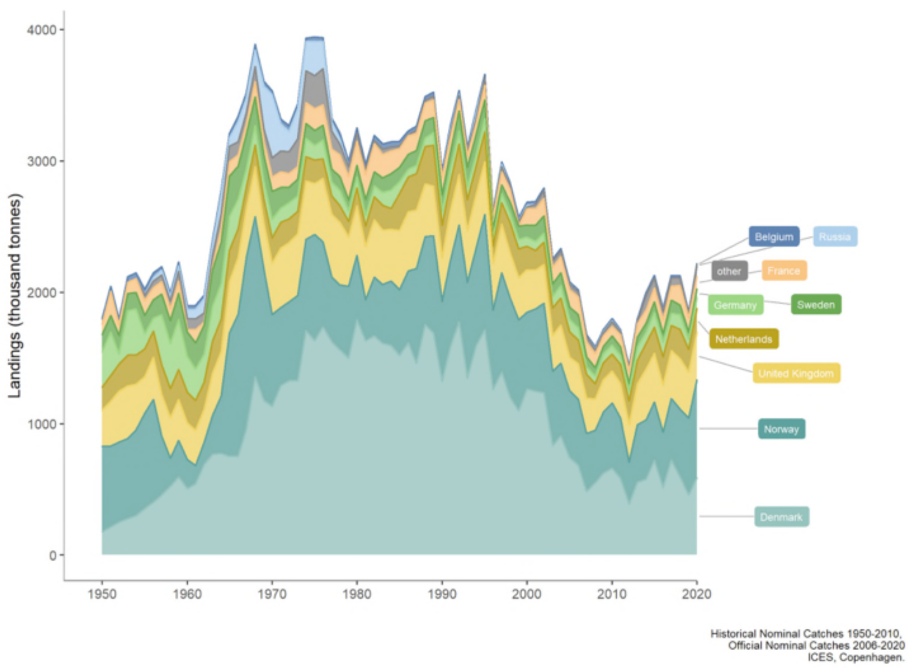

Figure 5.5. *Landings (thousand tonnes) from the greater North Sea 1950–2020, by country. The nine countries with the highest landings are displayed separately; the remaining countries are aggregated and displayed as "other" (ICES 2022).*

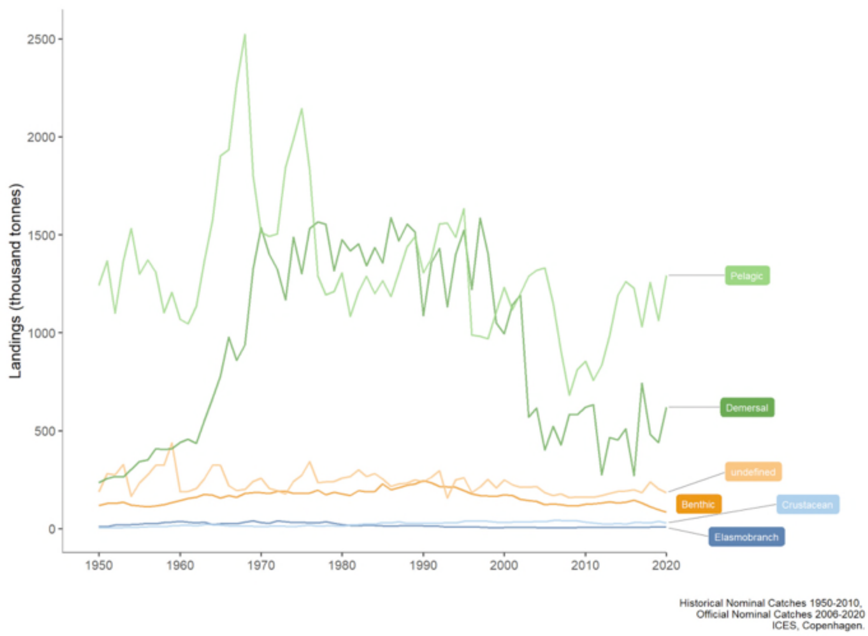

Figure 5.6. *Landings (thousand tonnes) from the greater North Sea in 1950–2020, by fish category. Table 1 in the Annex details which species belong to each fish category (ICES 2022).*

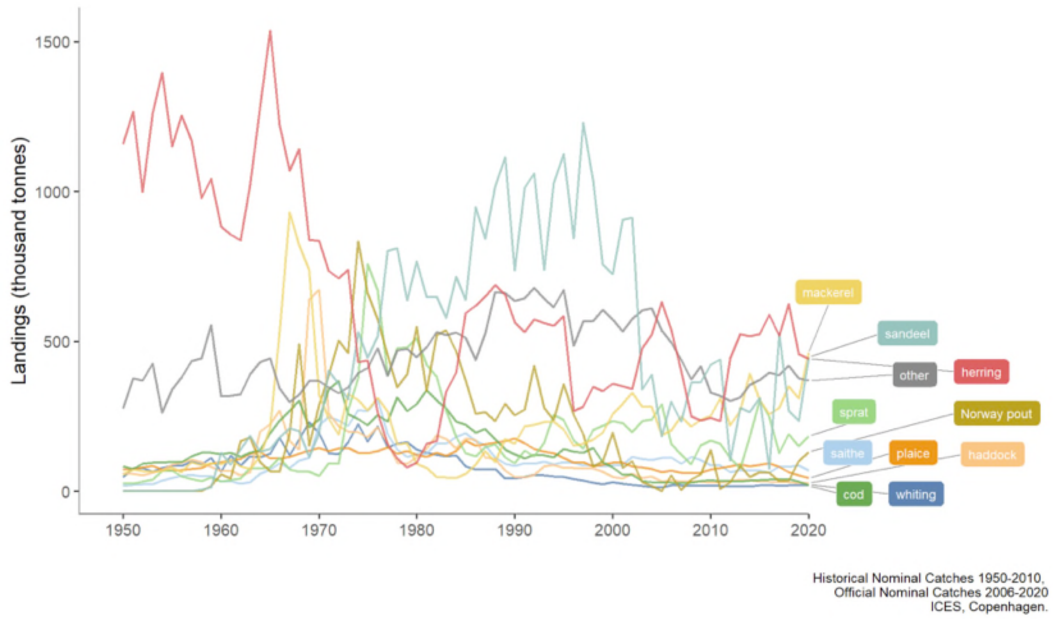

Figure 5.7. *Landings (thousand tonnes) from the greater North Sea 1950–2020, by species. The ten species with the highest landings are displayed separately; the remaining species are aggregated and labelled as "other". The main forage fish species: herring (red) and sandeel (light blue; ICES 2022).*

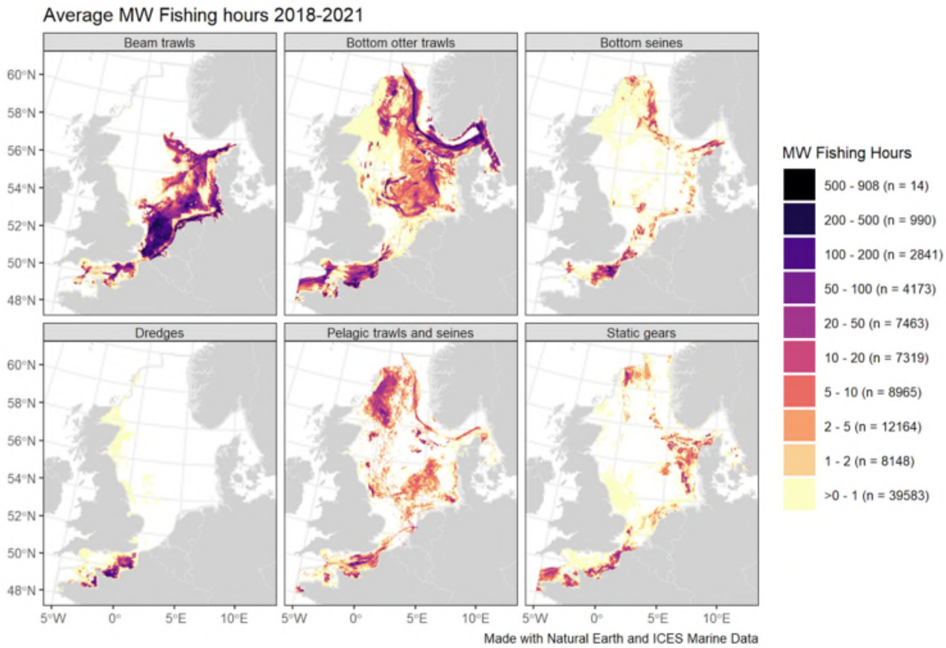

Figure 5.8. Spatial distribution of average annual fishing effort (MW fishing hours) in the Greater North Sea, by gear type. Fishing effort data are only shown for vessels >12 m with vessel monitoring systems (VMS; ICES 2022).

5.6 Predation

Seabird breeding colonies are often situated on cliffs or predator-free islands or experienced for decades low predation pressure in mainland colonies due to low densities of mammalian predators (e.g. foxes). Ground-nesting seabirds are especially vulnerable for mammalian predators. Therefore, the introduction of native (e.g. foxes, badgers, stoats) and invasive alien (rats, American mink, feral cats) mammalian predators can have very serious, unsustainable impacts on seabird populations, especially on smaller seabirds, as mammals tend to only attack seabirds that are smaller in size than they are (Furness *et al.,* 2013; Towns *et al.,* 2011). The presence or absence of brown rats, for example, in Orkney and Shetland (UK) is viewed as the “single most important influence” on storm-petrel breeding distribution (Furness *et al.,* 2013; de Leon *et al.,* 2006). Foxes, badgers, stoats, American mink, otters, rats, and feral cats have all been identified as major influences on productivity of some seabirds in the UK (Furness *et al.,* 2013). Not all impacts are from alien mammals. Otters, an endemic mammalian predator resident to Scottish coastlines, were the cause of a very low breeding success rate of Arctic terns in NE Scotland in 2005 (Mavor *et al.,* 2006).

Also in the Netherlands, areas that used to be predator-free nesting habitat, such as islands in the Wadden Sea and Delta area and coastal dunes have been invaded by mammal predators, in some cases naturally, but often because of human influences that have increased populations of these mammals or have assisted their colonization of seabird islands and coastal habitats (Furness *et al.,* 2013). Native cats and foxes, and invasive

American minks have been described as ‘superpredators’ because they kill adult seabirds as well as taking eggs and chicks. These predators may kill substantial numbers of seabirds, which are stored for subsequent meals (Towns *et al.,* 2011). Invasive rodents such as brown rats can be categorized as ‘mesopredators’ (Towns *et al.,* 2011). They usually take eggs and young, therefore, their impacts are predominantly on seabird breeding success rather than on adult survival and can increase where superpredators such as cats have been eliminated, allowing mesopredators such as rats to increase (Furness *et al.,* 2013; Rayner *et al.,* 2007; Le Corre 2008).

5.7 Offshore wind farm related pressure factors

5.7.1 Introduction

Offshore wind farms are considered to impact birds in general, and seabirds in particular, through collisions, habitat loss and barrier effects (e.g. Drewitt & Langston 2006; Searle *et al.,* 2014, 2020). The extent of each impact can vary by e.g. species, weather and environmental conditions, location, time of year and the characteristics of the wind farm itself. For habitat loss, the effects of displacement have been observed at more than 10 km from the wind farm, although in general there is a large degree of uncertainty around the extent to which displacement occurs (Furness 2013, Peschko *et al.,* 2020, Garthe *et al.,* 2023). The level to which displacement and the redistribution of birds occurs can be assessed using an array of monitoring methods such as boat-based surveys (Peschko *et al.,* 2020), digital aerial surveys (MacLean *et al.,* 2006), bird-borne telemetry (Peschko *et al.,* 2021, van Bemmelen *et al.,* 2023) or a combination of techniques (Heinänen *et al.,* 2020, Garthe *et al.,* 2023).

The degree to which collisions, habitat loss and barrier effects have an impact on population size depends on the species in question (e.g. van Kooten *et al.,* 2019). For example, collisions impact flying birds at rotor altitude, and not low-flying or swimming birds, whereas habitat loss affects only those considered local (i.e. using the area for foraging or resting). Of the seabirds, razorbill and common guillemot are most affected by both habitat loss and barrier effects. These risks are not mutually exclusive, with some species e.g. Sandwich terns, potentially at risk of both (i.e. displacement can also result in reduced collision risk).

5.8 Collision risk

Seabirds use the North Sea year-round for foraging and resting, with additional numbers passing through during migration. In addition, land birds migrate over the North Sea. Their presence in the North Sea is highly dependent on the time of the year, availability of prey and weather conditions. Each species has a characteristic size, flight pattern and flight height. A substantial number of seabirds regularly fly at heights that correspond to that of the rotor-swept area of wind turbines and consequently are at risk of collision with the rotor blades. In addition, marine bird species that fly at higher altitudes, roughly between 25 – 200 m, have a greater risk of colliding with turbine blades (Furness *et al.,* 2013; Madsen

2015; McGregor *et al.,* 2018; Caneco *et al.,* 2022). Bird species found to be vulnerable to collisions are northern gannets, terns, skuas and gulls (Martin & Banks 2023; Table 1 and 6). Weather conditions and time of day have an impact on the risk of collision as well, since these factors may decrease the visibility of the wind farms for the marine birds (Exo *et al.,* 2003; Drewitt & Langston 2006). Offshore wind farms are therefore considered to impact bird populations through direct mortality because of collisions.

The collision risk can be reduced or mitigated by adaptations in the wind farm layout and turbine design (number of turbines, turbine dimensions, rotor speed, tip height, air gap) and percentage time in operation (e.g. curtailment or active stand still of the turbine in relation to maintenance, cut-in or cut-out speeds). Collision risk highly depends on the bird species characteristics and wind farm design and operation (Table 5.2). Although various methods are being developed for measuring the number of bird collisions with offshore wind turbines, estimates of the numbers of collisions are currently only available from collision risk models (CRM). These models, such as the stochastic CRM of Madsen (2015), McGregor *et al.,* (2018) and Caneco *et al.,* (2022), use information on the species' abundance, size, and flight characteristics, along with wind farm and turbine specific information to estimate the monthly number of collisions (Table 5,2). Collision estimates are dependent on the input data with changes to some parameters having more influence on the output than others (Table 5.2). In addition, some parameters are well known and have low variability, whereas for others are poorly known or subject to high variability, which again influences the confidence of the results.

5.9 Habitat loss

Offshore wind farms may impact seabirds through displacement (resulting in fewer birds within the wind farm), which results in effective habitat loss for foraging and resting seabirds. Although very little habitat is actually directly lost (only the footprints of the monopiles), the area may also become less suitable for birds due to changes in the physical environment (e.g. increased sedimentation during construction, changes to currents, *etc*.), some of which may influence the distribution of prey species and/or birds ability to utilise those prey (particularly in the case of visual foragers), as well as the response of the birds to the physical presence of the turbines themselves (Dierschke *et al.,* 2016).

Furthermore, increased human activity, such as shipping activity, and temporary disturbance by the construction of the wind turbines and associated infrastructure, may affect seabird distributions. although it may be difficult to disentangle the effects from those of existing activities, particularly with regards to shipping (Exo *et al.,* 2003; Leopold *et al.,* 2011, Furness 2013, McGovern *et al.,* 2016, Burger *et al.,* 2019, Mendel *et al.,* 2019, APEM 2022). As a result, seabirds may move to areas of lower preference with a lower food abundance, lower food quality, or to areas with higher competition for food as other individuals or species may already be present in these redistribution areas (Fox & Petersen 2019; Lewis *et al.,* 2001, Wakefield *et al.,* 2013).

Table 5.2. Input parameters of the sCRM with an indication of the relative influence on model outcomes, quality of the data and the level of variability of the parameters (Madsen 2015), McGregor et al., (2018) and Caneco et al., (2022). [1]In relation with aerial bird density; [2] in relation with air gap; [3] in relation to flight height distribution; [4] in relation with rotation speed.

Category	Parameter	Effect on outcome	Quality of data	Variability
Bird	Flight type (flapping/gliding)	Low	Medium	Low
	Length	Low	High	Low
	Wingspan	Low	High	Low
	Flight speed	Medium	Medium	Medium
	Avoidance rate	High	Low	High
	Nocturnal activity	High[1]	Low	Medium
	Flight height distribution	High[2,3]	Low	High
	Aerial density (per month)	High	Medium	High
Wind farm	Latitude	Low	High	None
	Number of turbines	High	High	None
Wind turbine	Diameter	Medium[4]	High	None
	Air gap	High[3]	High	None
	Blade width	Low	High	None
	Blade pitch	Medium	High	Medium
	Rotation speed	Medium	High	Medium
	% time in operation (per month)	High	Medium	Medium

5.10 Displacement

Displacement is one of the key parameters that is studied in post-construction monitoring, and many species have been identified in the literature to be susceptible to displacement from wind farm areas (Searle *et al.,* 2014, 2020, Dierschke *et al.,* 2016). This has been shown for divers (Heinänen *et al.,* 2020, Garthe *et al.,* 2023), northern gannets (Peschko *et al.,* 2021), terns (van Bemmelen *et al.,* 2023) and Alcids (Peschko *et al.,* 2020).

The extent to which habitat loss has an impact on population size depends on a broad range of factors including the species in question (Table 2.1). Many of these species have been identified as showing some degree of displacement and are considered as potentially susceptible to habitat loss at offshore wind farms (Table 5.3). For example, in a study from offshore wind farm Borssele lower densities of northern gannet and common guillemot were found within the wind farm compared to outside, while an effect on auk densities was noted up to 4 km from the OWF near the UK coast during construction (McGovern *et al.,* 2016, Collier *et al.,* 2022). Nevertheless, there remains high levels of uncertainty as to the extent of displacement between species and between different areas, and some studies have shown little evidence for displacement even for common guillemot and black-legged kittiwake, and responses have been suggested to be partial or even negligible for northern gannet and auks in some wind farms (Furness 2013, APEM 2017). How displacement varies during the lifetime of the wind farm is also currently unknown.

The consequences of displacement at the individual and population levels were outline in Searle *et al.,* (2014, 2020). The results of monitoring and research programmes in modern wind farms and prior to- and after construction as well as over the long-term will contribute to the further understanding of these effects at the larger scale.

Impact

The impact of habitat loss on the target species depends on a range of factors, but food availability within the redistribution areas will play a key role (Furness *et al.,* 2013, Welcker & Nehls 2016). The impact of habitat loss will largely depend on the numbers displaced as well as the food availability in the redistribution area. When this food availability is sufficient for supporting not only the initial population of seabirds but also the displaced individuals, competition would not expect to increase, and any effects of displacement would be minimal., Were competition to increase, then individuals may have higher energetic costs or lower intake rates, leading to poorer condition and the possibility of higher mortality rates.

During the breeding season, displacement can also lead to longer commuting distances to and from breeding colonies, which increases the energy expenditure of these individuals (Peschko *et al.,* 2020). Distance to breeding colonies can play an important role: if birds travel further, energy expenditure is increased and can potentially result in reduced nest attendance and reduced provisioning rates, both of which may influence breeding success. Long-lived seabirds may prioritize their own survival over that of their chicks (Erikstad *et al.,* 2009), resulting in lower breeding success although not necessarily lower adult survival rates. The uncertainty around the effects of habitat loss on seabirds, particularly over the long-term, lends itself to reducing displacement and promoting the use of wind farms as foraging and resting areas for seabirds as the best solution to reduce any potential effects of habitat loss. Some approaches for assessing the effects of habitat loss from wind farms use a two-step matrix approach for estimating a proportion of birds displaced and a proportion of those that die. This approach has been largely superseded by individual-based models (Searle *et al.,* 2014, Searle *et al.,* 2018).

5.11 Barrier effects

Higher energetic costs

The barrier effect is the result of, here, wind farms creating a barrier between ecologically linked habitats or to migration (Exo *et al.,* 2003). This can result in functional habitat loss and increased energy expenditure when birds need to circumnavigate wind farms as part of their daily flight movements between foraging and resting sites or during migration (van Bemmelen *et al.,* 2023, Schwemmer *et al.,* 2023).

For seabirds, an area may become less accessible due to the increased energy expenditure or time needed to circumnavigate a wind farm, which may effectively deem an area as lower quality habitat. Where this occurs on the larger scale habitats may become fragmented and areas may become effectively lost. For migrant landbirds barrier effects may increase energy expenditure and time needed for migration, and in the case of offshore wind farms, this is often in areas where they are unable to stop and rest. Migrant land birds have been found to alter their flight paths or even altitude because of offshore wind farms, but in general the extra distance travelled is considered relatively small compared to the overall migration, although this can be expected to increase with the upscaling of offshore wind developments (Schwemmer *et al.,* 2023, Masden *et al.,* 2009).

Impact

Current research suggests that in isolation, the impact of barrier effects is likely comparable to energetic costs from head- or side winds or corrective flight (Arnett & May 2026; van Bemmelen *et al.,* 2023; Dierschke *et al.,* 2016; van Kooten *et al.,* 2019; May *et al.,* 2015; May 2019; Searle *et al.,* 2014, 2020). The additional distance of foraging trips due to barrier effects results in an increase in daily energy expenditure (DEE). For example, the common tern (*Sterna hirundo*) shows an increase in DEE of at least 1% per 500 meters increase in distance (Masden *et al.,* 2010). Research into the impact of barriers effects from multiple offshore wind farms on birds is limited and the consequences are unknown yet. Closer to the coast, and therefore potentially closer to breeding colonies, barrier effects may reduce foraging habitat for birds by effectively making it (energetically or in relation to time constraints) unprofitable to fly or swim around a wind farm to reach the area on the other side (van Bemmelen *et al.,* 2023; Thaxter in press).

Mitigation

Current attempts to reduce barrier effects at wind farms include the use of regular grid layouts with (approximately 1,000 m) wide corridors aligned with the main direction of travel for seabirds in specific locations in the North Sea. These corridors will allow seabirds to “see a way through”, based on evidence that seabirds follow straight line corridors when traversing a regularly spaced wind farm, maintaining a safe distance from turbines once within the wind farm (Masden *et al.,* 2009; Krijgsveld *et al.,* 2011; Skov *et al.,* 2018; Collier *et al.,* 2022; Schwemmer *et al.,* 2023).

Table 5.3. Specific pressure factors on seabirds related to offshore wind farms in the North Sea.

Bird species	Collision risk	Habitat loss - displacement	Barrier effect - avoidance
Northern gannet	High risk during breeding season due to long foraging ranges and flight heights (Furness *et al.,* 2013b). Shows violation of acceptable levels of impact in modelled scenarios (Potiek *et al.,* 2022) Vulnerable to collision mortality impacts (Furness *et al.,* 2013b; Martin & Banks, 2023)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Few but long foraging trips with efficient flight, which limits the avoidance costs (Masden *et al.,* 2010)
Arctic skua	Vulnerable to collision mortality impacts (Furness *et al.,* 2013b;	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Seem likely to be comparable to Great skua, but no clear evidence found in literature.
Great skua	Vulnerable to collision mortality impacts (Furness *et al.,* 2013b; Martin & Banks, 2023)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Avoidance is suggested (Vanermen *et al.,* 2015)
Little gull	Vulnerable to collision mortality impacts (Furness *et al.,* 2013b; Martin & Banks, 2023)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Efficient foraging trips, not as affected (Masden *et al.,* 2010)
Lesser black-backed gull	Vulnerable to collision mortality impacts (Furness *et al.,* 2013b; Martin & Banks, 2023)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Efficient foraging trips, not as affected (Masden *et al.,* 2010)
Herring gull	Higher risk due to attraction (Vanermen *et al.,* 2015). Shows violation of acceptable levels of impact in modelled scenarios (Potiek *et al.,* 2022) Vulnerable to collision mortality impacts (Furness *et al.,* 2013b; Martin & Banks, 2023)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Efficient foraging trips, not as affected (Masden *et al.,* 2010)
Great black-backed gull	Higher risk due to attraction (Vanermen *et al.,* 2015). Shows violation of acceptable levels of impact in modelled scenarios (Potiek *et al.,* 2022) Vulnerable to collision mortality impacts (Furness *et al.,* 2013b; Martin & Banks, 2023)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Efficient foraging trips, not as affected (Masden *et al.,* 2010)
Black-legged kittiwake	Higher risk due to attraction (Vanermen *et al.,* 2015). Shows violation of acceptable levels of impact in modelled scenarios (Potiek *et al.,* 2022) Vulnerable to collision mortality impacts (Furness *et al.,* 2013b)	Unlikely to be affected by displacement (Furness *et al.,* 2013b)	Efficient foraging trips, not as affected (Masden *et al.,* 2010)
Sandwich tern	Vulnerable to collision mortality impacts (Martin & Banks, 2023)	Evidence of displacement (Welcker & Nehls, 2016)	More energy costs in terns due to frequent foraging flights (Masden *et al.,* 2010)
Common tern	Vulnerable to collision mortality impacts (Martin & Banks, 2023)	Evidence of displacement (Welcker & Nehls, 2016)	More energy costs in terns due to frequent foraging flights. Most affected by additional distance due to avoidance (Masden *et al.,* 2010)
Razorbill	Less vulnerable to collision mortality impacts (Martin & Banks, 2023)	Shows significant displacement close (0.5 km) to the wind farms in a model (Vanermen *et al.,* 2015)	Responds negatively to the presence of wind farms, resulting in avoidance (Vanermen *et al.,* 2015)

Bird species	Collision risk	Habitat loss - displacement	Barrier effect - avoidance
Guillemot	Less vulnerable to collision mortality impacts (Martin & Banks, 2023)	Potential displacement effects, as the black guillemot (Cepphus grylle) has potential displacement effects (Furness *et al.,* 2013b)	More energy costs in terns due to frequent foraging flights (Masden *et al.,* 2010)

6 Enhancement measures for seabirds in the North Sea area

6.1 Introduction

A method used to prioritize the actions to minimize negative human impact is the mitigation hierarchy (Figure 6.1). This method consists of four actions designed to be taken in that sequence, which are (1) avoidance, (2) minimization, (3) restoration and (4) offset or compensation (Arlidge *et al.*, 2018). Most measures taken before, and mentioned in the previous paragraph, to minimize the negative impact of offshore wind farms are mitigation or minimisation measures located at the wind farms. These measures thus follow the first two steps of the mitigation hierarchy. However, this might not be sufficient when offshore wind farms will expand further and thus steps of restoration and compensation must be considered (Lüdeke, 2017). However, there is no clear overview of compensation measures for the negative impacts of offshore wind farms and their effects. This literature study will focus on compensation measures located outside of wind farms that can be taken to minimize and compensate negative effects of offshore wind farms on bird populations.

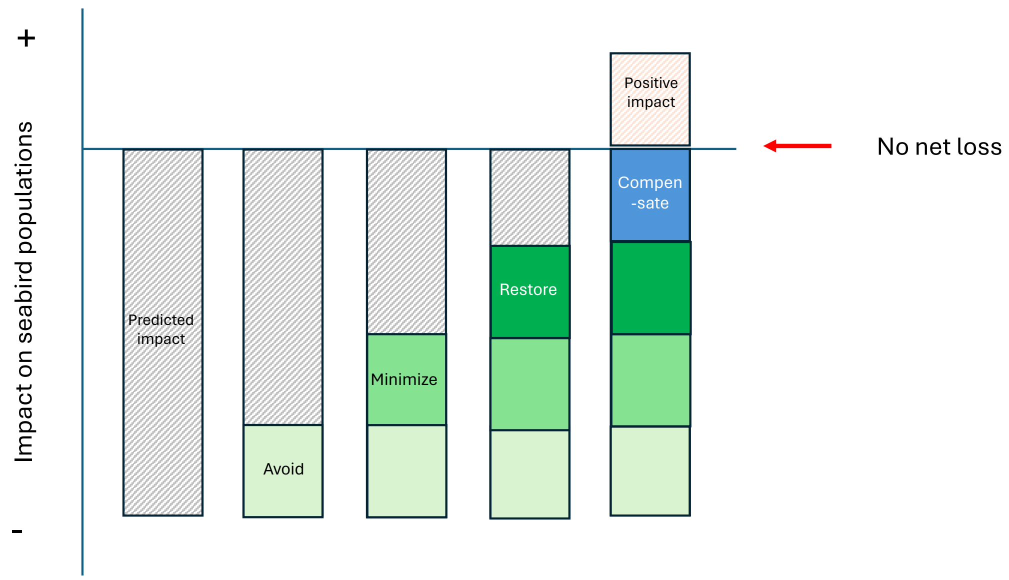

Figure 6.1. Mitigation hierarchy for the negative impact of offshore wind farms on seabird populations. The predicted impact (grey) is avoided (light green), minimized (mid-green), restored (dark green) or compensated (blue) up to no net loss is reached. By increasing efforts in one or more categories an overall positive impact may be reached (Based on Kiesecker et al., 2010).

6.1.1 Mitigation and compensation

The negative impacts of offshore wind farms on seabirds, including collisions, habitat loss and barrier effect can obstruct the large-scale rollout of offshore wind farms in the North Sea. Since these wind farms are of substantial importance to reach climate goals, it is essential to find solutions to mitigate the negative ecological impact. In the UK, a range of conservation measures have been recently proposed or taken to decrease the negative ecological effects of offshore wind farms (Table 6.1; general conservation actions: Furness *et al.,* 2013b; compensatory measures: MacArthur Green 2020; McGregor 2022; McGregor, Trinder & Goodship 2021; RHDHV 2021; RHDHV 2021; Skeate 2022). In most cases these compensatory measures were proposed for planned offshore wind farms relatively close to large seabird breeding colonies.

6.1.2 Minimize impact

Marine spatial planning: Location and layout of the wind turbines is of importance to minimalize negative ecological effects (Drewitt & Langston 2006). Important migration routes of migratory birds should be avoided when siting wind farms. When the distance between turbines increases it is expected that more birds will enter the wind park and thus some impacts such as displacement and barrier effects are reduced (Masden *et al.,* 2012). In Sandwich terns, avoidance of entire wind farm areas increased with increasing turbine density (van Bemmelen *et al.,* 2023).

Increased visibility: To prevent collisions there are vision-based mitigation measures, such as painting of the turbine blades to increase contrast that is more visible to marine birds (Martin & Banks 2023). On land, painted rotor blades resulted in a 70% decrease in annual fatality rates compared to unpainted turbines (May *et al.,* 2020), although the effectiveness offshore is yet to be assessed.

Smart curtailment: In addition, birds can be detected by radar or camera systems, after which the wind turbine can be shut down to prevent collision (Tomé *et al.,* 2017). This method can prevent most of the collisions but results in a lower output of wind energy. In griffon vultures (*Gyps fulvus*) the mortality rate was reduced by 50% by actively stopping turbines and the reduction in total energy production was only 0.07% (De Lucas *et al.,* 2012).

Information on compensatory measures for the negative effects of offshore wind farms on birds is limited, especially for offsite measures (Arnett & May 2016). Compensatory measures are the last step in the mitigation hierarchy and thus should be used for impacts that cannot be minimized, avoided or when mitigation measures are not sufficient (Croll *et al.,* 2022). In addition, financial motives can be considered when deciding which measures to take. This is however, outside of the scope of this literature review. It is expected that the cumulative impacts of offshore wind farms will increase when these are expanded in the North Sea to, for example, reduce CO_2 emissions further and reach climate goals. The mitigation hierarchy states that avoidance, minimization and remediation actions should be used before compensation measures to minimize the negative impacts of offshore wind farms (Figure 6.1). However, despite the use of mitigation and avoidance measures the impact on marine bird populations is expected to remain and offset (i.e. compensation) will thus be necessary (Lüdeke 2017; Figure 6.1).

Table 6.1. Overview of seabird species for which conservation actions (Furness et al., 2013b) and potential compensatory measures were developed in the UK in relation to six specific offshore wind farms.

Seabird species/OWF UK	UK	Norfolk Vanguard	Berwick Bank	8 SPAs	Green Volt	Hornsea 4	Berwick Bank
Northern gannet *Morus bassanus*	✓			✓	✓	✓	
Arctic skua *Stercorarius parasiticus*	✓						
Great skua *Stercorarius skua*	✓						
Little gull *Hydrocoloeus minutus*	✓						
Lesser black-backed gull *Larus fuscus*	✓			✓			
Herring gull *Larus argentatus*	✓				✓		
Great black-backed gull *Larus marinus*	✓						
Black-legged kittiwake *Rissa tridactyla*	✓	✓	✓	✓	✓	✓	✓
Sandwich tern *Thalasseus sandvicensis*	✓			✓			
Common tern *Sterna hirundo*	✓						
Razorbill *Alca torda*	✓		✓	✓	✓	✓	✓
Guillemot *Uria aalge*	✓		✓	✓	✓	✓	✓
Puffin *Fratercula arctica*	✓		✓	✓	✓		✓
Authors	Furness et al., 2013b	MacArthur Green 2020	McGregor 2022	McGregor, Trinder & Goodship 2021	RHDHV 2021	RHDHV 2021	Skeate 2022

6.2 Compensatory measures

Several assumptions for compensatory measures should be made according to Arnett & May (2016). The measures should mitigate mortality at least equal to the losses of birds caused by the offshore wind farms. In addition, habitat measures will replace impacted habitat in such a way that there is no net-loss in the bird population in comparison to the situation before wind farms. On top of this, the possibility to offset all habitats or conditional uses of habitat such as reproduction should be provided, so there is a possibility to compensate for losses making use of offsetting habitat.

To achieve the required compensation there are two options: (1) acting on biological factors that influence the bird population and with this enhance the population (e.g. food abundance and predation) or (2) minimize impacts caused by other human factors, such as fisheries and pollution (Marques *et al.,* 2014). In the following paragraphs we will elaborate on examples of compensatory measures that can be taken and taking into considering the assumptions (Table 6.2).

Seabird populations suffer from habitat loss due to the presence of offshore wind farms (Croll *et al.,* 2022). As mentioned before, habitat loss is often the result of avoidance behaviour in birds. The decline of multiple different marine bird populations could be compensated by expansion, creation or restoration of their habitat (Arnett & May 2016; Marques *et al.,* 2014; Lüdeke 2017; Croll *et al.,* 2022). In addition, removal or managing of threats in for example reproduction, foraging or nesting areas, can improve survival rates in marine bird species (Brooke *et al.,* 2018; Croll *et al.,* 2022; Marques *et al.,* 2014).

6.2.1 Food availability

Food availability plays a big role in seabird species conservation, as it is strongly correlated with survival and thus attracts birds. It is known to affect breeding numbers in seabirds, especially in small, surface feeding birds with a lack of alternative foods (Furness *et al.,* 2013b). Food availability is however decreased due to habitat loss; so increasing food abundance could contribute as compensation measure (Lüdeke 2017). If the targeted species is a predator, prey population management can be of use (Mascarenhas *et al.,* 2018). Prey fostering could contribute to the conservation of predator species through an increase in prey availability (Marques *et al.,* 2014; Arnett & May 2016).

Supplementary food creation to increase prey availability is a measure already used as compensation and found to increase reproduction rates in, for example, Arctic skuas (Mascarenhas *et al.,* 2018; Furness *et al.,* 2013b). Higher food availability due to, for example, aggregation of fish around offshore wind turbines can increase the collision risk of birds at offshore wind farms (Marques *et al.,* 2014). Increasing food availability in other places could help prevent this collision. However, no effect size was found for the increase in collision risk due to fish aggregation around wind turbines.

6.2.2 Habitat management

Very little is known about habitat creation, restoration, or expansion in relation to breeding habitats and breeding colony sites in relation to compensation for offshore wind farms. Habitat management or creation of new habitats could be effective to compensate for losses in populations, as it has already been found effective in other contexts.

6.2.3 Vegetation control

As an example, vegetation control at Sandwich tern populations is expected to increase their productivity, as they breed on bare ground (Furness *et al.,* 2013b). Attempts of starting a new colony, by use of attraction with decoys and sound, in created or restored habitat has been successful, as it restored about 49 seabird species over 14 countries (Jones *et al.,* 2011). However, these projects can be time consuming. For example, a project restoring Atlantic puffins (*Fratercula arctica*) in Maine took 35 years of sustained effort to achieve a population of 100 puffins (Jones & Kress 2012). This method has the potential to contribute to no net loss in marine bird populations, but changes in habitat and the creation of habitat take a long time before results can be seen.

Another limitation is that choice of habitat is species-specific, and creation, restoration or expansion might not be the best compensatory measure for all seabird species simultaneously (Table 6.2 and 6.3). Which bird species are targeted should be considered before using this compensation measure.

In addition, habitat could be managed by removal of threats such as predators and/or invasive species, as these are known to impact marine bird populations (Marques *et al.,* 2014; Croll *et al.,* 2022).

6.2.4 Invasive species removal

Removal of invasive species has been found to result in population growth in seabirds (Brooke *et al.,* 2018; Spatz *et al.,* 2017). Eradication attempts have been performed globally, with an 88% success rate (Spatz *et al.,* 2022; Croll *et al.,* 2022). For example, invasive mammal species have a large negative impact on some seabird populations as whole colonies of terns, gulls and storm petrels have been eradicated due to brown rats (*Rattus norvegicus*) and minks (*Mustela lutreola*) (Furness *et al.,* 2013b; Jones *et al.,* 2008; Table 8).

Examples of innovations to achieve predator eradication are predator-proof fencing and trapping techniques (Spatz *et al.,* 2022; Carter *et al.,* 2022). As well as habitat choice, predators are species specific and targeted bird species should thus be considered. Removal of predator species results in a decline in those populations, which should be considered if this is desirable.

6.2.5 Fisheries

Fisheries can influence food availability for seabird species, particularly for certain species where prey are species-specific. Overfishing of forage fish is a threat to seabird populations (Croxall *et al.,* 2012), so avoidance of overfishing and fishing in key habitats can contribute to seabird conservation.

After the closure of the sandeel fishery in East Scotland in 1998, the breeding success of black-legged kittiwakes within the fishery area improved (Frederiksen *et al.,* 2004) and matched that in a control (unfished) area (Frederiksen and Wanless, 2006). The breeding conditions for Sandwich terns were also found to be improved by the closure of sandeel fisheries, however, no significant increase in breeding conditions was found for other species such as guillemot and razorbill (Furness *et al.,* 2013b). These observed effect sizes were based on commercial fishing on sandeel and overfishing, which might be less relevant for other populations in the North Sea as pelagic trawling of forage fish is concentrated in the northern North Sea and around the Dogger Bank (Figure 5.8; Furness *et al.,* 2013b;

ICES 2022). Legal restrictions and compensation payments may limit or hamper regional closures of fisheries (Lüdeke 2017).

In addition, population growth of for example great skua colonies is found to be correlated to the discards of demersal fisheries. Reduced rates of discard can result in a use of other prey, such as an increase in kleptoparasitising other seabirds (Votier *et al.,* 2004). Reduction in fisheries can lead to a reduction in discards and thus even a decline in seabird populations, which benefit from discards. In addition, bycatch of seabirds in fisheries has a large impact on seabird survival (Anderson *et al.,* 2011; Dias *et al.,* 2019). This will be further elaborated in the next section.

6.2.6 Minimization anthropogenic impacts

Next to habitat management and fisheries, the negative effects of offshore wind farms can be compensated by the minimization of other human induced impacts (Lüdeke 2017; Marques *et al.,* 2014). The impact of human disturbance and use of the marine bird habitat is substantial (Wolf *et al.,* 2006; Croxall *et al.,* 2012; Rodríguez *et al.,* 2017; Dias *et al.,* 2019). These human induced pressure factors are relatively well known, and some already have solutions that benefit the threatened populations, which makes them suitable to use as compensation measures (Croll *et al.,* 2022). Human disturbance, pollution and fisheries are examples of these anthropogenic threats (Furness *et al.,* 2013b), which we will discuss in the following sections.

6.2.7 Disturbance

Reduction of anthropogenic marine use and disturbance, such as fisheries or other forms of hunting, improve the survival of seabirds and consequently their populations (Croll *et al.,* 2022; Dias *et al.,* 2019). Ground-nesting seabird species are of greater risk than cliff- or burrow-nesters (Furness *et al.,* 2013b). Human disturbance is seen in many different forms with different consequences for marine bird populations. Direct disturbance, for example in the form of tourism, can be significant and result in population declines (Wolf *et al.,* 2006). Reductions in breeding success due to human disturbance are seen in for example kittiwakes, common guillemots and common gull (Furness *et al.,* 2013b).

6.2.8 Hunting

The impact of hunting, trapping or disturbance is however relatively low in comparison to bycatch, invasive species, overfishing and pollution. A total of 46% of seabird species being affected by invasive species, while 27% are affected by hunting and trapping (Dias *et al.,* 2019). Minimizing human disturbance in key habitats can contribute as compensation measure (Marques *et al.,* 2014). To minimize the effects of human activities on bird populations, buffer zones could be created, creating a neutral zone between the breeding places of the seabirds and human activities. However, these need research before being put into use, as guidance for the designing of these zones does not yet exist, and they will be species-specific (California Energy Commission 2007). In addition, seabirds may be killed by hunters outside Europe in the wintering range.

6.2.9 **Bycatch**

Fisheries, including long-lining and standing rigging, can result in bycatch of different species of seabirds, which leads to high annual impacts, and thus form a threat (Anderson *et al.,* 2011; Dias *et al.,* 2019). Long-line fishing has been found to cause mortality in great skuas, northern gannets and northern fulmars due to bycatch (Furness *et al.,* 2013b). According to Dias *et al.,* (2019) bycatch affects about 100 seabird species worldwide. Although seabirds are affected by fisheries in the form of bycatch, the effect sizes of this impact have not been reported. Mitigation measures in long-lining and passive fisheries, such as not using long-lines during sunset and sunrise, lead to a reduction in bycatch of seabirds and could thus function as compensation measure (Anderson *et al.,* 2011; Belda & Sanchez 2001). However, in this review (North Sea) the mortality of auks due to bycatch was found to be insufficient to cause population declines (Furness *et al.,* 2013b). It would thus be beneficial to assess the impacts of bycatch due to fisheries on the species of interest, before using mitigation of fisheries as compensation measure.

6.2.10 **Pollution**

In addition, the reduction of other impacts, such as marine pollution or human infrastructures in other places (e.g. on mainland), positively influences bird survival and could thus function as compensation measure (Rodríguez *et al.,* 2017). Pollution can for example be in the form of light pollution, resulting in an increase attraction to wind farms and an increased mortality risk in birds due to collision (Rodríguez *et al.,* 2017). To reduce the mortality risk of light pollution different types of lights can be used. The use of metal halide lights multiplied the mortality risk with a factor of 1.9 compared to the use of light emitting diodes (Rodríguez *et al.,* 2017). Other forms of pollution that increase mortality risk, such as ingestion of plastics, could also be of use for compensatory measures. Ingestion of plastics are known to contribute to mortality in seabirds (Furness *et al.,* 2013b). Plastics are expected to have a higher impact on small seabirds, such as storm petrels and auklets (Dias *et al.,* 2019). In a study on northern fulmars in the North Sea, 58% of the birds had an amount of plastic in their stomach that exceeded the critical level of 0.1 g (Furness *et al.,* 2013b). Concrete impacts at the population level are hard to determine.

Reductions in the amounts of plastics seabirds are exposed to could potentially decrease mortality rates. In addition, oil pollution affects seabirds, especially auks (Furness *et al.,* 2013b). However, oil pollution is found to have large impacts but not a significant impact on long-term (Furness *et al.,* 2013b). To compensate for the negative effects of offshore wind farms the minimization of other infrastructures could be used. For example, reduction of collision with grid connections, as these power lines are a cause of, on estimate, many millions of deaths in birds via electrocution or collision (Lüdeke 2017; van der Winden *et al.,* 2014). It is thus expected that mitigation measures on grid connections will lead to a decrease in additional deaths in seabirds, but no evidence has found been yet.

Table 6.2. Offshore wind farm related risks and potential compensatory measures for a selection of seabirds, summarized in five main categories (reduction of predation, deployment of nesting platforms, increase food abundance and reduction of pollution).

Bird species	Collision risk	Habitat loss	Barrier effect	Potential compensation measure	Reduce predation	Nesting platforms	Food abundance	Fisheries	Pollution
Northern gannet	High	Low	Medium	Ending harvest of chicks, encourage establishment of new colonies and reduce bycatch in fisheries (McGregor *et al.*, 2022).	✓		✓	✓	
Arctic skua	Medium	Low	Unknown	Closure of sandeel and sprat fisheries and exclusion of great skuas from buffer zone (Furness *et al.*, 2013b)	✓		✓	✓	
Great skua	Medium	Low	Low	Closure of sandeel and sprat fisheries (Furness *et al.*, 2013)			✓	✓	
Little gull	Medium	Low	Low	No clear examples can be found in literature.				✓	
Lesser black-backed gull	Medium	Low	Low	Eradication of minks and rats, exclusion of foxes from colonies and closure of sandeel and sprat fisheries (Furness *et al.*, 2013b)	✓		✓	✓	
Herring gull	High	Low	Low	Eradication of minks and rats, exclusion of foxes from colonies and closure of sandeel and sprat fisheries (Furness *et al.*, 2013b)	✓		✓	✓	
Great black-backed gull	High	Low	Low	Eradication of minks and rats, exclusion of foxes from colonies and closure of sandeel and sprat fisheries (Furness *et al.*, 2013b)	✓		✓	✓	
Black-legged kittiwake	High	Low	Low	Closure of sandeel fisheries and creation of artificial nesting colonies (McGregor *et al.*, 2022).		✓	✓	✓	
Sandwich tern	Medium	Medium	High	Fencing out foxes from colonies, stoat control/eradication, flood and vegetation control at colonies, closure of sandeel and sprat fisheries close to Sandwich tern colonies (McGregor *et al.*, 2022). Creation of breeding habitat, rat control in existing colony.	✓		✓	✓	
Common tern	Medium	Medium	High	Eradication of minks, feral cats and rats, exclusion of foxes and large gulls from colonies, stoat control, closure of sandeel and sprat fisheries and creation of nest platforms (Furness *et al.*, 2013b)	✓	✓	✓	✓	
Razorbill	Low	High	Medium	Closure of sandeel and sprat fisheries, rat eradication and prevention of oil spills (McGregor *et al.*, 2022).	✓		✓	✓	✓
Guillemot	Low	High	Medium	Closure of sandeel and sprat fisheries, rat eradication and prevention of oil spills (McGregor *et al.*, 2022).	✓		✓	✓	✓

6.2.11 **Conclusions**

The most important measures proposed in compensation project plans in the UK in addition to mitigation of collision mortality in offshore wind farms (Table 6.2):

- *Increase food availability:* all project plans for compensatory measures for threatened seabirds include the aim to improve food availability, which is likely to enhance all focal seabird species, except perhaps for little gull (Table 6.2). This can be realized by reducing the fishery impact on forage fish stock through lower quota or closure of sandeel (Figure 4.13) and sprat (Figure 4.7) fishery in parts of the North Sea.

- *Reduce invasive mammals at breeding colonies*. The reduction of invasive mammals at breeding sites is effective for many threatened seabirds (Table 6.2).

- *The creation of artificial nesting sites* This has been developed for only two species: black-legged kittiwake (artificial cliffs) and common tern (floating islands).

Other measures include minimizing pollution and litter, minimizing bycatch in fisheries. Most of these proposed measures are also mentioned in the species conservation plans for four seabird species (Bos *et al.*, 2024).

6.3 Ecosystem-based management

An alternative or complementary approach these enhancement measures is ecosystem-based management (EBM), which is introduced in Chapter 3 and is potentially an important framework for the Nature Enhancement North Sea programme.

Interlinkages: food web
The first principle of EBM is to consider the relevant interlinkages to guide management actions. This can be implemented, among many other actions, by looking at the food web interactions, such as the key position of forage fish. Forage fish are important food for large fish (including commercially important species, seabirds and mammals of conservation concern and subjected to large-scale industrial fishing (Figure 6.2). This implies that larger forage fish stocks probably will have a positive contribution to commercially exploited large fish and to threatened seabird and marine mammal populations as well.

Interlinkages: structured habitats
Other important interlinkages are the ecological value of coastal and offshore “structured habitats” for seabirds as production sites of small fish and forage fish (see Chapter 4 and Figure 4.2-4.3). These 3D-structured habitats include shellfish reefs, polychaete reefs, kelp forests and seagrass beds in coastal areas (Figure 6.3 and geogenic reefs (stones) and biogenic reefs (shellfish and polychaetes) in offshore areas (Figure 6.4). Most of these habitats are absent in the North Sea or degraded and the focus of an increasing number of restoration projects in and around the North Sea and worldwide. Again, the conservation and restoration of these fish-producing habitats is also important for fisheries.

Humans as part of the ecosystem

Another important principle to include in the Nature Enhancement North Sea programme is to consider humans as part of the ecosystem with the aim to realise coexistence. The most important user group with respect to fish is fisheries. Single-species management is applied to most commercially exploited species. As discussed above, a food web-based approach and management/restoration of fish-producing habitats can provide common objectives between the Nature Enhancement North Sea programme and fisheries.

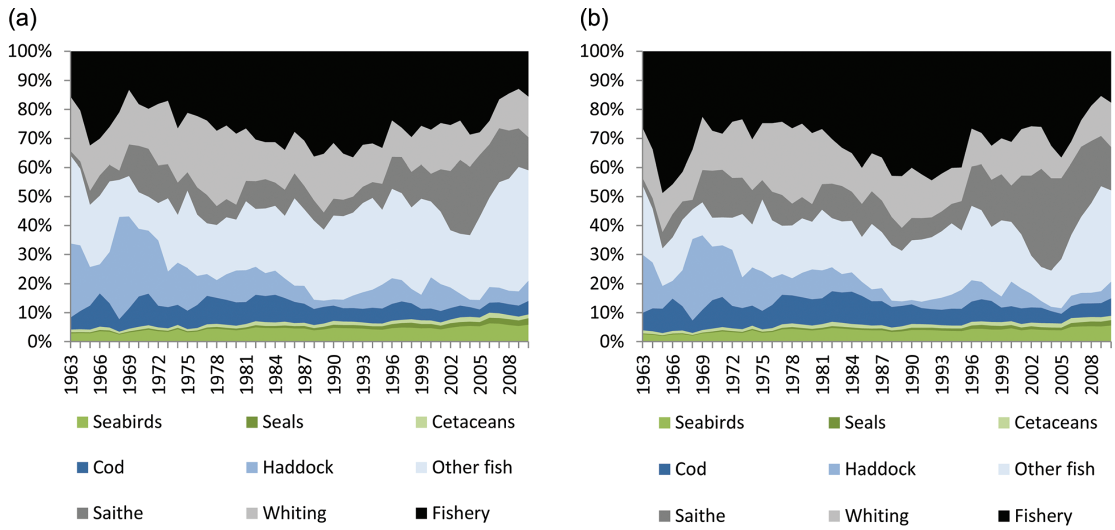

Figure 6.2. Removals by different predators and the fishery of North Sea forage fish per year (1963–2010). (a) Proportion of forage fish removed as a percentage of total removals by weight per year. (b) Proportion of value (Euros) of removals of foraging fish by source per year (right). Output from the SMS model (ICES, 2011). c 60-70% of forage fish is predated by large (ground) fish, 20% by fisheries, 10% by birds, 10 % by mammals (Dickey-Collas et al., 2014).

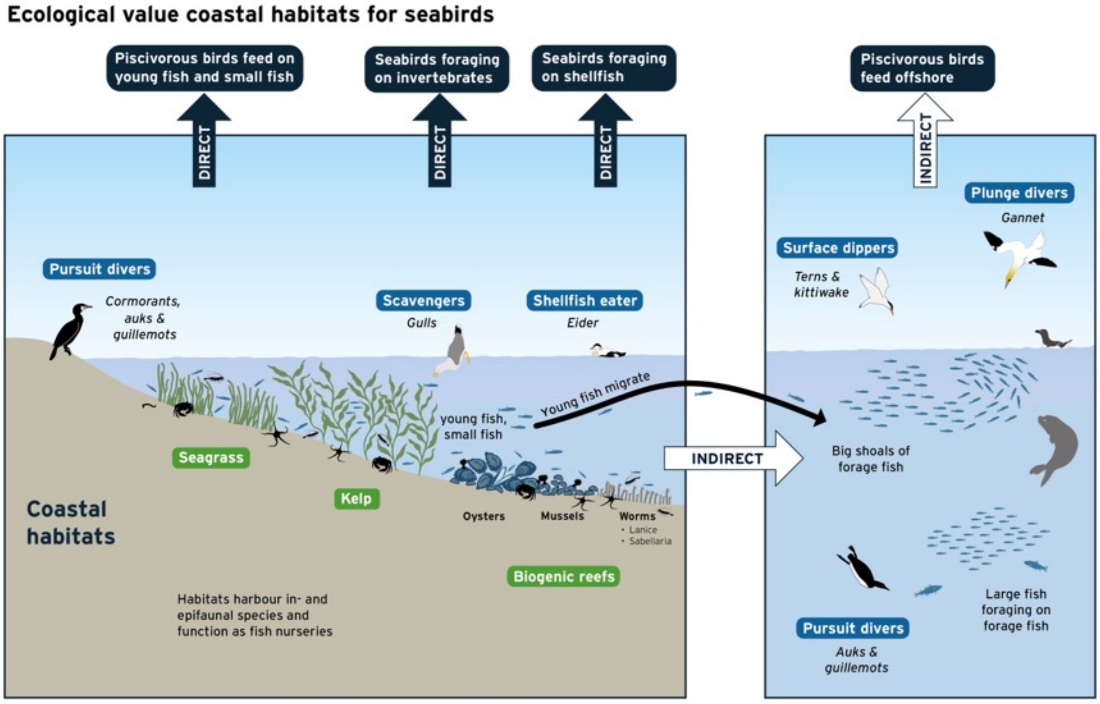

Figure 6.3. Conceptual diagram: the importance of coastal habitats to seabirds as providers of food.

Ecosystem-based management is the integrative or inclusive approach of management actions which considers (as much as possible) the positive interactions between complex marine habitats formed by ecosystem engineers and associated ecological groups which interact within the larger food web, such as invertebrates, fish, seabirds and marine mammals.

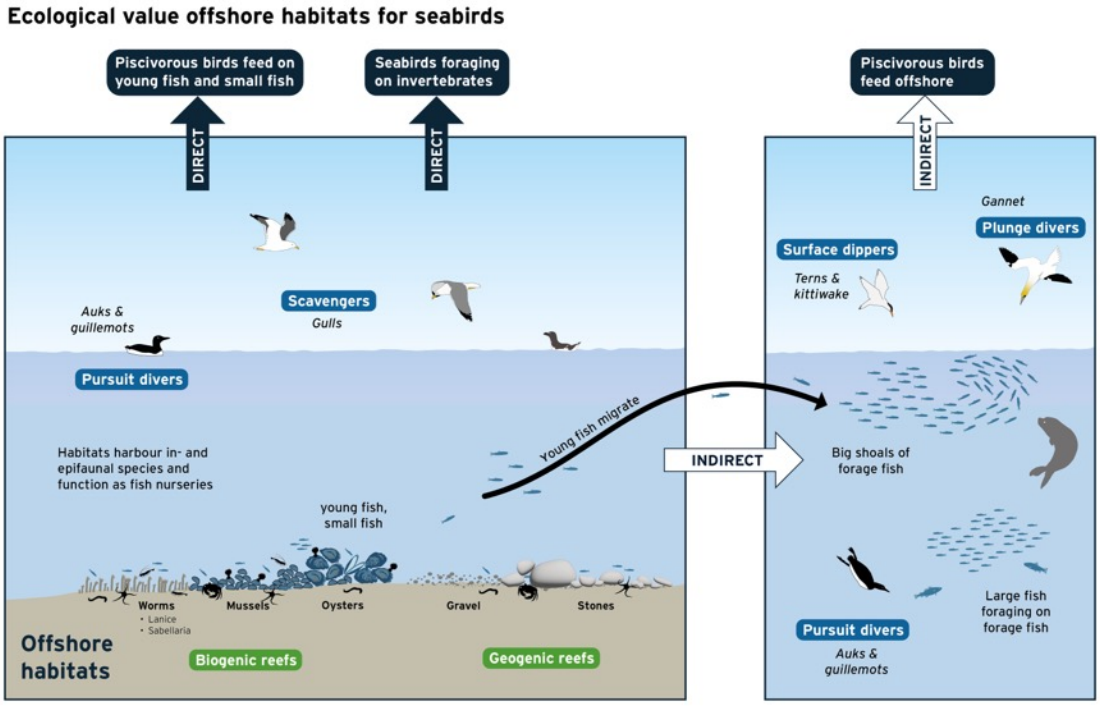

Figure 6.4. Conceptual diagram: the importance of offshore habitats to seabirds as providers of food.

6.4 Forage fish

6.4.1 Herring spawning sites

Herring populations in the North Atlantic including the North Sea differ in spawning locations, preferred substrates and timing and show morphological and genetical differences. These characters are sustained by a high return rate to the spawning sites.

As mentioned in Chapter 4, the ICES advises that no activities on spawning habitats should be allowed unless the effects of these activities have been assessed and shown not to be detrimental.

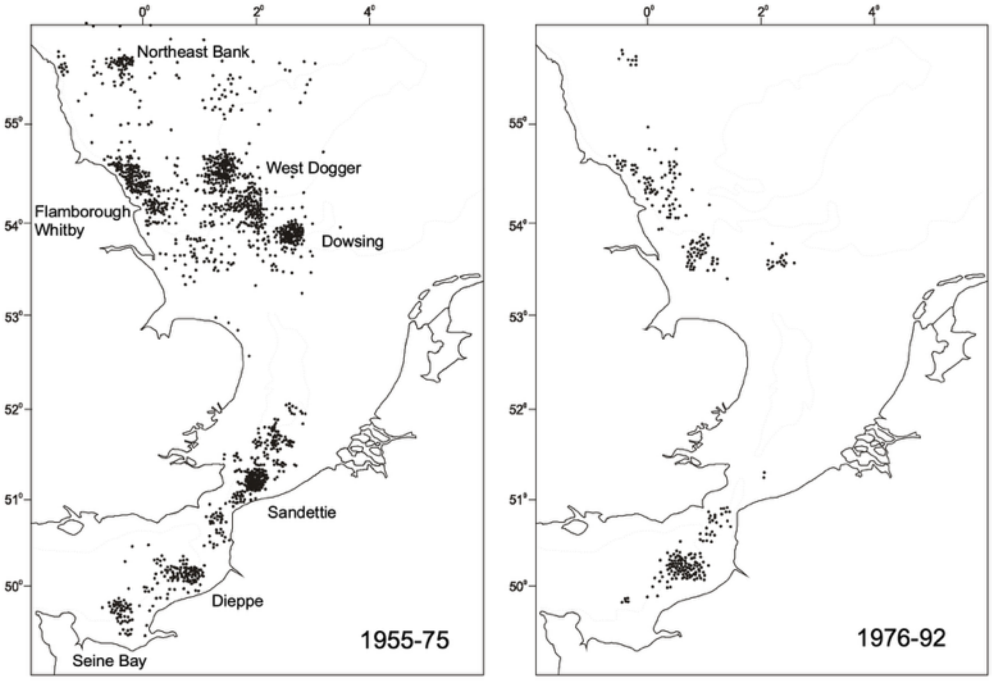

Figure 6.5. *The lasting reduction of the number of spawning grounds in the central and southern North Sea, following the depletion of the stock in the early 1970s. Each dot represents a catch of spawning herring from which a sample was obtained by the Dutch fisheries research institute. Data combined for the years before the stock collapse (1975-75) and for the period of the recovery (1976-92; Corten, 2001).*

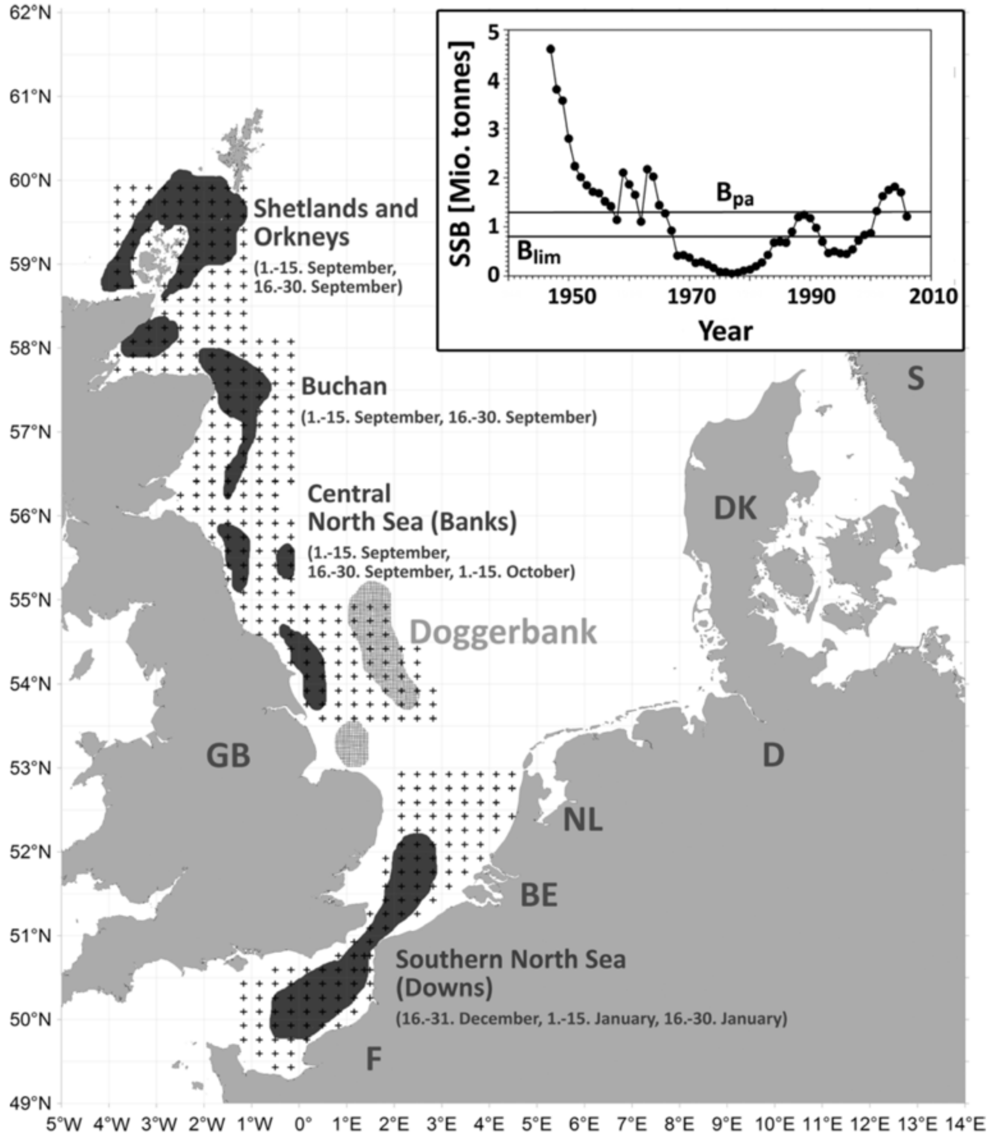

Figure 6.6. *Recent (dark grey) and historic (light grey) spawning grounds of North Sea autumn- and winter-spawning herring (sampling periods in brackets); the small crosses indicate the station grid of the International Herring Larval Survey (ihlS). Spawning grounds redrawn from Nash et al., (2009) and Hodgson (1957). Inset shows the time series of spawning stock biomass (SSB) of North Sea herring, plus the SSB threshold biomass reference point (Schmidt et al., 2009).*

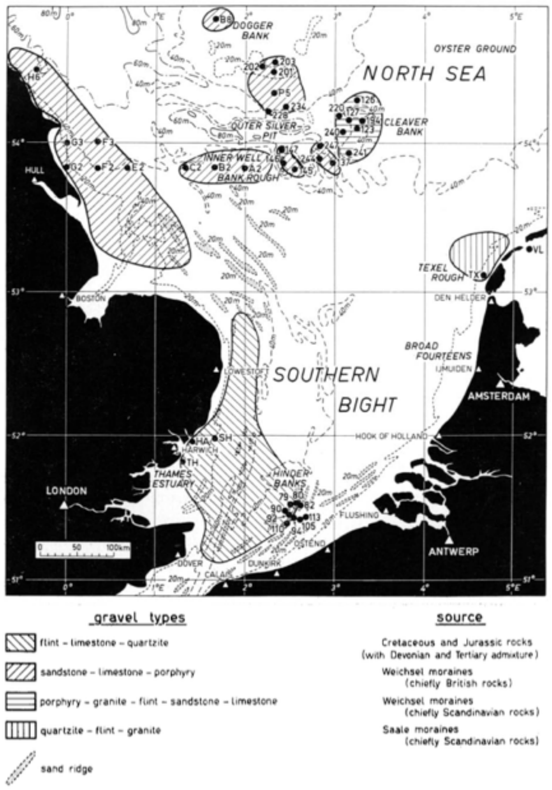

Figure 6.7. *Map of the southern North Sea with locations of gravel banks, gravel types and grab samples (Veenstra, 1969). The herring spawning sites in the southern North Sea roughly overlap with the occurrence of gravel banks for the Downs populations (near the Channel) and Banks population (Figure 6.5-6.6). The former populations of West Dogger and Dowsing spawned on the gravel banks of the Cleaver Bank, Inner Well Bank Rough and western Dogger Bank. The Texel Rough apparently never supported a herring spawning population.*

6.4.2 Sandeel distribution in the North Sea

Lesser sand eel and related sand eel-species stay year-round in the same localities in soft sediments with a specific grain size and silt content. This implies that spawning sites are within their year-round distribution range. Until recently, the main information about distribution and stock size was based only on fishery data.

As mentioned in Chapter 4, the ICES advise that no activities on spawning habitats should be allowed unless the effects of these activities have been assessed and shown not to be detrimental (ICES 2023b, 2024b).

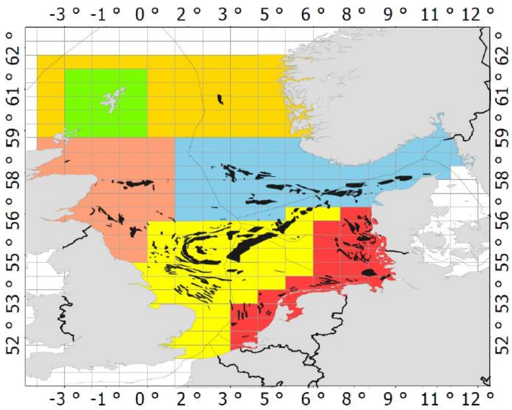

Figure 6.8. *Sandeel assessment areas in the North Sea as used by ICES since 2009. The main fishing grounds are marked in black within each division (Furness, 2020).*

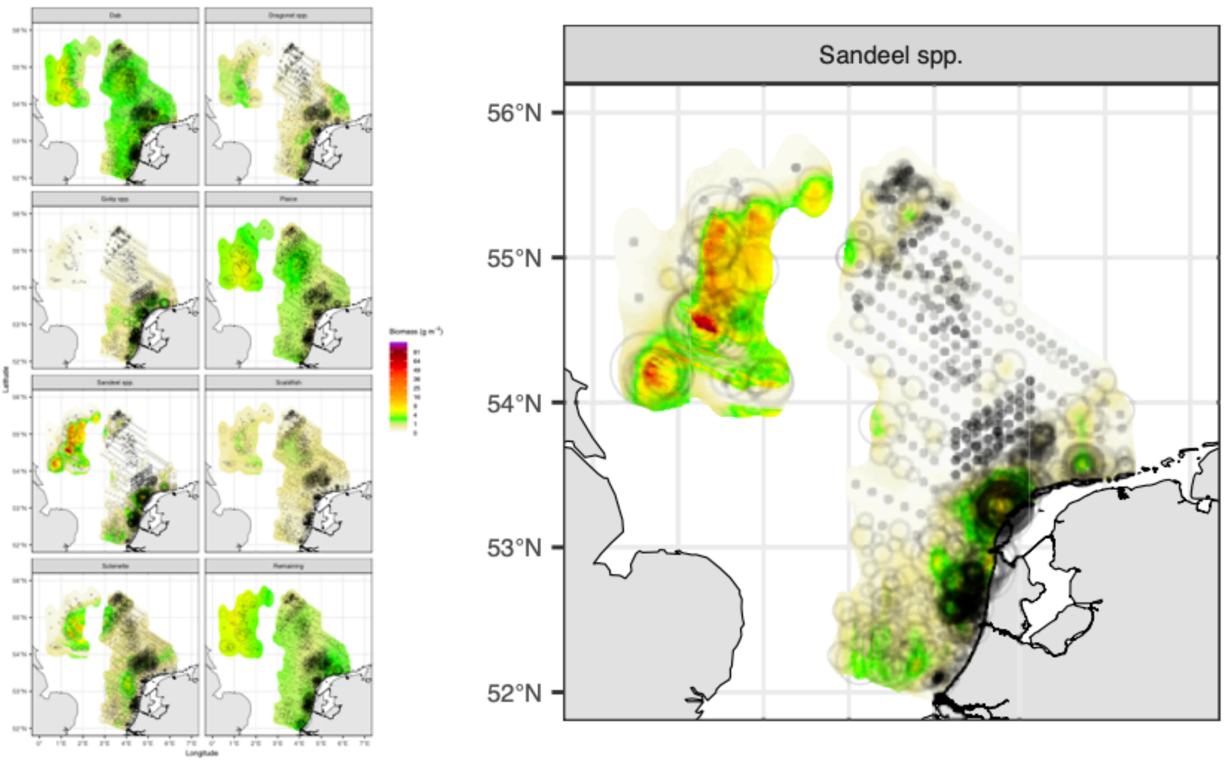

Figure 6.9. *Distribution of biomass per small (<30 cm) fish species and all remaining small fish pooled in the southern North Sea (left) and sandeel (right). Biomass estimates for the Dutch EEZ are a winter prediction, while estimates for the UK Dogger Bank reflect summer conditions. Size of black circles correspond with the observed biomass densities per station (corrected for haul distance and sorting fraction). The 40 m depth contour of the Dogger Bank is indicated by the black dashed line (Parmentier et al., 2025).*

6.4.3 Food reservation & fisheries management

The central position of forage fish in the North Sea food web (Figure 2.1) and their importance for large fish species (including commercially important species), direct pelagic fisheries, seabirds and marine mammals is illustrated by Figure 6.7 (Dickey-Collas *et al.*, 2014). Most forage fish (in biomass) are consumed by larger, mainly demersal fish species like Atlantic cod, haddock, saithe, whiting (Figure 6.7, blue and grey). Seabirds and marine mammals (Figure 6.7, green) take a relatively small proportion of the forage fish biomass, and the remaining is taken by industrial fishing on forage fish (Figure 6.7, black). The forage fish stocks are managed mainly to ensure that the stock sizes are within biologically safe limits. The importance for predatory fish (and their fisheries), seabirds and marine mammals are not considered. This also implies that the commercial fishery on larger fish and conservation of threatened large fish, seabirds and marine mammals have a common interest that forage fish stocks are maintained at a much higher level than the biologically safe limit.

6.5 Innovation

Artificial nesting sites

Recently, artificial nesting structures have been developed and deployed as compensation for collision mortality of kittiwakes in newly constructed offshore wind farm in the United Kingdom in the port of Lowstoft (Figure 6.10) and near-shore near South Beach, Lowstoft (Figure 6.11).

Each artificial nesting structures provide hundreds of small ledges designed to mimic the birds' steep cliff dwellings. Every year, a team will monitor how many nests are occupied and how productively the kittiwakes are able to breed. The studies will be shared with local wildlife trusts like the Lowestoft Kittiwake Partnership. The first results show that the artificial nesting sites have been used by kittiwakes and successfully reared young.

Figure 6.10. Renewable developers Vattenfall and Scottish Power Renewables have just completed construction of a kittiwake 'hotel' with new nesting structures in the port of Lowestoft, for around 430 pairs of black-legged kittiwakes. Source: https://www.scottishpowerrenewables.com/news/pages/lowestoft_kittiwake_hotels_open_for_business.aspx

Figure 6.11. Kittiwake hotel near South Beach, Lowestoft, and the Minsmere Nature Reserve, Suffolk. Placed in 2023 and first chicks hatch on structures in 2024.

Floating seaweed
Furness & Furness (2025) made a innovative suggestion that placement of seaweed farms close to selected seabird colonies could act as compensation for mortality associated with offshore wind farms. Many seabirds construct nests with seaweed that they collect at sea. These birds may also construct nests from plastic waste, which can kill seabirds by entanglement. Supplemented availability of seaweed could reduce this mortality by reducing use of plastic in nest construction. The authors argue that this novel approach has more advantages over other enhancement and compensation measures. It could benefit northern gannets not yet addressed by existing compensation measures. In addition, seaweed farming as a compensation measure also contributes to carbon sequestration and gives other environmental benefits. An example of other benefits to seabirds is that floating seaweed attracts small fish and forage fish, which subsequently attracts seabirds foraging on small fish (Vandendriesche *et al.*, 2007).

Highly selective fishing gear
Fisheries discards are viewed as irresponsible harvesting and therefore a discard ban was introduced in the CFP. Discarded fish are food for a range of scavenging seabird species; and therefore, the discard ban may have ecological consequences. Heath *et al.,* (2014) investigated in a modelling study the sensitivity of ecological effects to the discard ban using an ecosystem model of the North Sea - a region where 30–40% of trawled fish catch is currently discarded. The authors show that because of the discard ban the entire catch while fishing as usual has conservation penalties for seabirds, marine mammals and seabed fauna, and no benefit to fish stocks. However, combining landing obligations with highly selective fishing methods to limit the capture of unwanted fish results in trophic cascades that can benefit birds, mammals and most fish stocks. The results of this study highlight the importance of considering the broader ecosystem consequences of fishery management policy. This study also shows that developing highly selective fishing methods contributes both to sustainable fishing and conservation goals.

6.6 List of possible actions

This study identifies a range of possible actions with respect to food availability, safety and reproduction. The availability of food, for most species the availability of forage fish, is year-round of importance, both during breeding and in the non-breeding areas. Safety, such as predation and disturbance, and reproductive output are important during the breeding period. An additional issue is disturbance caused by shipping and fishing vessels during the non-breeding period.

Increase food availability
An increase of forage fish stocks will likely enhance all focal seabird species, except perhaps for little gull (Table 6.2). This can be realized by reducing the fishery impact on forage fish stock through closures of sandeel, herring and sprat fishery in parts of the North Sea, at least during the periods of spawning.

This can be realized by various actions:

- Increase food availability: restore mussel beds for direct (mussels) and indirect (fish) prey.

- Increase food availability: seagrass and salt marsh management.

- The conservation, enhancement and restoration of biogenic reefs as nursery habitats for fish to increase food availability.

- Enhance forage fish (herring, sprat, sandeel) stocks by protection and restoration of spawning sites. These measures will increase food availability for large fish, seabirds and marine mammals.

- Enhance forage fish (herring, sprat, sandeel) stocks by reducing catch.

- Enhance sandeel populations by reducing bottom disturbing activities (bottom trawling, sand mining)

- The conservation, enhancement and restoration of structured habitats like shellfish and polychaete reefs, kelp forests and seagrass beds as nursery habitats for fish will increase food availability for large fish, seabirds and marine mammals.

- The management of forage fish stocks well above the biological safe limits will increase food availability for large fish, seabirds and marine mammals.

- The protect and restoration of spawning grounds of forage fish including herring and sandeels will increase food availability for large fish, seabirds and marine mammals. This is already included in the annual ICES-advice for stock management (see also paragraph 4.4).

- These measures will also contribute positively to the exploitation and sustainability of large fish populations (e.g. Atlantic cod, haddock, and threatened species like sharks and rays).

Reduce invasive mammals at breeding colonies.
- The reduction of invasive mammals at breeding sites is effective for many threatened seabirds (Table 6.2).

The creation of new or artificial nesting sites
- This has been developed for only two species: black-legged kittiwake (artificial cliffs) and common tern (floating islands), Sandwich tern (new habitat).

6.7 Prioritizing framework

6.7.1 Ranking criteria

The overall suitability of compensation measures can be assessed with the six ranking criteria set out within the European Commission (2007) and DEFRA (2021) for compensation guidance and implemented by RHDHV (2023). Each criterion can be ranked on a scale of one to five, with five being the maximum score. This procedure allocates a score out of a maximum of 30 for each compensation measure, which provides a quantitative metric to rank each measure.

1. **Specificity:** The proposed compensation measure should focus on providing benefits to the conservation objectives of the potentially affected qualifying feature at the impacted location (e.g. seabirds on the North Sea). Maximum score: the compensation measure benefits the impacted species or habitat at the impacted site. Minimum score: the compensation measure benefits a different feature at a different site.

2. **Effectiveness:** How high is the confidence level that the measure will deliver effective and sustainable compensation for the impact of the project (e.g. on seabirds)? Maximum score: there is strong evidence of the effectiveness of the measure. Minimum score: there is little or no evidence of the measure.

3. **Delivery time frame:** What is the time frame within which the compensation measure is expected to be functioning and contributing to the relevant populations of seabirds? Maximum score: there is certainty that the compensation measure will be functioning within immediate implementation. Minimum score: there is no certainty that compensation measure will be functioning within 10 years.

4. **Technical feasibility/ delivery:** Can the measure be delivered successfully from a technical, financial, and legal perspective, and be monitored and managed appropriately? Maximum score: there is strong evidence that the delivery of this compensation measure is achievable. Minimum score: there is no evidence of the technical delivery of this measure with considerable uncertainty regarding expected outcomes.

5. **Conservation value:** What is the wider environmental benefit provided by the proposed measure in addition to the impact on seabirds?

6. **Extent:** Can the scale of the proposed compensation measure be accurately quantified/predicted?

6.7.2 Comparison of measures

Compensatory measures, such as habitat management and minimization of anthropogenic impacts, are aimed to improve survival rates and/or reproduction rates and thereby enhance population size. However, except for the positive impact of fishery closures, statistically significant results were not observed with all compensatory measures. Measures can have different effects on different target groups, and the compensatory measure should be adjusted to the species-specific ecological requirements and circumstances. Compensation measures often require a longer time frame before the effects are observed (Mascarenhas *et al.,* 2018). The benefits and drawbacks of the proposed compensatory measures are compared in Table 6.3. These are based on the time span for the measure to become effective, effect size, feasibility, and potential damage to the habitat.

Table 6.3. Comparison of compensatory measures with category of the measure, specification of measures discussed in the previous paragraphs and a short summary of the benefits and drawbacks of the measures.

Category	Measure	Benefits	Drawbacks
Minimization anthropogenic impacts	Increase food availability by reservation of forage fish for seabirds, large fish and mammal. decrease bycatch	Increases food availability for large fish, most threatened seabirds and marine mammals. Proven effect size. Decreases bycatch mortality.	Complex interactions between nature conservation directives and CFP. International compliance needed.
Minimization anthropogenic impacts	Design highly selective fishing gear	Increases food availability for large fish, most threatened seabirds and marine mammals. Decreases discards. Increases fisheries sustainability and profitability	Innovation process is costly and time-consuming
Habitat management	Habitat expansion, creation or restoration	Compensates for population losses, mainly via reproduction increase. Starting of new colonies has been successful.	Species-specific impact. Longer time needed. Limited research in the context of offshore wind farms.
Habitat management	Removal of threats (i.e. predators and invasive species)	Results in population growth. Existing and effective methods. Large impact on reproductive success.	Species-specific impact. Longer time needed. Damages predator populations.
Minimization anthropogenic impacts	Minimization of pollution	Expected decrease in mortality risk.	Not all pollutions have long-term effects.
Minimization anthropogenic impacts	Mitigation in and minimization of other infrastructures	Clear decrease in mortality rates.	Targeted at birds that live both at sea and onshore. Little information on the possibilities and effect size.

7 Research programs and international cooperation

7.1 National research programmes in the Netherlands: MONS/WOZEP

It is important that new initiatives for compensatory measures are guided with research and monitoring efforts to produce representative and additional meaningful results. This can be achieved if the research and monitoring efforts are aligned national and international research and monitoring programmes. At the national level, the most important programmes are the Nature Strengthening and Species Protection Survey (MONS) and the independent sub-programme Offshore Wind Ecological Programme (Wozep). Both research programmes are currently scheduled to finish around the early 2030s.

MONS

The MONS programme aims to answer whether, and how, the changing use of the North Sea, including offshore wind farms, can be carried out without a negative impact on the ecological carrying capacity. It emphasises research of the marine food web, including abiotic parameters, primary production, zooplankton, fish and birds as well as marine mammals (Asjes 2021). Preferably, the monitoring and research plan of the compensatory measures will contribute to all the research areas mentioned above. First, the research and monitoring of the compensation measures should be sufficiently detailed and frequent to ensure the results provide additional insight. This detail can be readily incorporated in overall North Sea impact assessments and modelling. Second, the proposed time scale of the research and monitoring should be aligned to the MONS programme to enable testing and validation by MONS results and model outcomes. Third, the monitoring of the mitigation impacts of compensatory measures will help fill knowledge gaps on the effectiveness of these measures. This in turn will provide current and future offshore wind farms with additional understanding of how to mitigate negative and enhance positive ecological impacts.

WOZEP

The aim of the Wozep research programme is to map out the ecological impacts of offshore wind and expand the knowledge base to better predict and understand the current and future cumulative ecological impacts of offshore wind in the Dutch North Sea. This includes developing models to calculate the potential ecological impact in the future if larger areas are set aside for wind farms.

The Wozep programme focuses on a range of ecological themes including, birds (collisions and habitat loss), bats (collisions), marine mammals and underwater noise, benthos, fish, and electromagnetic fields, and possible ecosystem effects.

The Wozep programme has the following overarching goals:

- To reduce the uncertainty surrounding the assumptions and knowledge gaps of the KEC, Environmental Impact Assessments (EIAs) and appropriate assessments (AAs).

- To reduce the uncertainty surrounding the assumptions and knowledge gaps concerning long-term effects in scaling up of offshore wind energy (for future road maps for the deployment of offshore wind energy).
- To gain insight into the effectiveness of mitigation measures.

Monitoring and research on the effects of the compensation measures will contribute to the Wozep programme with respect to species population data and will help the understanding of the wind farm's impact on species and population densities.

7.2 International programmes

In the North Sea area there are several recent international research programmes (based in the UK) related to the impact of offshore wind farms on seabirds (PrediCtOr, ReSCUE, ECOWind) and possible biodiversity enhancement and compensation measures (ECOWINGS, OWEC). Cooperation and alignment of research and monitoring of compensatory measures in the Dutch part of the North Sea with these programmes would strengthen the knowledge base of compensatory measures for seabirds in the North Sea area.

Ecowings
Uncertainty around impacts on seabird populations remains a key issue for offshore wind development in the North Sea area, affecting progress towards the increase in deployment of offshore windfarms needed to meet the targets of the various countries around the North Sea. Seabirds are impacted through collisions, displacement from feeding grounds and barrier effects on migratory routes or regular flight paths. The cumulative effects of these impacts, the underlying causal relationships behind them, and the extent of habituation over time are currently not well understood. The ECOWINGS project will transform the existing evidence base on the cumulative effects of offshore wind on key seabird species, establishing pathways for strategic compensation to ensure net gain for seabird populations and the wider marine ecosystem, while accounting for the projected effects of climate change. https://ecowind.uk/projects/ecowings/

Offshore Wind Evidence + Change (OWEC) Programme (UK)
OWEC aims to ensure the UK's roll-out of offshore wind does not come at the expense of the marine environment by creating a wide-ranging base of data and evidence to fill critical knowledge gaps on the subject and making these easily available to relevant parties. OWEC aims to create a wide-ranging base of data and evidence to fill critical knowledge gaps on the impact of offshore wind and making these easily available to relevant parties. OWEC is investing in projects aiming to close knowledge gaps on enhancing biodiversity through a comprehensive evidence base. The research and monitoring of compensatory measures, and biodiversity enhancement measures will contribute to OWEC's evidence base. Analysis of the results of these measures will provide a reference point with which other researchers and developers can make informed decisions about future ecological measures.
https://www.thecrownestate.co.uk/our-business/marine/offshore-wind-evidence-and-change-programme

Prevalence of Seabird Species and Collision Events in Offshore Windfarms (PrediCtOr; UK/NL)
The PrediCtOr programme (part of OWEC) sets out to develop an internationally coordinated approach to reduce bird collision risk uncertainty, thereby reducing consenting risk. This programme includes detailed collision and species population density data, as well as guidance on the roll out of collision detection systems, which can be used to reduce the uncertainty of collisions with offshore wind turbines.

Reducing Seabird Collisions Using Evidence (ReSCUE; UK)
The ReSCUE programme, funded by OWEC (UK) aims to develop our understanding of seabird flight heights to improve collision risk assessments and inform measures to mitigate collisions.

Strategic Compensation Pilots for Offshore Wind (UK)
Project led by Offshore Wind Industry Council (OWIC, UK) with the aim to deliver strategic ecological compensation pilots, which are applicable to foresee adverse effects from offshore wind farms to designated sites and by developing of a suite of measures and mechanisms.

7.3 International cooperation

International cooperation for the implementation of compensatory measures can be established at (1) the governmental level (e.g. implementation of EU Directives and conventions) and (2) at the level of research institutes (research and monitoring).

The Northeast Atlantic region is the “working range” of several conventions including OSPAR (focus on general marine biodiversity), ICES (focus on sustainable use, including fish stocks) and HELCOM (focus on marine biodiversity in the Baltic). Within the EU, their aims generally overlap with the EU Marine Strategy Framework Directive (Good Environmental Status) and spatially overlap with the Marine Protected Areas of the EU Natura 2000 network.

The rapid development of the rollout of renewable energy in the North Sea area has prompted several very recent initiatives for more cooperation: (1) the Joint Working Group on Seabirds (initiated in 2020); (2) the OSPAR Marine Bird Recovery Action Plan (initiated in 2022); (3) Intersessional Correspondence Group on Offshore Renewable Energy Development (ICG-ORED, initiated in 2023); and (4) Greater North Sea Basin Initiative (GNBSI, initiated in 2023).

The international cooperation in research and monitoring we first describe are the national research programmes for the local impact of offshore wind farms on biodiversity in general and birds and bats in particular (WOZEP) and the ecosystem-wide impact at the level of the Dutch Continental Shelf (MONS). In addition, we highlight several very recent and ongoing research programmes on mitigation and compensation of impacts of offshore wind farms on seabirds in the UK. Finally, we give a brief overview of relevant national and international databases that are closely linked to the EU Directives and international conventions.

7.3.1 Governmental level

OSPAR Convention

The OSPAR Convention aims to protect the marine environment in the North-East Atlantic as clean, healthy and biologically diverse marine environment that is used sustainably. The combined impacts of pollution, over-exploitation and climate change threaten the biodiversity and ecosystems that underpin the provision of food, jobs and enjoyment for millions of people in this region. The OSPAR vision is that this can be achieved by international cooperation. https://www.ospar.org/about/introduction

Since 1972, the Contracting Parties to the OSPAR Convention have worked to identify threats to the marine environment and have put in place programmes and measures to ensure effective collective and national action to mitigate these threats. In doing so, OSPAR has pioneered ways of monitoring and assessing the environmental status of our seas and set internationally agreed goals and commitments for participating Governments to deliver results. It has a proven record of success, which makes the OSPAR Commission a vital mechanism in helping governments to cooperate in the region and a key partner in further efforts to improve the protection and restoration of the North-East Atlantic. OSPAR works closely together with the Convention on the Protection of the Marine Environment of the Baltic Sea Area, also known as the Helsinki Convention (HELCOM).

Another relevant international organization is the International Council for the Exploration of the Sea (ICES), which is an intergovernmental marine science organization that aims to provide impartial evidence on the state and sustainable use of our seas and oceans.
https://www.ices.dk/about-ICES/who-we-are/Pages/Who-we-are.aspx
The goal of ICES is to advance and share scientific understanding of marine ecosystems and the services they provide and to use this knowledge to generate state of the art advice for meeting conservation, management and sustainability goals.

Joint OSPAR/HELCOM/ICES Working Group on Seabirds (JWGBird)

The above-mentioned OSPAR and HELCOM conventions work together with the ICES to implement the policy goals of the Marine Strategy Framework Directive for the relevant seabird species. The JWGBird will address both "pure science" topics, as well as more applied issues. The applied work includes requests for advice from OSPAR (e.g. Ecology Quality Objectives) and the development of common bird indicators as requested by the EU's Marine Strategy Framework Directive. The JWGBird holds annual meetings that are focused on the needs of OSPAR but are also motivated by the interests of the participants.
https://www.ices.dk/community/groups/Pages/JWGBIRD.aspx

Intersessional Correspondence Group on Offshore Renewable Energy Development (ICG-ORED)

The overall aim of OSPAR's work on offshore renewables is to support the implementation of the OSPAR North-East Atlantic Strategy (NEAES) 2030 in developing guidance on

promoting and facilitating sustainable development and scaling up of offshore renewable energy with minimal cumulative environmental impacts. To meet this goal, an Intersessional Correspondence Group on Offshore Renewable Energy Development (ICG-ORED) was established in March 2021. ICG-ORED is prioritising the impacts of offshore renewable energy developments on birds: *"By 2025 at the latest, OSPAR will take appropriate actions to prevent or reduce pressures to enable the recovery of marine species and benthic and pelagic habitats in order to reach and maintain good environmental status as reflected in relevant OSPAR status assessments, with action by 2023 to halt the decline of marine birds."* The ICG-ORED initiated the development of a framework for assessing the cumulative impacts of offshore wind energy on marine ecosystems on a regional sea scale, e.g. the North Sea. In line with OSPAR's operational objectives, this framework for cumulative impacts assessments will be developed and first applied to assess the impacts of offshore wind energy on birds.
https://www.ospar.org/meetings/archive/intersessional-correspondence-group-on-offshore-renewable-energy-1-2023developments

Greater North Sea Basin Initiative (GNBSI)
The Greater North Sea Basin Initiative (GNSBI) was officially established in November 2023, setting the framework for the (ministerial) collaboration between nine countries from the North Sea (Belgium, Denmark, France, Germany, Ireland, Netherlands, Norway, Sweden and United Kingdom), to strengthen cooperation on maritime spatial planning. The GNSBI aims to provide a regional platform for spatial integration of all uses by making proposals for better alignment of marine spatial planning (MSP), efficient management processes, and coordinating sectoral interests across boundaries - to tackle the spatial and ecological challenges of the Greater North Sea Basin. On 21st November 2023 governmental officials and agency representatives signed the ministerial conclusions, including a roadmap, six work tracks and a plan for the organisation of a ministerial summit in Belgium by the end of 2024.

The GNSBI countries share the Greater North Sea and, consequently, also share the common challenges of nature conservation in a heavily pressured marine environment, which is substantially affected by human activities and in a relatively poor ecological shape. Based on the premise that nature is without borders, the GNSBI aims to improve current and future conservation actions, enhancement, mitigation and compensation measures, explore synergies in national policies, and scale up regional cooperation.

8 Conclusions, knowledge gaps and recommendations

8.1 Conclusions

The principles and objectives of ecosystem-based management (EBM) have been briefly reviewed with respect to the implementation of the EU-Directives and regulations, and the national policies of the North Sea Agreement (NSA) and Nature Enhancement North Sea (NN) program. It is concluded the NSA and potentially also the NN-programme can become a bridge between fisheries management and conservation if common goals are determined and further developed.

Forage fish ecology and their management are crucial: they have a key role in the North Sea food web by transferring the primary production and zooplankton to higher trophic levels including large fish of both commercial and conservation concern, as well as threatened seabirds and marine mammals. This implies that the EBM of forage fish will contribute both to commercial fisheries and the conservation of threatened large fish, seabirds and marine mammals.

A list of possible measures is presented together with a prioritizing framework, and an overview of relevant national and international research projects and programs.

8.2 Knowledge gaps

Several knowledge gaps which are not yet addressed in existing research programs like MONS/WOZEP. These are phrased as research questions.

Food availability
Which stock sizes of forage fish (herring, sprat, sandeel spp.) in the North Sea are necessary to restore and threatened seabird populations to a favourable conservation status?

To what extent will larger forage fish stocks contribute to the stock size of larger fish, threatened fish species and marine mammals?

What are the effects of increasing water temperatures caused by climate change on the stock sizes of forage fish, large fish, seabirds and marine mammals in the next 10 years?

Population dynamics
How will positive changes in food availability, invasive species management and other enhancement measures effect reproduction and mortality of threatened seabird species?

Climate change
How will changes in food availability and quality because of increases in water temperature add to other cumulative effects as analysed in the KEC5.0 study?

8.3 Recommendations

Propose these research questions to the MONS programme and explore if they are included in other international research programmes.

Organise an international expert meeting and workshop with the following themes:

Accounting for food availability
- Spatial variation in forage fish density
- Protecting spawning populations of forage fish
- Effects of climate change on food availability

Strengthening reproduction
- Restoring and establishing new breeding colonies
- Protecting nests against predators and invasive species

Protecting marine habitats
- Prevent pollution in seabird habitats
- Availability and quality of migration corridors
- Seabird access to important foraging areas in relation to offshore windfarms

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Appendix I Conservation status seabirds North Sea

Table A.1. Conservation status seabirds Norths Sea in the Netherlands and internationally.

	NL: Conservation status					KRM/OSPAR		IUCN-status		
Species (English, *Dutch*)	**Season[1]**	**Svl[2]**	**Red List[3]**	**trend 1980[4]**	**trend 12 yr[5]**	**D1C2[6]**	**D1C3[7]**	**Europe[8]**	**EU-28**	**HPAI[10]**
Red-throated Diver *Roodkeelduiker*	nb	G		~	=	.	.	LC	LC	-
Northern Fulmar	br	.		.	.	0.61	(EN)	VU	EN	-
Noordse Stormvogel	nb	MO		--	-					
Northern Gannet	br	.		.	.	2.76	(LC)	LC	LC	††
Jan-van-gent	nb	G		+						
Common Scoter *Zwarte zee-eend*	nb	ZO		=	-	.	.	LC	LC	-
Great Skua *Grote Jager*	nb	G		=	=	0.89	(EN)	LC	LC	††
Little Gull	br	ZO	EB	--	~	.	.	LC	LC	-
Dwergmeeuw	nb	G	.	=	=					
Lesser Black-backed Gull	br	G		+	-	1.29	(EN)	LC	LC	†
Kleine Mantelmeeuw	nb	G		+	++					
European Herring Gull	br	ZO		-	-	0.61	(CR)	NT	VU	†
Zilvermeeuw	nb	MO		=	=	0.68	.			
Great Black-backed Gull	br	G		++	+	0.57	(EN)	LC	NT	†/††
Grote Mantelmeeuw	nb	ZO		-	=					
Black-legged Kittiwake	br	G	GV	+	~	0.36	(EN)	VU	EN	†
Drieteenmeeuw	nb	G		+	=					
Sandwich Tern	br	ZO	KW	+	-	1.02	(LC)	LC	LC	††
Grote Stern	nb	G	.	+	+					
Common Tern	br	ZO	GV	-	-	0.52	(CR)	LC	LC	†
Visdief	nb	ZO	.	+	++					
Common Guillemot *Zeekoet*	nb	G		+	+	0.96	(LC)	LC	LC	†
Razorbill *Alk*	nb	G		?	?	1.41	(LC)	NT	NT	-

1 Season: season to which Dutch conservation status (SvI, below) refers: br=breeding, nb=non-breeding.

2 SvI: formal conservation status (Staat van Instandhouding SvI) in NL: G = favourable, MO = unfavourable, ZO = quite unfavourable (SOVON-nl).

3 Red List: species is on the list of threatened and vulnerable breeding birds in NL: EB severely threatened, BE threatened, KW vulnerable, GV sensitive (Ministerie LNV, 2004)

4 Trend 1980: numerical trend in NL since 1980 (SOVON-nl)

5 Trend 12 yr: numerical trend in NL over most recent 12-year period. (SOVON.nl)

6 D1C2: KRM/OSPAR indicator for population abundance of seabirds in the Greater North Sea: favourable (green) if ≥0.7 of ≥0.8, otherwise unfavourable.

7 D1C3: KRM/OSPAR) indicator for seabird breeding productivity: expressed as the IUCN status category in which the population would hypothetically fall if the current level of breeding productivity were maintained for three bird generations.

8 Europe: IUCN-status category for the European population: LC least concern, NT near-threatened, VU vulnerable, EN endangered, CR critically endangered. (IUCNredlist.com)

9 EU 28: IUCN-status category for the population in the 28 EU member states.

10 HPAI: mortality by Highly Pathogenic Avian Influenza in 2022-2023: - no exceptional mortality in W-Europe, † above-average mortality with limited impact on population, †† exceptional mortality that may lead to downgrading of SvI or IUCN status.

Appendix II Glossary of terms

Adaptive management
The integration of programme design, management and monitoring to systematically test assumptions to adapt and learn (OSPAR 2023).

Baseline inventory
A description of current biotic and abiotic elements of site prior to enhancement or restoration, including its structural, functional and compositional attributes and current condition. The inventory is implemented at the commencement of the enhancement or restoration planning stage, to inform planning including enhancement or restoration goals, measurable objectives and treatment prescriptions (McDonald *et al.,* 2016).

Best available technology
The latest stage of development (state of the art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting discharges, emissions and waste OSPAR 2023).

Best environmental practice
The application of the most appropriate combination of environmental control measures and strategies OSPAR 2023).

Carrying capacity (ecological)
The upper limit of biomass that can be supported by a set primary production and within a variable food web structure is reached when total system respiration equals the sum of primary production and detritus import (Christensen & Pauly, 1998).

Connectivity
"An essential feature of nature. It is necessary for the functionality of ecosystems, underpinning key ecological processes and features such as maintenance of genetic diversity, flow of energy and organisms, hydrological processes, nutrient cycling, pollination, seed dispersal and disease resistance across all biomes and spatial scales. It is key for the survival of wild animals and plant species and is crucial to ensuring their migration HELCOM 2024).

Conservation
The protection, care, management and maintenance of ecosystems, habitats, wildlife species and populations, within or outside of their natural environments, in order to safeguard the natural conditions for their long-term permanence (IUCN 2021).

Critical habitat
Areas of high biodiversity conservation significance based on the existence of a habitat of significant importance to critically endangered or endangered species, endemic and/or range-restricted species, highly threatened and/or unique ecosystems and key evolutionary

processes, as well as globally significant concentrations of migratory and/or congregatory species (IFC 2012).

Designer ecosystem

An ecosystem that is primarily created to achieve mitigation, conservation of a threatened species, or other management purpose rather than achieve the re-establishment of a reference ecosystem (McDonald *et al.,* 2016).

Ecosystem engineers

Ecosystem engineers are defined by Jones *et al.,* (1994) as those species that “directly or indirectly modulate the availability of resources to other species by causing physical state changes in biotic or abiotic materials. In doing so they modify, maintain, and create habitats”. These include marine habitats with provide high habitat complexity by 3D-structures, such as seagrass meadows, kelp forests and biogenic reefs formed by shellfish or polychaete worms

Ecological integrity

The continuity and full character of a complex system, including its ability to perform all the essential functions throughout its geographic setting; the integrity concept within a managed system implies maintaining key components and processes throughout time HELCOM 2024).

Ecological opportunity

The availability of ecologically accessible resources that may be evolutionarily exploited (Stroud & Losos 2016).

Ecological risk

The probability of the occurrence of an undesired ecological event (Suter 2016).

Ecological restoration

The process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (McDonald *et al.,* 2016).

Ecosystem functions

The workings of an ecosystem arising from interactions and relationships between biota and abiotic elements. This includes ecosystem processes such as primary production, decomposition, nutrient cycling and transpiration and emergent properties such as competition and resilience. Functions represent the potential that ecosystems will be able to deliver ecosystem goods and services to humans (McDonald *et al.,* 2016).

Ecosystem services

The direct and indirect contributions of ecosystems to human well-being. They include the production of clean soil, water and air, the moderation of climate and disease, nutrient cycling and pollination, the provisioning of a range of goods useful to humans and potential for the satisfaction of aesthetic, recreation and other human values (McDonald *et al.,* 2016).

Ecosystem (or Ecosystem-based) approach

The comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, to identify and act on influences which are critical to the health of the marine ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity (OSPAR 2023).

Ecosystem-based management

A process that integrates biological, social, and economic factors into a comprehensive strategy aimed at protecting and enhancing sustainability, diversity and productivity of natural resources. The ecosystems (biosphere) are considered the fundament for social and economic development (OSPAR 2023).

Ecosystem resilience

i The capacity of a system to recover from stress and disturbance while retaining its essential functions, structure, feedback, and identity. Resilient ecosystems sustain biological diversity and human livelihoods in times of severe and wide-ranging change (IUCN).

ii Ecosystem functioning and resilience depends on a dynamic relationship within species, among species and between species and their abiotic environment, as well as the physical and chemical interactions within the environment. The conservation and, where appropriate, restoration of these interactions and processes is of greater significance for the long-term maintenance of biological diversity than simply protection of species. (CBD)

iii The capacity of an ecosystem to return to the pre-condition state following a perturbation, including maintaining its essential characteristics taxonomic composition, structures, ecosystem functions, and process rates. (Holling 1973).

iv The level of disturbance that an ecosystem or society can undergo without crossing a threshold to a situation with different structure or outputs. Resilience depends on factors such as ecological dynamics as well as the organizational and institutional capacity to understand, manage, and respond to these dynamics. (IPBES; HELCOM 2024).

Ecosystem stability

The ability of an ecosystem to maintain its structure (such as species diversity, variability in species densities) and function (nutrient and water cycling, biomass production, energy flows, etc.) over a long period of time despite disturbances (Elton, 1958; Paine, 1966; MacArthur, 1955).

Forage fish

Forage fish are usually defined as species that occupy an important intermediary trophic position and that retain that ecological role throughout their life. Excluded from this definition are fish species that assume this role early in life but later move into higher trophic categories as they age (e.g. Atlantic cod) (Engelhard *et al.*, 2014; Pikitch *et al.*, 2014).

Good environmental status

Good Environmental Status is the status of the environment that EU Member States aspire to attain by applying an ecosystem-based approach in their marine waters as required by the EU Marine Strategy Framework Directive (EU 2008).

Marine Protected Area
An area within the maritime area for which protective, conservation, restorative or precautionary measures, consistent with international law have been instituted for the purpose of protecting and conserving species, habitat, ecosystems or ecological processes of the marine environment (OSPAR 2023).

Mitigation hierarchy
The sequence of actions to anticipate and avoid and, where avoidance is not possible, minimise and, when impacts occur, restore and, where significant residual impacts remain, offset for biodiversity-related risks and impacts on affected communities and the environment (Stephenson & Carbone 2021).

Nature-based Solutions
Actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (taken from IUCN; OSPAR 2023).

Restoration
Activities that initiate or accelerate the recovery of an ecosystem from a degraded State HELCOM 2024).

Precautionary approach
Management approach where preventive measures are to be taken when there are reasonable grounds for concern that substances or energy introduced, directly or indirectly, into the marine environment may bring about hazards to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea, even when there is no conclusive evidence of a causal relationship between the inputs and the effects (OSPAR 2023).

Pressures
Natural and anthropogenic threats that influence biodiversity and ecosystem processes (Stephenson & Carbone 2021).

Reference ecosystem
A community of organisms and abiotic components able to act as a model or benchmark for restoration. A reference ecosystem usually represents a non-degraded version of the ecosystem complete with its flora, fauna, abiotic elements, functions, processes and successional states that would have existed on the restoration site had degradation, damage or destruction not occurred – but should be adjusted to accommodate changed or predicted environmental conditions. An alternative term for reference ecosystem is ‘ecological reference’ (McDonald *et al.,* 2016).

Sustainable use
The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations (HELCOM 2024).

Sustainability
Sustainability is "a characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs" (Millenium Ecosystem Assessment 2005).

Structural diversity
Ecosystem structure refers to the physical organisation of an ecological system including density, stratification, and distribution of species (their populations, habitat size and complexity), canopy structure and pattern of habitat patches, as well as abiotic elements (McDonald *et al.,* 2016).

Translocation
The intentional transporting (by humans) of organisms to a different part of a given landscape or aquatic environment or to more distant areas. The purpose is generally to conserve an endangered species, subspecies or population (McDonald *et al.,* 2016).