



Food-web perspectives for marine management

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Report summary

The North Sea food web is a network of trophic relationships and ecological interactions between organisms such as plankton, fish, birds, and marine mammals. The food web can be altered by environmental changes resulting from factors such as large-scale offshore wind farm construction, changes in fishing pressure, eutrophication, climate warming, as well as nature restoration. These changes in the ecosystem may benefit some species while negatively affecting others, leading to shifts in species interactions and, consequently, changes in the food web. In this project, the potential additional value for marine management of applying relevant food web indices to monitor changes in food webs will be investigated.

When analysing food webs, it is necessary to consider how food web components vary across space and time. By applying food web indicators to assess the environment, the functional role of species within an ecosystem or food web can be clarified. Taking differences regarding functional roles or sensitivities of the included species into account, habitats where food web dynamics are more vulnerable may be identified. This may help management protect species and ecosystem functions and stimulate development of ecosystem-based management according to visions for nature and responsible resource use.

The main research questions for this study are:

- How can marine food web assessments be used to support ecosystem-based management and guide environmental policy?
- Which food web indicators are most suitable for assessing the impacts of human activities and environmental change on marine food webs, including both bottom-up- and top-down-effects?
- Which indicator species or functional groups can serve as effective indicators of food web change, and how can they be integrated into management and policy frameworks?

For ecosystem assessments (e.g. under MSFD), the use of simplified food-web indicators requires explicit decisions on food-web boundaries and aggregation levels. Complex food-web approaches, such as applying Ecopath with Ecosim modelling, Ecological Network Analysis and cross-habitat connectivity analyses, can be used to inform on boundaries and aggregation levels by identifying the functional components, trophic pathways, and spatial linkages that are essential for maintaining food-web structure and functioning. In this way, complex indicators can support the development of policy-ready indicators that remain sensitive to pressures on trophic interactions, thereby strengthening ecosystem-based management and the assessment of Good Environmental Status. In chapters [2](#) and [3](#), we outline the principles of North Sea food web categorization in the context of MSFD Descriptor 4 'Food webs'. Operational food web indicators are listed, categorized, and evaluated in chapter [4](#), where recommendations of complementary indicators are given and motivated.

In chapter [5](#), we present two contrasting case studies that illustrate the added value of complex food-web indicators. In the Dutch Voordelta, such indicators can reveal changes in benthic-pelagic coupling that may be masked by functional redundancy and apparent stability at higher trophic levels. In the Dutch coastal zone and wider North Sea, they can help identify ecological mechanisms underlying seabird population trends, including changes in prey availability, trophic energy transfer, and connectivity between habitats, when changes in the food web can otherwise remain undetected when shifts in species composition and distribution balance each other out.

Together, these case studies show that complex food-web indicators provide mechanistic insight that complement simpler policy indicators. They can reveal trophic bottlenecks, distinguish ecological resilience from compensatory dynamics, and provide early warning signals of ecosystem change, thereby improving the interpretation of environmental status and strengthening the ecological basis for ecosystem-based management. While the relatively strong monitoring available in these systems enables detailed food-web analyses, challenges remain in quantifying interaction strengths and disentangling trophic effects from environmental drivers such as climate change, hydrodynamics, and species redistribution.

Policy synthesis note

Food-web approaches for MSFD Descriptor 4 and Ecosystem-Based Management in the Dutch North Sea

Purpose

General question: *What does this report mean for MSFD Descriptor 4 implementation and ecosystem-based management, and what should LVVN do next?*

The report '**Food-web perspectives for marine management**' contains scientific analyses and technical details. The report's outcomes were synthesized and structured into a policy synthesis note (*Beleidssynthese*) with support from Microsoft Copilot, while all scientific interpretation, validation, and final conclusions remained the responsibility of the authors.

This note synthesises the key findings of the report and translates them into implications for policy and management, including main conclusions, management implications, and recommendations on next steps for LVVN. It focuses on how food-web approaches can support implementation of Marine Strategy Framework Directive (MSFD) Descriptor 4 (Food Webs) and strengthen ecosystem-based management (EBM) in the Dutch North Sea.

Key messages

1. Food-web information adds value, but no single indicator can capture food-web status

The study confirms that food webs provide a useful framework for understanding ecosystem functioning because they describe the trophic interactions and energy flows linking plankton, benthic fauna, fish, seabirds, and marine mammals.

However, food-web complexity cannot be adequately represented by a single indicator. Indicators operating at the scale of the entire North Sea are often too general to detect important ecological changes occurring within specific habitats or trophic groups.

The most promising approach is therefore a combination of complementary indicators that together capture different components of food-web functioning.

2. Food-web approaches support ecosystem-based management

Food-web analyses provide insights that are often not visible through traditional assessments focused on individual species, habitats, or pressures.

The case studies demonstrate that food-web approaches can:

- reveal trophic bottlenecks and vulnerabilities;
- identify indirect effects of human activities;
- distinguish genuine ecosystem resilience from temporary compensatory responses;
- improve understanding of cumulative pressures;
- provide mechanistic explanations for observed ecological trends.

This makes food-web approaches particularly valuable in a North Sea that is changing rapidly under the combined influence of climate change, fisheries, offshore wind development, shipping, as well as nature restoration measures designed to conserve and restore marine ecosystems.

3. Different tools are needed for assessment and management

A key conclusion of the study is that **two complementary food-web perspectives** should be distinguished:

Assessment perspective (MSFD Descriptor 4)

This objective is to assess and report on food-web status. This requires operational indicators that can be applied consistently over time and integrated within MSFD assessment frameworks.

Management perspective (ecosystem-based management)

The objective is to support decisions that move the ecosystem towards Good Environmental Status (GES). This requires models and analytical tools capable of evaluating direct and indirect ecosystem responses to management measures.

Although related, these purposes require different approaches and should not be collapsed into a single assessment and management framework.

Implications for MSFD Descriptor 4

- Descriptor 4 is most effective when integrated with wider ecosystem assessments.
- Descriptor 4 should focus on ecosystem functioning and trophic interactions that are not captured by other descriptors.

Changes in habitats, fish communities, seabirds, marine mammals, nutrient dynamics, and benthic ecosystems all affect food-web functioning. Consequently, Descriptor 4 assessments should be interpreted alongside assessments under other biodiversity-related descriptors, particularly Descriptor 1 (Biodiversity) and Descriptor 6 (Seafloor Integrity).

A combined indicator approach is the most realistic pathway

The report indicates that an operational Descriptor 4 assessment is unlikely to be achieved through a single "best" indicator. Instead, a practical assessment framework could combine:

- a broad North Sea-scale food-web indicator;
- indicators representing major trophic levels;
- habitat- or ecosystem-specific indicators for ecologically sensitive areas;
- targeted food-web analyses where additional ecological interpretation is required.

This approach balances scientific robustness with practical implementation needs.

International alignment remains essential

The development of operational food-web indicators and Good Environmental Status thresholds remains scientifically challenging and has progressed slowly across Europe. Because MSFD and OSPAR assessments depend strongly on international coordination, major advances in food-web indicators are most likely to emerge through international processes such as ICES and OSPAR.

Active Dutch participation in these developments is therefore important.

Implications for Ecosystem-Based Management

Existing ecosystem-based management can already incorporate a food-web perspective

The study concludes that management action does not have to wait for the development of fully operational Descriptor 4 indicators. Current assessments already indicate that the North Sea is not yet in Good Environmental Status. Additional food-web indicators are unlikely to fundamentally change this conclusion.

Instead, food-web knowledge can strengthen ecosystem-based management by improving understanding of how pressures affect ecosystem functioning.

Food-web models can help evaluate indirect effects

Current cumulative impact assessment tools such as SCAIRM provide state-of-the-art support for assessing direct effects of multiple pressures on ecosystem components. However, they do not explicitly represent trophic interactions and indirect ecological effects.

A food-web model such as Ecopath with Ecosim (EwE) can complement existing assessment tools by:

- evaluating indirect impacts;
- analysing trophic pathways;
- identifying ecological trade-offs;
- exploring management scenarios;
- strengthening the ecological basis of EBM.

The report therefore identifies integration of food-web modelling within existing EBM frameworks as a promising next step.

Recommended actions for LVVN

Short term (next MSFD assessment cycle)

Assessment perspective (MSFD Descriptor 4)

- Continue developing a combined food-web indicator framework for assessing the food web as a whole.
- Test candidate indicators using existing monitoring data.
- Clarify how trophic-level and habitat-based perspectives can be integrated in assessment.

Ecosystem-based management

- Ensure food-web considerations are incorporated into ongoing EBM developments.
- Maintain active engagement in international indicator development initiatives through ICES and OSPAR.

Medium term (3-5 years)

Assessment perspective (MSFD Descriptor 4)

- Evaluate indicator performance in vulnerable habitats and ecosystem components.
- Identify the knowledge gaps that currently limit food-web assessment and prioritise monitoring efforts that deliver the greatest improvement in management-relevant information.
- Translate food-web indicators into policy-relevant assessment outcomes that can support evaluation of management effectiveness.

Ecosystem-based management

- Explore integration of Ecopath with Ecosim within existing Dutch EBM frameworks.
- Strengthen the connections between cumulative impact assessments and food-web analyses.
- Use food-web approaches to evaluate cumulative effects of fisheries, offshore wind development, climate change, and restoration measures.

Long term (5-10 years)

- Develop an integrated food-web assessment framework that combines indicators, monitoring, and ecological modelling.
- Develop a comprehensive ecosystem model that integrates major ecosystem components and trophic linkages, enabling assessment of food-web activity, organisation, and resilience.
- Align future monitoring investments with the information needs of ecosystem-based management.
- Strengthen the ecological understanding underpinning Descriptor 4 assessments.
- Contribute to international development of operational food-web indicators and GES thresholds.

Strategic conclusion

The central finding of this study is that food-web approaches can strengthen both MSFD assessments and ecosystem-based management, but their greatest value lies in complementing rather than replacing existing assessment frameworks. This addition is important for obtaining sufficient insight into the North Sea and for enabling effective management.

Regarding the **assessment perspective (MFSD Descriptor 4)**, the most realistic pathway is to use a combination of indicators representing different trophic levels, habitats, and ecological functions, supported by continued participation in international indicator development.

For **ecosystem-based management**, the priority should be to integrate food-web modelling and cumulative impact assessment tools so that both direct and indirect ecosystem effects can be considered in management decisions.

The above approaches and recommended actions together provide a practical pathway towards a stronger food-web perspective within Dutch North Sea policy, while remaining compatible with existing MSFD obligations, monitoring programmes, and ecosystem-based management initiatives.

Samenvatting rapport

Het Noordzeevoedselweb bestaat uit een netwerk van trofische relaties en ecologische interacties tussen organismen zoals plankton, vissen, vogels en zeezoogdieren. Dit voedselweb kan veranderen door grootschalige ontwikkelingen zoals klimaatveranderingen, de aanleg van offshore windparken, veranderingen in visserijdruk of natuurherstelmaatregelen. Veranderingen in milieu en ecosysteem kunnen bepaalde soorten bevoordelen en andere benadelen, waardoor de structuur en functie van het voedselweb veranderen. In dit project wordt onderzocht welke meerwaarde relevante voedselwebindicatoren kunnen bieden voor het monitoren van veranderingen in voedselwebben en voor het ondersteunen van marien beheer.

Bij voedselwebanalyses is het essentieel om rekening te houden met ruimtelijke en temporele verschillen in de samenstelling en dynamiek van voedselwebcomponenten. Door voedselwebindicatoren toe te passen bij de beoordeling van het mariene milieu kan de functionele rol van soorten binnen een ecosysteem of voedselweb beter worden begrepen. Door rekening te houden met verschillen in functionele rollen en gevoeligheden van soorten kunnen habitats worden geïdentificeerd waarin de voedselwebdynamiek relatief kwetsbaar is. Dit kan beheerders helpen om soorten, soortgroepen en ecosysteemfuncties beter te beschermen en de ontwikkeling van ecosysteemgericht beheer te ondersteunen, in lijn met beleidsdoelen voor natuurbehoud en duurzaam gebruik van natuurlijke hulpbronnen.

De belangrijkste onderzoeksvragen van deze studie zijn:

- Hoe kunnen voedselwebanalyses worden toegepast ter ondersteuning van ecosysteemgericht beheer en de implementatie van nationale en internationale beleidskaders?
- Welke voedselwebindicatoren zijn het meest geschikt om de effecten van menselijke activiteiten en milieuverandering op mariene voedselwebben te beoordelen, rekening houdend met zowel bottom-up- als top-downprocessen?
- Welke indicatorsoorten of functionele groepen geven betrouwbare signalen van veranderingen in voedselwebben, en hoe kunnen deze signalen worden geïntegreerd in nationale en internationale beheer- en beleidskaders?

Het gebruik van vereenvoudigde voedselwebindicatoren in ecosysteembeoordelingen, zoals onder de Kaderrichtlijn Mariene Strategie (KRM), vereist expliciete keuzes over de afbakening van het voedselweb en het aggregatieniveau. Complexere voedselwebbenaderingen, zoals Ecopath with Ecosim, Ecological Network Analysis en analyses van connectiviteit tussen habitats, kunnen deze keuzes onderbouwen door de functionele componenten, trofische routes en ruimtelijke verbindingen te identificeren die essentieel zijn voor het behoud van de structuur en het functioneren van voedselwebben. Op deze manier kunnen complexe indicatoren bijdragen aan de ontwikkeling van beleidsrelevante indicatoren die gevoelig blijven voor veranderingen in trofische interacties, en zo ecosysteemgericht beheer en de beoordeling van een Goede Milieutoestand versterken. In hoofdstukken **1** en **3** worden de uitgangspunten voor de indeling van Noordzeevoedselwebben in de context van KRM Descriptor 4 ('Voedselwebben') beschreven. In hoofdstuk **4** worden operationele voedselwebindicatoren geïnventariseerd, geclassificeerd en geëvalueerd, waarna aanbevelingen worden gedaan voor complementaire indicatoren.

In hoofdstuk **5** worden twee casestudies gepresenteerd die de toegevoegde waarde van complexe voedselwebindicatoren illustreren. In de Nederlandse Voordelta kunnen dergelijke indicatoren veranderingen in de benthisch-pelagische koppeling zichtbaar maken die door functionele redundantie en schijnbare stabiliteit op hogere trofische niveaus verborgen kunnen blijven. In de Nederlandse kustzone en de bredere Noordzee kunnen zij helpen ecologische mechanismen achter trends in zeevogelpopulaties te identificeren, waaronder veranderingen in prooibeschikbaarheid, trofische energiedoorvoer en connectiviteit tussen habitats. Dergelijke veranderingen zijn niet altijd zichtbaar in geaggregeerde trofische indicatoren, doordat onderliggende veranderingen in soorten en hun verspreiding elkaar kunnen opheffen.

Gezamenlijk laten deze casestudies zien dat complexe voedselwebindicatoren mechanistische inzichten bieden die een waardevolle aanvulling vormen op eenvoudigere beleidsindicatoren. Zij kunnen trofische knelpunten blootleggen, onderscheid maken tussen ecologische veerkracht en compenserende dynamiek, en vroege signalen van ecosysteemverandering detecteren. Hiermee verbeteren zij de interpretatie van milieutoestand en trends en versterken zij de ecologische basis van ecosysteemgericht beheer. Hoewel de relatief uitgebreide monitoring in deze systemen gedetailleerde voedselwebanalyses mogelijk maakt, blijven er uitdagingen bestaan bij het kwantificeren van interactiesterktes en het onderscheiden van trofische effecten van omgevingsfactoren, zoals klimaatverandering, hydrodynamiek en veranderingen in de ruimtelijke verspreiding van soorten.

Beleidssynthese

Voedselwebbenaderingen voor KRM Descriptor 4 en ecosysteemgebaseerd beheer in de Nederlandse Noordzee

Doel

Algemene vraag: *Wat betekent dit rapport voor de implementatie van KRM Descriptor 4 en ecosysteembeheer, en wat moet LVVN hierna doen?*

Het rapport '**Food-web perspectives for marine management**' bevat wetenschappelijke analyses en technische details. Met ondersteuning van Microsoft Copilot zijn de resultaten en inzichten uit het rapport samengevat en gestructureerd in deze Beleidssynthese (*Policy synthesis note*), waarbij alle wetenschappelijke interpretatie, validatie en eindconclusies de verantwoordelijkheid van de auteurs bleven.

Deze notitie vertaalt de belangrijkste inzichten naar implicaties voor beleid en beheer, waaronder de voornaamste conclusies, beheerimplicaties en aanbevelingen voor vervolgstappen voor LVVN. De notitie richt zich op de wijze waarop voedselwebbenaderingen kunnen bijdragen aan de implementatie van Descriptor 4 (Voedselwebben) van de Kader Richtlijn Marien (KRM) en aan de versterking van ecosysteemgericht beheer (*Ecosystem-Based Management*, EBM) in de Nederlandse Noordzee.

Kernboodschappen

1. Voedselwebinformatie voegt waarde toe, maar geen enkele indicator kan de status van het voedselweb vastleggen

De studie bevestigt dat voedselwebben een bruikbaar kader vormen voor het begrijpen van het functioneren van ecosystemen, omdat zij de trofische interacties en energiestromen beschrijven die plankton, benthische fauna, vissen, zeevogels en zeezoogdieren met elkaar verbinden.

De complexiteit van voedselwebben kan echter niet adequaat worden weergegeven door één enkele indicator. Indicatoren die op de schaal van de gehele Noordzee werken, zijn vaak te algemeen om belangrijke ecologische veranderingen binnen specifieke habitats of trofische groepen te detecteren.

De meest veelbelovende benadering is daarom een combinatie van complementaire indicatoren die samen verschillende componenten van het functioneren van voedselwebben vastleggen.

2. Voedselwebbenaderingen ondersteunen ecosysteem-gebaseerd beheer (EBM)

Voedselwebanalyses leveren inzichten die vaak niet zichtbaar zijn bij traditionele beoordelingen die zich richten op individuele soorten, habitats of drukfactoren. Dit maakt voedselwebbenaderingen bijzonder waardevol in een Noordzee die ingrijpend verandert onder invloed van klimaatverandering, toenemend ruimtegebruik op zee - en natuurherstelmaatregelen die gericht zijn op het beperken van negatieve ontwikkeling en het behoud en herstel van natuurwaarden.

De casestudy's tonen aan dat voedselwebbenaderingen:

- trofische knelpunten en kwetsbaarheden kunnen onthullen;
- indirecte effecten van menselijke activiteiten kunnen identificeren;
- onderscheid kunnen maken tussen echte ecosysteemveerkracht en tijdelijke compenserende reacties;
- het begrip van cumulatieve drukfactoren kunnen verbeteren;
- mechanistische verklaringen kunnen geven voor waargenomen ecologische trends.

3. Er zijn verschillende instrumenten nodig voor beoordeling en beheer

Een belangrijke conclusie van de studie is dat **twee complementaire voedselwebperspectieven** moeten worden onderscheiden:

Beoordelingsperspectief (KRM Descriptor 4)

Dit doel is het beoordelen en rapporteren van de status van voedselweb. Dit vereist operationele indicatoren die consistent over de tijd kunnen worden toegepast en geïntegreerd kunnen worden binnen MSFD-beoordelingskaders.

Beheerperspectief (ecosysteem-gebaseerd beheer)

Het doel is om beslissingen te ondersteunen die het ecosysteem richting een Goede Milieustatus (GES) brengen. Dit vereist modellen en analytische instrumenten die in staat zijn directe en indirecte ecosysteemreacties op beheersmaatregelen te evalueren.

Hoewel gerelateerd, vereisen deze doelen verschillende benaderingen en kunnen ze niet worden samengevoegd tot één enkel beoordelings- en beheerskader.

Implicaties voor MSFD Descriptor 4

- Descriptor 4 is het meest effectief wanneer deze wordt geïntegreerd met bredere ecosysteembeoordelingen.
- Descriptor 4 zou zich moeten richten op het functioneren van het ecosysteem en trofische interacties die niet door andere descriptoren worden vastgelegd.

Veranderingen in habitats, visgemeenschappen, verspreiding van zeevogels en zeezoogdieren, nutriëntendynamiek en bentische ecosystemen beïnvloeden allemaal het functioneren van voedselwebben. Daarom moeten beoordelingen van Descriptor 4 worden geïnterpreteerd naast beoordelingen van onder andere biodiversiteits-gerelateerde descriptoren, met name Descriptor 1 (Biodiversiteit) en Descriptor 6 (Integriteit van de zeebodem).

Een gecombineerde indicatorbenadering is het meest realistische pad

Het rapport geeft aan dat een operationele Descriptor 4-beoordeling waarschijnlijk niet zal worden bereikt via één enkele "beste" indicator. In plaats daarvan zou een praktisch beoordelingskader kunnen combineren:

- brede voedselwebindicatoren op Noordzeeschaal;
- indicatoren die belangrijke trofische niveaus weergeven;
- habitat- of ecosysteem-specifieke indicatoren voor ecologisch gevoelige gebieden;
- gerichte voedselwebanalyses waarbij aanvullende ecologische interpretatie vereist is.

Deze aanpak balanceert wetenschappelijke robuustheid met praktische implementatie-behoefte.

Internationale afstemming blijft essentieel

De ontwikkeling van operationele voedselwebindicatoren en het vaststellen van drempelwaarden voor een goede milieustatus blijft wetenschappelijk uitdagend en is langzaam gevorderd in heel Europa. Omdat KRM- en OSPAR-beoordelingen sterk afhankelijk zijn van internationale coördinatie, zullen grote vooruitgang in voedselwebindicatoren waarschijnlijk voortkomen via internationale processen zoals ICES en OSPAR.

Actieve Nederlandse deelname aan deze ontwikkelingen is daarom belangrijk.

Implicaties voor ecosysteem-gebaseerd beheer

Bestaand ecosysteem-gebaseerd beheer kan al een voedselwebperspectief bevatten

De studie concludeert dat beheersmaatregelen niet hoeven te wachten op de ontwikkeling van volledig operationele Descriptor 4-indicatoren. Huidige beoordelingen geven al aan dat de Noordzee nog niet in een goede milieustatus verkeert. Extra voedselwebindicatoren zullen deze conclusie waarschijnlijk niet fundamenteel veranderen.

In plaats daarvan kan kennis van voedselwebben ecosysteembeheer versterken door het begrip te verbeteren van hoe drukfactoren het functioneren van ecosystemen beïnvloedt.

Voedselwebmodellen kunnen helpen bij het evalueren van indirecte effecten

Huidige instrumenten voor cumulatieve impactbeoordeling zoals SCAIRM bieden geavanceerde ondersteuning voor het beoordelen van directe effecten van meerdere drukken op ecosysteemcomponenten. Ze vertegenwoordigen echter niet expliciet trofische interacties en indirecte ecologische effecten.

Een voedselwebmodel zoals Ecopath met Ecosim (EwE) kan bestaande beoordelingsinstrumenten aanvullen door:

- het evalueren van indirecte effecten;
- het analyseren van trofische banen;
- het identificeren van ecologische afwegingen;
- het verkennen van managementscenario's;
- het versterken van de ecologische basis van EBM.

Het rapport identificeert daarom de integratie van voedselwebmodellering binnen bestaande EBM-kaders als een veelbelovende volgende stap.

Aanbevolen acties voor LVVN

Korte termijn (volgende KRM-beoordelingscyclus)

Beoordelingsperspectief (KRM Descriptor 4)

- Blijf een gecombineerd voedselweb-indicator kader ontwikkelen dat het voedselweb als geheel beoordeelt.
- Test kandidaat-indicatoren met bestaande monitoringsgegevens.
- Verduidelijk hoe trofische en habitat-gebaseerde perspectieven kunnen worden geïntegreerd in de beoordeling.

Ecosysteem-gericht beheer

Zorg ervoor dat voedselweb-overwegingen worden meegenomen in de lopende EBM-ontwikkelingen. Blijf actief betrokken bij internationale indicator-ontwikkelingsinitiatieven via ICES en OSPAR.

Middellange termijn (3-5 jaar)

Beoordelingsperspectief

- Evalueer indicatorprestaties in kwetsbare habitats en ecosysteemcomponenten.
- Identificeer de kennisgaten die momenteel de voedselwebbeoordeling beperken en prioriteer monitoringsinspanningen die de grootste verbetering opleveren in beheerrelevante informatie.
- Vertaal voedselwebindicatoren naar beleidsrelevante beoordelingsresultaten die de evaluatie van de effectiviteit van het beheer kunnen ondersteunen.

Ecosysteemgericht beheer

- Verken de integratie van Ecopath met Ecosim binnen bestaande Nederlandse EBM-kaders.
- Versterk de verbanden tussen cumulatieve impactbeoordelingen en voedselwebanalyses.
- Gebruik voedselwebbenaderingen om de cumulatieve effecten van visserij, offshore windontwikkeling, klimaatverandering en herstelmaatregelen te evalueren.

Langdurige periode (5-10 jaar)

- Ontwikkel een geïntegreerd voedselwebbeoordelingskader dat indicatoren, monitoring en ecologische modellering combineert.
- Ontwikkel een integraal ecosysteemmodel dat voedselwebdynamiek in kaart brengt en beoordeling van voedselwebactiviteit, -organisatie en -veerkracht mogelijk maakt.
- Stem toekomstige monitoringsinvesteringen af op de informatiebehoeften van ecosysteembeheer.
- Versterk het ecologisch begrip dat ten grondslag ligt aan beoordelingen van Descriptor 4.
- Draag bij aan de internationale ontwikkeling van operationele voedselwebindicatoren en GES-drempels.

Strategische conclusie

De centrale bevinding van deze studie is dat voedselwebbenaderingen zowel MSFD-beoordelingen als ecosysteem-gebaseerd beheer kunnen versterken, maar hun grootste waarde ligt in het aanvullen van in plaats van het vervangen van bestaande beoordelingskaders. Deze aanvulling is van belang voor voldoende inzicht en effectief beheer van de Noordzee.

Vanuit **beoordelingsperspectief (KRM Descriptor 4)** is een combinatie van indicatoren die verschillende trofische niveaus, habitats en ecologische functies vertegenwoordigen, de meest realistische aanpak, ondersteund door voortdurende deelname aan internationale indicatorontwikkeling.

Voor **ecosysteem-gebaseerd beheer** moet de prioriteit liggen bij het integreren van voedselwebmodellering en cumulatieve impactbeoordelingsinstrumenten, zodat zowel directe als indirecte ecosysteemeffecten kunnen worden meegenomen in beheerbeslissingen.

De bovenstaande benaderingen en aanbevolen acties bieden samen een praktische weg naar een sterker voedselwebperspectief binnen het Nederlandse Noordzeebeleid, terwijl ze compatibel blijven met bestaande MSFD-verplichtingen, monitoringsprogramma's en ecosysteem-gebaseerde beheersinitiatieven.

1 Introduction

1.1 Policy background

In the coming years, the Ministry of Agriculture, Fisheries, Food Security and Nature (LVVN) will face major nature conservation and restoration challenges. When addressing trade-offs in ocean use, marine ecosystem-based management (EBM) is often targeted, but has been found to be challenging to implement (Haugen et al., 2024). Ecosystem-based management requires understanding of food webs (e.g. Korpinen et al., 2022).

Major challenges faced by North Sea ecosystems as a result of anthropogenic pressures and environmental change are being addressed through ecosystem restoration measures under European legislation, as well as through nature enhancement and conservation initiatives under the National Programme. Safeguarding the ecological functioning and natural variability of the marine environment requires a systematic observation, measurement, and assessment of the effects of environmental change and human uses of marine resources, including fisheries, sand extraction and sediment disposal, offshore wind energy, mariculture, and climate change. These effects should be evaluated from a food-web perspective to ensure that impacts across trophic levels and ecosystem processes are adequately understood. The goal for Descriptor 4 'Food webs' (D4) under the Marine Strategy Framework Directive (MSFD) is: "All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity." (European Commission 2017). A clear definition of scales as well as methods for applying a food web perspective is needed, both for the implementation of species-specific policies (regarding, e.g. birds and other top predators), as well as for the aim to achieve a good environmental status according to the MSFD.

With the introduction of the EU Nature Restoration Regulation (2024/1991), Member States including the Netherlands must implement National Restoration Plans for national nature improvement and conservation by 2026. These plans include monitoring frameworks, baseline data, and specified indicators to track ecosystem recovery. In this context, ecosystem and food web models support ecosystem-based management by linking pressures, species interactions, and habitat conditions to policy targets, enabling scenario analysis and evaluation of restoration measures (Korpinen et al., 2022; Rodriguez-Perez et al., 2023). Consequently, applying food web indicators as essential tools to capture the state and development of food webs for assessing ecosystem health, thereby providing knowledge that can support ecosystem-based management and biodiversity conservation goals at both EU and national levels.

A food web approach can strengthen the implementation and evaluation of restoration and conservation policies by explicitly linking species, habitats, ecological processes, and human pressures. Because food webs integrate interactions across multiple ecosystem components, food web indicators can provide information on the ecological consequences of management measures and the progress towards policy objectives. Such analyses can therefore support evidence-based decision-making, by helping managers to assess trade-offs, evaluate restoration outcomes, and track progress towards ecosystem health and biodiversity targets.

1.2 Food webs and food-web indicators

All organisms in and around the North Sea are connected to each other in a food web. Food webs may be defined at many different spatial scales, and at various levels of detail. A food web is a network of trophic relationships and ecological interactions between organisms, in which energy is typically transferred from sunlight through successive trophic levels. The species composition of food webs varies by habitat and region, and the interactions between species in a food web are complex and constantly changing. Different impacts, such as fisheries, sand extraction, sediment dumping, wind energy, shipping, marine aquaculture, and environmental effects of climate change, impose changes in living conditions for marine organisms and

the ecosystem. Some organisms may be more sensitive to these changes while others may benefit. If the relative abundance of species in an ecosystem changes, this will imply effects on the dynamics and ecological functioning of the food web.

Ecological function is the contribution of species or groups of species to the processes that sustain an ecosystem, including energy flow, nutrient cycling, and species interactions within the food web. In food web studies, ecological functions are often grouped into broader categories, e.g. production, consumption, nutrient cycling, and habitat provision. These functions influence biodiversity by regulating energy availability, nutrient dynamics, habitat structure, and species interactions, thereby determining which species can persist and coexist within an ecosystem. To monitor and assess ecosystem functions, food web indicators are commonly applied (Chakravorty et al., 2024; ICES, 2025a; Tam et al., 2017). Such indicators may be based on taxonomy, ecological traits, or the abundance and composition of species at different trophic levels. Food web indicators are often selected because they reflect specific environmental factors or human pressures (Boldt et al., 2014), allowing changes in ecosystem state to be monitored and assessed (Machado et al., 2021). In particular, trait-based approaches, which consider the ecological characteristics of species, can provide insight into the functional roles of species and species groups within food webs. By linking species traits and ecosystem functions, these approaches can help identify how sensitive ecosystems are to environmental change and human impacts. Applying food-web-related indicators can therefore improve understanding of ecosystem functioning and support the development of ecosystem-based management aimed at protecting biodiversity and maintaining ecosystem functions.

There are several cases in marine policy where species traits and functions have been developed into food web indices to monitor the health of marine food webs and to study the impact of stressors (see chapter 4). Hereby, not only the taxonomic diversity of species but also their functional diversity, i.e. phenology (i.e. timing of biological events and how these are influenced by environmental conditions), habitat use, lifestyle (e.g. food consumption), sensitivities to environmental change, and thereby ecosystem functioning can be examined. Focusing on food-web ecosystem functioning enables meaningful comparisons across diverse habitats and improves our understanding of how ecosystems respond to environmental and human stressors. Hereby, changes in the environment and ecosystem health can be monitored, to support ecosystem-based management and biodiversity policies at national and international levels. Incorporating trait-based functional groups into food-web indicators provides practical tools for a food-web approach that strengthens ecosystem-based management (**Figure 1.1**). Applying a trait-based approach facilitates comparisons among ecosystems and supports a shift from species- and stock-level assessments towards an ecosystem perspective centred on food webs and ecological functions. By focusing on the characteristics of organisms rather than on species identity alone, this approach can reveal common patterns across ecosystems, improve understanding of ecosystem functioning, and strengthen links to ecosystem services and their responses to management actions or environmental change.

Species in ecosystems can be described using a chosen set of traits. As a result, ecosystems with different species compositions may if they are compared nevertheless be recognized as functionally similar if their species share comparable traits. This enables meaningful comparisons among ecosystems. Traits can also provide insight into the ecological functions of species within ecosystems and food webs. For example, adults of one fish species and larvae of another fish species may both share the trait of being plankton feeders. In addition, traits can help predict how sensitive species are to environmental changes or human-induced disturbances. Traits can be used to scale ecological understanding from individuals and species to populations, communities, and entire ecosystems. For instance, a community dominated by large-bodied individuals may respond differently to increasing temperatures than one dominated by small-bodied individuals, because temperature affects metabolism, which is closely linked to body size. By linking species traits to ecological functions and processes, connections can be made to ecosystem services, such as habitat formation, water filtration, and food provision (**Figure 1.1**).

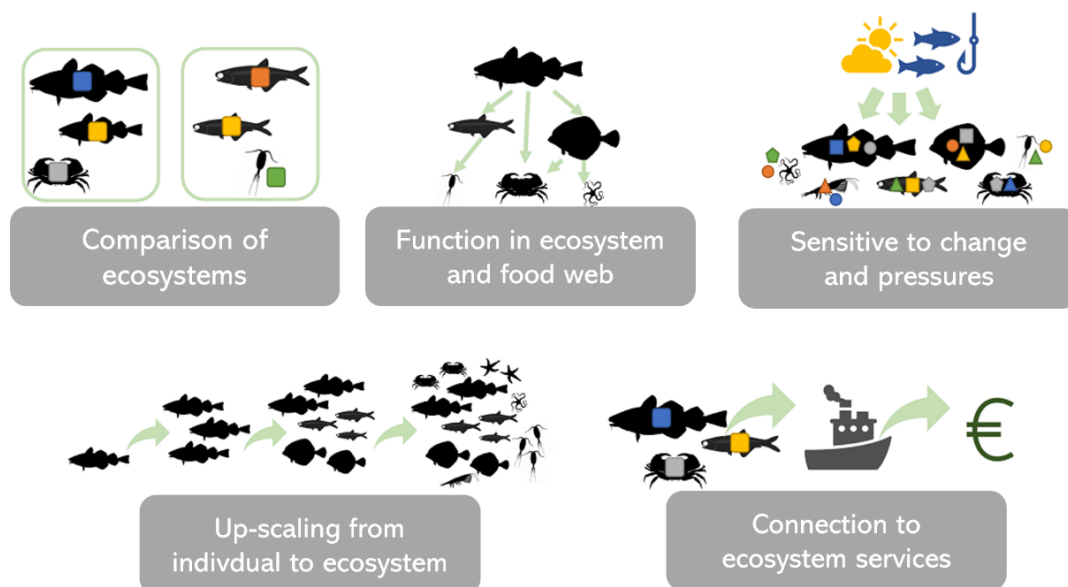


Figure 1.1. The role or function by traits of species in a food web can illustrate, e.g. the degree of sensitivity to change and disturbance, and the connection to ecosystem services. The colours and shapes here symbolize various traits of species from different aspects of ecological function, as well as sensitivity to environmental change or pressures. See text for elaboration. After Beukhof et al. (2021).

1.3 Project overview and objectives

This project investigates how a food web perspective can be operationalized to assess ecological changes and support environmental management in the North Sea. It established a clear pipeline from theoretical concepts to practical, policy-aligned case studies. The main question of this project is to investigate how a marine food web perspective can be applied to assess ecological changes across different spatial and temporal scales in the North Sea. Three sub-questions arise from the main question: 1) How can marine food web assessments be used to support ecosystem-based management and guide environmental policy? 2) Which food web indicators are most suitable for assessing the impacts of human activities and environmental change on marine food webs, including both bottom-up and top-down effects? 3) Which indicator species or functional groups can serve as effective indicators of food web change, and how can they be integrated into management and policy frameworks? To systematically address these questions, the study is channeled through four interconnected parts, each directly mapping to a core project component. Within chapters 1-3 we outline the principles of North Sea food web categorization within the framework of MSFD Descriptor 4. In chapter 4 the added value of applying food web indicators is demonstrated, which is highlighted in two concrete examples in chapter 5.

Chapter 2 – Review of the marine food web concept

Objective: Establish the theoretical foundation for structural and functional food web descriptions.

For this chapter, we conducted a targeted literature review focusing on general and theoretical food web concepts within marine environments. This included a brief historical overview of the concept's development to clarify core features and baseline terminology. Research sub-questions:

- How can food webs be described in relation to topology, including characteristics such as spatial or temporal context, resilience, shape, complexity, level of detail, or other characters, e.g. related to species traits and ecological function?

-
- Can category-dependent conclusions be made regarding the usefulness of a food-web perspective to evaluate, e.g. effects of climate change or other stressors?

Chapter 3 – Review of the North Sea food web concept

Objective: Contextualize the food web framework within the specific environmental and governance landscape of the North Sea.

For this chapter, a review was conducted of the current state of knowledge on North Sea food-web dynamics and the application of the food-web concept in marine ecosystem management. Particular attention was given to the use of food-web indicators in national and international management frameworks. The results provide an overview of selected examples that illustrate how food web indicators have been applied to support management and policy development at national and international levels.

Research sub-questions:

- How can changes in ecosystem functioning be detected using food-web indicators?
Clarification
 - Which indicators are expected to respond to changes in ecosystem functions such as primary production, trophic transfer, nutrient cycling, or benthic-pelagic coupling?
- How can information regarding food web indicators be compiled on logical spatial scales for use in assessment?
Clarification
 - Which spatial scales apply for assessment? If chosen food web indicators are applied, is there an overlap or non-overlap in the spatial scales?

Chapter 4 – Food web indicators for nature restoration, improvement and conservation

Objective: Map food web indicators against national and European regulatory frameworks.

This chapter contains our evaluation of how food web indicators can support nature restoration and conservation objectives, with a primary focus on the EU MSFD Descriptor 4. By linking specific habitat types and key species to their wider trophic networks (**Figure 1.2**), information from ecological data can be bridged with management targets. We incorporated concrete management examples, such as evaluating food availability for seabirds relative to the closure of sandeel fisheries in Scottish and English waters, to demonstrate how indicators can track ecological status and pilot future management scenarios. Additionally, we proposed an indicator classification matrix based on ecological complexity and explicitly map their sensitivity to anthropogenic pressures (e.g. fisheries, eutrophication, etc.) using frameworks like ODEMM (Piet et al., 2014). Research sub-questions:

- How can status/changes in the North Sea at the food web level be evaluated by using food web indicators, with respect to EU nature restoration (EU) and national nature improvement and conservation?
- What are the links between applying food web indicators and the goals for the Marine Strategy Framework Directive, EU Biodiversity strategy for 2030, EU Birds and Habitat directives, and with Effective Area-Based Conservation Measures (OECM)?

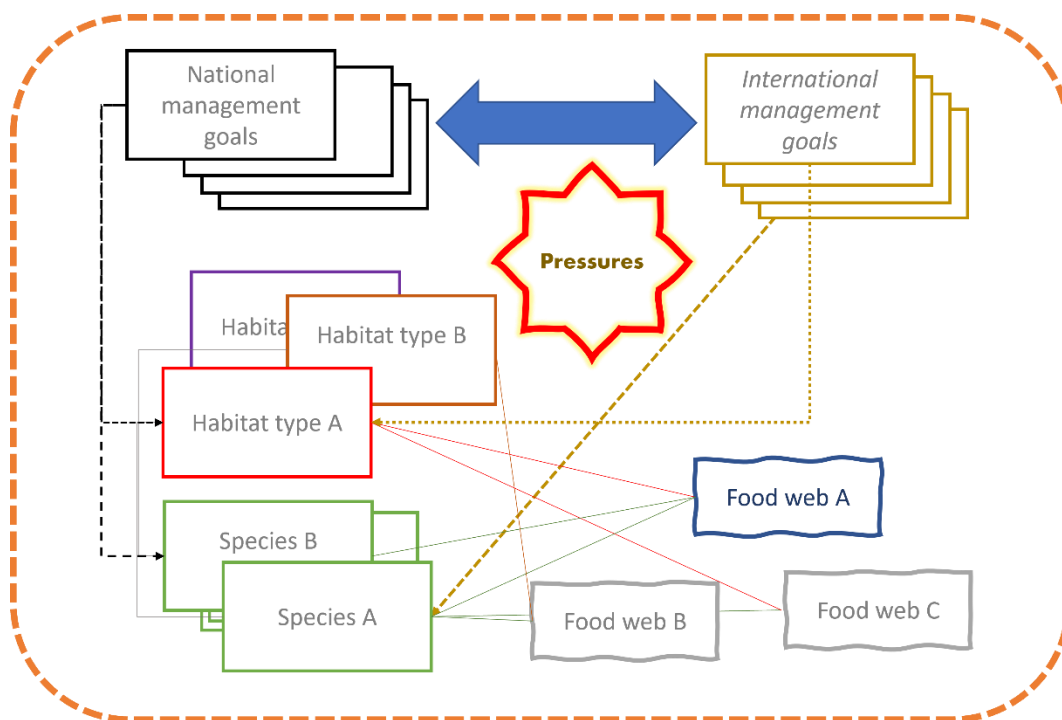


Figure 1.2. Illustration of possible links between nationally and internationally formulated management goals, linked to defined habitats where specified species occur. The habitat types and species occurring there together form food webs, which can then be assessed to evaluate the effects of pressures.

Chapter 5 – Elaboration of selected case studies

Objective: Demonstrate the empirical application and added value of food web indicators through concrete North Sea examples.

Within this chapter, we applied the theoretical and indicator frameworks elaborated in Tasks 1-3 to demonstrate the practical application of proposed food web indicators for two case studies relevant to the Dutch North Sea. The case studies were selected based on: (a) their relevance for illustrating trophic coupling across spatial scales, and (b) the availability of recent empirical data. For each case study, we include a classification of habitats and species in accordance with MSFD-relevant ecosystem components.

The selected examples illustrate how trophic levels are coupled across varying spatial scales, capturing both highly mobile, regionally governed species, as aligned with OSPAR and ICES frameworks (ICES, 2025b; OSPAR, 2023) and sedentary, locally dominant components. We show proposed food web indicators possible to apply for these two example systems, and elaborate on the clear added value of multi-trophic food web indicators to complement other MSFD indicators as well as traditional, single-component assessments (e.g. monitoring commercial fish stocks or seabirds in isolation).

Research sub-question:

- Based on collected information, how can examples of food webs in the (Dutch) North Sea be categorized regarding their characteristics?

2 Review of the marine food web concept

Research sub-question:

- How can food webs be described in relation to topology, including characteristics such as spatial or temporal context, resilience, shape, complexity, level of detail, or other characters, e.g. related to species traits and ecological function?

2.1 Theoretical foundation and the stability debate

The interplay between organisms in nature has been acknowledged by people for many centuries. Elton (1927) introduced the scientific foundation for the concept of food webs, as organisms were divided into functional groups depending on their habitat and prey. The complex network that illustrates feeding relationships among organisms in the ecosystem can be described as a **food web**. Food-web structure is partly determined by **species traits** (morphological, physiological, or phenological characteristics of organisms), which influence who interacts with whom and the strength of those interactions. These interactions define the **ecological function** of species and thereby fundamentally influence the functioning and stability of the ecosystem.

To resolve how complex food webs persist in the real world without collapsing, modern ecology relies on **network theory**. A food web is hereby translated into a formal mathematical framework made up of **nodes** and **links** connecting them (**Figure 2.1**). The roots of network theory lie primarily in mathematics (i.e. graph theory), but the approach has been widely adopted and further developed across ecology, sociology, and other disciplines. Network theory applied in ecology defines food webs as species, populations, functional groups, or habitats in an ecosystem, that are linked by feeding relationships indicating nutrient flow, e.g. from prey to predator (Newman, 2003).

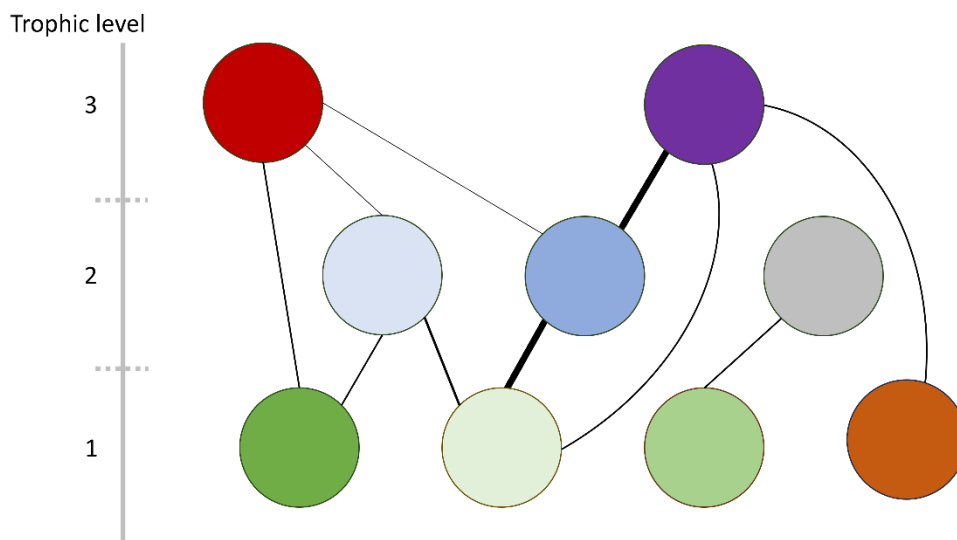


Figure 2.1. A network consisting of nodes (circles) and links connecting them, depicting a simplified food web where the different nodes symbolize species or groups of organisms characterized by their ecological function, and links symbolize consumption, i.e. flow of energy or nutrients. Primary producers are at the lowest trophic level 1, consumers at level 2, and predators at level 3. The thickness of the links between nodes indicates transfer strength, i.e. the amount of transferred energy or nutrients.

The links in a food web may be stronger or weaker depending on how much energy is transferred through them. It was early argued that structurally diverse or complex ecosystems tend to be more stable (Elton, 1958). This was empirically corroborated for, e.g. intertidal zones (Paine, 1966). However, this view was challenged by May (1972) who by using models of complex networks could show that many species and strong connections could in fact reduce stability. The long-standing “complexity-stability” debate (McCann, 2000) stimulated researchers to look beyond simple species counts and examine the specific architecture of ecological networks. It has indeed been demonstrated that complex ecological networks can remain highly stable and resilient when they are characterized by many weak and relatively few strong interactions (McCann et al., 1998; McCann, 2000). Studying food-web networks helps understanding how the structure influences ecosystem functioning, resilience to change, and the spread of effects in the system (Ings et al., 2009; Montoya et al., 2006).

2.2 Key food-web properties

Real-world food webs are not randomly structured. Food-web **topology** refers to the organization of relationships within the food web. It describes how nodes (i.e. species, functional groups, or trophic species) are linked through feeding interactions within the network (**Figure 2.1**). The number and arrangement of these links, for example between prey and predators, can influence the properties of a food web by affecting how disturbances propagate through the network. Species or groups at the same trophic level may influence one another indirectly through common prey or predators. **Table 2.1** provides an overview of food-web properties, their definition and overarching structural and functional traits which can be categorized as high or low. Key features for defining food-web topology include:

- **Trophic levels** represent the positions that organisms occupy within a food chain or food web and indicate the number of energy-transfer steps from primary producers. Energy typically flows from primary producers (e.g. phytoplankton) to primary consumers or herbivores (e.g. zooplankton), secondary consumers or carnivores (e.g. fish), and finally to top predators (e.g. predatory fish, seabirds, or marine mammals).
- **Connectance** describes the proportion of realised feeding links relative to all possible feeding links among species or guilds (i.e. functional groups of species) within a food web.
- **Link density** refers to the average number of feeding links per species in a food web.
- **Interaction strength** describes the magnitude of the effect that one species has on another by a feeding interaction. It influences the sensitivity of a food web to perturbations; systems dominated by strong interactions are often more responsive to changes than systems in which interactions are predominantly weak.

Table 2.1. Food-web properties.

Property	Definition	Category “High”	Category “Low”
Complexity	Structural intricacy of the web of feeding relationships	High species count, connectance, interactions	Simple chains or low interconnectivity
Robustness	Resistance to species loss	Withstands species removal well	Rapid collapse after key losses
Sensitivity	Response to perturbations by abiotic or biotic factors	Small changes in one part can rapidly affect the entire food web through trophic cascades	Changes are buffered; system adapts or absorbs shocks so that changes are limited or local
Resistance	Short-term ability to withstand perturbations	No immediate change	Apparent changes appearing directly
Resilience	Recovery from disturbance	Quick return to equilibrium	Permanent shift or collapse

Complexity refers to the structural intricacy of a food web, i.e. how rich it is in links and trophic levels, and to which degree the links are interwoven. The key metric on which complexity is defined is species richness, i.e. the number of species (nodes) occurring in the food web. In general, higher complexity is often assumed to buffer ecosystems, but very high complexity may lead to instability as shown by some theoretical models.

Furthermore, the effects of perturbations in highly complex food webs may be more difficult to track, making the impacts of environmental change and human-induced pressures harder to predict.

Robustness means the ability of a food web to maintain structure and function when species are removed or added. Robust food webs can lose many species without collapsing, while fragile food webs may collapse or reconfigure drastically following removal of few species. An indicator of robust food webs is that they have multiple species fulfilling similar roles (high redundancy).

Sensitivity describes the degree to which an ecosystem, habitat, or biological community responds to disturbances (e.g. species loss, invasive species) and environmental change (e.g. temperature, nutrient availability). Highly sensitive systems rapidly show detectable effects, often across a larger spatial area, whereas less sensitive systems may exhibit slower or more localized responses.

Resistance refers to the ability of a food web to withstand disturbance while maintaining its structure and functioning. A highly resistant food web experiences little change in species composition, interactions, or energy flows during or immediately following a perturbation, whereas a less resistant food web shows more pronounced alteration.

Resilience describes how quickly and completely a food web recovers after it has been altered by a disturbance. A highly resilient food web may initially undergo substantial change but is able to return to its pre-disturbance state within a relatively short period. In short, while resistance is about avoiding change, resilience means recovering from change once it has occurred. For example, a food web may have low resistance (markedly affected by a heatwave) but high resilience (rapidly returning to its original structure at normalized temperatures).

Beyond topological and other characteristics, food webs can also be described in terms of the traits and ecological functions of the species they contain. Attention is often given to **keystone species**, which occupy critical positions in ecological networks and can exert disproportionate effects on the structure, stability, and sensitivity of the food web relative to their biomass. Food-web organization is further influenced by species traits such as feeding strategies, including the prevalence of **generalist** versus **specialist** species, trophic level, body size, and life-history characteristics. In addition, the functional diversity and functional redundancy of species, i.e. the extent to which different species perform similar ecological roles, help determine how food webs respond to perturbations and maintain ecosystem functioning.

2.3 Spatial and temporal contexts

Research sub-question:

- *Can category-dependent conclusions be made regarding the usefulness of a food-web perspective to evaluate, e.g. effects of climate change or other stressors?*

The utility of a food web perspective depends on the specific properties of different categories of marine food webs (see below). Food webs can be categorized based on their structure and complexity, their sensitivity, resistance, resilience, and capacity to adapt to environmental change (see section 2.2). Different food web types can react differently to disturbances because energy flows through them in different ways, e.g. from phytoplankton to zooplankton to fish. As a result, changes affecting one species can have different consequences depending on the structure of the food web. For example, a simple food web may be strongly affected if one ecologically important key species declines (or increases), whereas a complex food web may be better able to absorb such changes because other species can fill similar roles. Examining different marine ecosystems through a food web perspective can provide non-intuitive insights into effects of climate change and other human pressures. Integrating food web approaches with, e.g. knowledge about habitats and traits of species is necessary to capture the full spectrum of impacts of environmental change and pressures on food webs.

When analysing food webs, it is also necessary to consider how they vary across space and time. Marine food webs are highly dynamic across space and time, which affects which species interact and how strong the interactions are. The **spatial structure** can be divided horizontally and vertically. **Horizontal** heterogeneity refers to distinct geographical gradients across space, such as more shallow to deeper coastal-to-open-ocean transitions, estuarine-to-shelf gradients, or localized environmental patches. **Vertical** structure refers to depth-based layering (e.g. pelagic vs. benthic habitats). Stratification and depth gradients heavily regulate light availability, primary production, and predator-prey encounters, dictating how energy transfers through the system. Highly mobile species move between different spatial patches, linking distinct local webs into a larger 'meta-food web'. The connectivity and mobility of species by migration patterns, dispersal of predators and prey, and their larvae, shape their encounter rates, which influences food web characteristics and dynamics. In this way, food webs can be seen as spatially explicit networks where nodes or links vary across space.

In a **temporal context**, time influences food web configuration and dynamics. In temperate regions, such as the North Sea, food webs change significantly across seasons. Long-term environmental changes can create phenological mismatches where prey population peaks no longer align with predator breeding seasons. Such dynamics can be observed in species turnover rates, recruitment pulses, species succession, regime shifts, and as lagged effects. Temporal dynamics are in many cases known to be affected by climatic oscillations (e.g. NAO, ENSO) that may alter trophic pathways. Marine organisms navigate this temporal variability through interaction plasticity, which is the behavioral flexibility to dynamically switch habitats and diets across seasons. The ecological roles of organisms may also change as they grow (ontogenetic niche shifts, i.e. where species change their traits and ecological function by switching prey or habitat during their development or growth).

In **pelagic food webs**, productivity and trophic interactions are strongly bottom-up regulated, which makes food web approaches particularly effective for detecting climate-driven shifts acting on, e.g. primary production, and stratification (Behrenfeld et al., 2006; Edwards and Richardson, 2004). This enables the assessment of changes in productivity, temporal mismatches between trophic levels, and shifts in predator-prey phenology.

Benthic food webs, by contrast, often display slower turnover, higher omnivory (i.e. having multiple food sources), and strong dependence on habitat structure or detrital inputs, meaning that food web models must be complemented by habitat- or trait-based analyses to capture responses to warming, acidification, sediment dynamics or physical disturbance (Danovaro et al., 2008; Harley et al., 2006).

Coastal and estuarine food webs, where climate drivers often interact with eutrophication, pollution, and habitat loss, exhibit strong feedbacks and have frequently observed alternative stable states (Cloern et al., 2016; Scheffer et al., 2001). Here, a food web perspective is indispensable for integrating effects of multiple stressors but needs to account for strong local drivers and that changes can appear at a certain threshold of disturbance.

In **top-predator-dominated systems**, top predators are often in focus, but food web models help to further clarify indirect effects that may cross trophic levels, e.g. climate-driven prey shifts or range changes. However, the outcomes of perturbations may remain uncertain where predator data are sparse (Estes et al., 2011; Sydeman et al., 2015).

In summary, marine food webs are best described as dynamic networks whose structure and functioning are shaped by trophic interactions, species traits, and spatial and temporal variability. Although the applicability of food-web approaches depends on ecosystem characteristics and the pressures considered, they offer a useful framework for understanding and assessing the ecological consequences of environmental change and human-induced stressors.

3 Review of the North Sea food web concept – implications for analyses

Research sub-question:

- *How can changes in ecosystem functioning be detected using food-web indicators?*
Clarification:
 - *Which indicators are expected to respond to changes in ecosystem functions such as primary production, trophic transfer, nutrient cycling, or benthic-pelagic coupling?*

3.1 Energetic pathways of the North Sea food web

The North Sea is a shallow shelf sea, a physical characteristic that strongly shapes the structure and organization of its food web. Because most of the system is relatively well mixed and sunlight often reaches the seabed in coastal and southern areas, primary production may occur simultaneously in both the water column via phytoplankton and on or near the seabed via microalgae and benthic algae, i.e. at the first trophic level.

At the second trophic level, energy is transferred from small-sized organisms, such as zooplankton, to higher levels, like benthic invertebrates in two distinct ways: (a) the **pelagic pathway** dominated by zooplankton grazing on phytoplankton and (b) the **benthic pathway** driven by benthic invertebrates feeding on organic matter and sediment-associated microalgae. Mid-level predators such as small pelagic and benthopelagic fish, e.g. sandeel, sprat, herring and juvenile cod, feed upon zooplankton and small invertebrate benthic species. Larger fish, on the other hand, can prey upon both benthic invertebrates and smaller fish. Seabirds, marine mammals, and also large fish - as well as fisheries - occupy the highest trophic levels, relying heavily on the mid-level fish communities that link the upper and lower levels of the food web (Duffill Telsnig et al., 2019; ICES, 2024a).

3.2 Benthic-pelagic coupling and anthropogenic pressures

A key feature of the North Sea food web is the strong coupling between benthic (seabed) and pelagic (water-column) habitats. Because ecosystem functions such as nutrient cycling, organic matter processing, and energy transfer depend on exchanges between these compartments, indicators reflecting benthic-pelagic coupling can provide important evidence of changes in ecosystem functioning. As the North Sea is a relatively shallow shelf sea, exchanges of energy, organic matter, and nutrients between the seabed and water column are rapid. Consequently, changes in sediment conditions, benthic communities, or nutrient cycling can influence pelagic productivity and fish populations, while shifts in pelagic production can strongly affect benthic food resources and community structure (Griffiths et al., 2017; Richardson and Cedhagen, 2001). Benthic-pelagic coupling is particularly strong in coastal regions of the North Sea, where close physical and trophic linkages between the water column and seabed make food webs especially sensitive to natural and anthropogenic disturbances (Cibic et al., 2022; Provoost et al., 2013). In addition, many benthic species have pelagic larval stages, creating an important biological link between water-column processes and benthic community dynamics (Van Der Meer et al., 2001). This life-cycle connection means that pelagic conditions influence larval dispersal, settlement, and recruitment, which subsequently affect benthic population dynamics and ecosystem functioning (Fernandes and Da Gama, 2024; Nishizaki and Ackerman, 2019).

Another important feature is spatial openness and mobility. Many fish, seabirds, and mammals move across large parts of the North Sea or beyond. This means that local changes (for example in prey availability or habitat quality) may be masked at larger scales, because mobile species can redistribute and compensate

elsewhere. As a result, food-web indicators based on averages across the North Sea can appear stable even when local trophic interactions change considerably (OSPAR, 2023; Thorpe et al., 2022). The highly used North Sea is subject to intense, overlapping human activities, such as commercial fishing, shipping, offshore energy, sand extraction (OSPAR, 2023). Human pressures can affect trophic levels in different ways, making it particularly important to consider food-web relationships rather than individual species alone (OSPAR, 2023).

3.3 From trophic indicators to integrated food-web assessment

Food webs in the North Sea have been described through an evolving set of quantitative approaches that reflect advances in ecosystem ecology. Early studies focused on trophic level indicators, particularly mean trophic level and the Marine Trophic Index (MTI), to assess long-term impacts of fishing on ecosystem structure. Based on stable isotopes, size spectra, and catch data, declines in trophic position of demersal fish communities consistent with “fishing down the food web” were concluded for the North Sea (Jennings et al., 2002; Pauly and Watson, 2005). Trophodynamic and ecosystem-modeling approaches further described changes in energy pathways, highlighting bottom-up control in pelagic compartments and fishing-driven top-down release of benthic systems (Heath, 2005). However, while useful for tracking long-term trends and supporting management assessments, trophic level indicators provide limited insight into underlying trophic interactions and ecosystem processes (Rombouts et al., 2013).

More recent scientific work has emphasized food-web structure and energy flow within food webs. Analyses of the North Sea food web showed that pelagic and benthic compartments can respond differently to environmental change and exploitation, highlighting the value of food-web approaches for interpreting ecosystem pressures and state changes (Heath, 2012). Later, food-web network approaches have been developed that quantify structural properties such as connectance, omnivory, and redundancy at spatially explicit scales. Applied to North Sea ecosystem data, such indicators can thereby provide additional insight into ecosystem organization and resilience, beyond that available from single-species or aggregated trophic metrics (Frelat et al., 2022). Together, this demonstrates the progression from traditional trophic indicators towards more integrated food-web assessment. Deriving from structural fisheries surveys and ecosystem models, food-web indicators can support ecosystem-based evaluations and implementations of the MSFD by North Sea countries to evaluate Descriptor 4.

Understanding how North Sea habitats are connected, and how energy flows between them, is essential for interpreting ecological change and managing the North Sea as an integrated shelf-sea ecosystem. To be able to identify changes in ecological function, e.g. energy flow, nutrient cycling, and species interactions within the food web, several indicators representing different (fish) guilds and multiple trophic levels would be needed which could demonstrate such change. To capture ecological change and food-web interactions adequately, a food-web model should be developed that represents all main ecosystem compartments and the trophic relationships among them. Rather than relying on multiple smaller sub-models, a comprehensive model that encompasses ecosystem components and their connections should likely be established, to ensure that large-scale, system-wide dynamics are not missed. By doing that, the food web can be analyzed with respect to:

- **Activity** - amount of energy flowing through the food web
- **Organization** - how the energy flows are structured
- **Resilience** - influenced by the degree of functional redundancy among species and by the efficiency of nutrient recycling within the food web (see chapter 2).

3.4 Spatial and temporal scales for assessment of North Sea food webs

Research sub-question:

- *How can information regarding food-web indicators be compiled on logical spatial scales for use in assessment?*

Clarification:

- *Which spatial scales apply for assessment? If chosen food-web indicators are applied, is there an overlap or non-overlap in the spatial scales?*

The spatial and temporal contexts need to be considered when assessing the status of food webs (**Table 3.1**). The **spatial** perspective determines where borders are set for what is being assessed. Spatial scales of the North Sea are both horizontal and vertical. On these scales, coastal areas and estuaries are inevitably connected to the open sea. Sub-food-webs of different areas together create meta-food-webs having different levels of exchange with each other. A complex assembly of connected habitats and food webs may enhance recovery after disturbance, e.g. through re-colonization, but can also transmit disturbance across habitats. On the **temporal** scale, seasonal dynamics act on the short term, i.e. on a yearly basis, but the temporal pattern of phenology, i.e. the timing of biological lifetime events, can be shifted by long-term environmental or ecological changes in the food web.

In MSFD Descriptor 4 ('Food webs') assessments of the North Sea, the **spatial context** is generally clear in principle but may be uneven in practice. Assessments are typically conducted at the spatial scale of the Greater North Sea sub-region, in line with MSFD regionalization and ICES ecosystem boundaries. These are often further disaggregated into national waters or eco-hydrographic sub-areas for reporting, such as variable-salinity, coastal, shelf, and oceanic areas (Frelat et al., 2022; Jennings et al., 2002). Studies underpinning Descriptor 4 have shown that food-web structure varies strongly along north-south gradients and between coastal, shelf, and offshore domains, indicating that regional and national-scale spatial resolution is both ecologically meaningful and necessary for robust assessment (Frelat et al., 2022). As a result, national strategies in, e.g. the Netherlands, UK, and Germany increasingly recognize the need for spatially explicit indicators rather than single, basin-wide food-web metrics.

By contrast, the **temporal context** of the MSFD food-web assessment in the North Sea is comparatively weaker and remains less clearly defined, particularly with respect to baselines and acceptable variability. Many Descriptor 4 indicators rely on multidecadal fisheries or survey time series, which implies assumptions that ecosystem change is relatively slow. Yet, historical reconstructions demonstrate that North Sea food webs were already substantially altered by fishing before the MSFD reference period (Heath, 2005; Jennings et al., 2002). Ecosystem-level analyses show that energy pathways and trophic control mechanisms can shift over decadal scales in response to both fishing and climate variability, which complicates the identification of stable conditions or thresholds for Good Environmental Status (Heath, 2005).

While spatial scale is broadly agreed (regional to national sub-regional), the ecologically relevant temporal scale for Descriptor 4 remains an open methodological issue. Although the MSFD requires Member States to assess status and progress towards GES within a six-year reporting cycle, determining the most appropriate ecological timescale against which to evaluate changes in food-web structure and functioning, whether interannual, decadal, or relative to historical reference conditions, remains a challenge in both international (ICES) advice and national MSFD implementation across the North Sea.

Spatial and temporal context strongly influence the structure and functioning of marine food webs. Spatial processes determine where species occur, how habitats are connected, and how energy moves across ecosystems, while temporal processes affect the timing, persistence, and flexibility of trophic interactions. The Dutch North Sea provides a range of examples that illustrate how these dimensions shape food-web organization, from estuarine - shelf connectivity and seasonal plankton blooms to long-term climate-driven regime shifts and adaptive feeding strategies (**Table 3.1**).

Regarding the spatial context, the Western Scheldt - southern North Sea shelf system illustrates **horizontal spatial heterogeneity** by estuarine, coastal, pelagic, and benthic habitats supporting distinct communities

and trophic pathways. Differences in salinity, turbidity, productivity, and habitat structure create interconnected sub-food webs that are linked through species movements and material exchange between these sub-habitats. As an example of **vertical structure**, seasonal thermoclines of the stratified Oyster Grounds separate productive surface waters from deeper bottom habitats. Organic matter produced in the surface layer sinks and fuels benthic consumers, demonstrating how vertical structure regulates energy transfer between pelagic and benthic food webs. The Wadden Sea nursery areas and the migratory corridors linking the Rhine-Meuse estuary, Wadden Sea, and North Sea highlight the importance of **connectivity and movement**. Juvenile fish use sheltered coastal habitats before moving offshore, while migratory species transfer energy and nutrients across ecosystem boundaries and facilitate recolonization after disturbance.

The spring phytoplankton bloom-zooplankton-herring/sandeel system exemplifies **seasonal dynamics** by strong seasonal coupling in the North Sea. Successful recruitment depends on the synchronization of fish spawning and larval development with prey availability peaking. Similarly, juvenile flatfish in the Wadden Sea depend on seasonally productive nursery habitats for growth and survival. Regarding **long-term dynamics**, the late-1980s North Sea regime shift, associated with climatic variability and changes in the North Atlantic Oscillation, illustrates how food webs can reorganize over decadal timescales. Furthermore, eutrophication followed by nutrient reduction in Dutch coastal waters has altered primary production, species composition, and trophic pathways, demonstrating long-term ecosystem reconfiguration.

Species such as plaice, whiting, and mullets (*Chelon* spp.) change their diets, habitats, and trophic roles throughout their life cycles or in response to seasonal food availability, illustrating **trophic plasticity**. For example, juvenile plaice rely on Wadden Sea nursery grounds before moving offshore, while mullets shift among detrital, algal, and animal food sources. While staying in coastal areas, juvenile whiting may switch between different prey and habitats depending on their size and the availability of benthos, i.e. shrimp, or fish. Such plasticity increases food-web resilience by allowing consumers to exploit alternative resources when environmental conditions change.

The above examples demonstrate that Dutch North Sea food webs are shaped not only by species composition but also by the spatial arrangement of habitats, the movement of organisms, and the temporal variability of ecological interactions across scales, but also by the spatially and temporally heterogeneous effects of pressures such as climate change, fisheries, offshore wind development, eutrophication, and habitat alteration. Food-web indicators do not necessarily share the same spatial scale, and assessment scales should be determined by the ecological processes represented by each indicator (rather than by administrative boundaries). Multiple spatial scales are often required. Consequently, there may be both overlap and non-overlap among the spatial scales used for individual indicators.

Some indicators can be applied consistently across multiple spatial scales, whereas others are only meaningful within specific habitats or ecosystem compartments. For example, indicators based on primary production, plankton biomass, or pelagic trophic structure may be most appropriate at the scale of a relatively homogeneous hydrographic region (e.g., the Southern Bight, Oyster Grounds, or Dogger Bank). In contrast, indicators related to nursery function, benthic-pelagic coupling, or estuarine connectivity may require assessment at smaller habitat-specific scales, such as the Wadden Sea, Western Scheldt estuary, or coastal zone. Highly mobile predators, migratory fish, and food-web connectivity indicators may require assessment across larger regional scales that encompass multiple habitats and management areas. A hierarchical spatial framework can be applied, in which indicators are first evaluated at ecologically relevant subregional scales and subsequently aggregated to larger assessment units. This approach preserves important spatial variability while allowing integrated ecosystem assessments.

Practical assessment scales could be:

Habitat scale – e.g. Wadden Sea, estuaries, offshore banks, Oyster Grounds.

Subregional North Sea scale – e.g. Southern Bight, central Dutch North Sea, northern stratified areas.

Regional North Sea scale – entire Dutch EEZ or the wider North Sea.

Eco-hydrographic sub-area scale – i.e. variable-salinity, coastal, shelf, oceanic

In chapter **5** we elaborate on two North Sea systems relevant for the Netherlands, where applying food-web indicators can be applied to clarify the interactions between sub-habitats on spatial and temporal scales.

Table 3.1. *Spatial and temporal contexts of North Sea systems with examples relevant for food webs in Dutch marine waters.*

Dimension	Category	Key characteristics	What it controls in the food web	Ecological implications	Marine systems	Dutch North Sea examples
Spatial context	Horizontal spatial heterogeneity	Habitat differences (pelagic vs. benthic, coastal vs. oceanic, estuarine vs. shelf); spatial patchiness	Which species interact and how strongly; formation of sub-webs	Creates meta-food-web dynamics , promotes habitat-specific trophic pathways, enhances regional resilience but increases spatial complexity	Estuaries vs. adjacent continental shelf	Western Scheldt estuary - southern North Sea shelf system (Netherlands)
	Vertical structure	Depth stratification, light gradients, thermoclines	Primary production depth, predator-prey encounter rates, vertical energy transfer	Controls coupling between surface production and deep consumers ; influences biological pumping and trophic efficiency	Epipelagic-mesopelagic coupling	Surface - benthic coupling in the stratified Oyster Grounds (Dutch North Sea)
	Connectivity and movement	Species mobility, migration, larval dispersal; mobile vs. resident consumers	Encounter rates, cross-habitat energy transfer, recolonization	Enhances recovery after disturbance but can also spread perturbations across habitats	Diadromous fish in nearshore areas and estuaries; migratory fish, e.g. sharks; larval dispersal; nursery areas	Wadden Sea nursery areas connected to North Sea; diadromous fish connectivity between the Rhine-Meuse estuary, Wadden Sea, and Dutch North Sea
Temporal context	Seasonal dynamics	Phenology shifts, seasonal blooms, recruitment pulses	Timing of predator-prey interactions, match-mismatch dynamics	Drives short-term variability in food-web structure, strongly affects reproductive success and survival	North Sea plankton-fish systems	Spring phytoplankton bloom - zooplankton - herring / sandeel recruitment dynamics (Dutch North Sea); juvenile flatfish recruitment in nursery areas (Dutch Wadden Sea)
	Long-term dynamics	Succession, regime shifts, hysteresis, climatic oscillations (NAO, ENSO)	Persistent reorganization of trophic pathways and dominant species	Can cause irreversible food- web reconfiguration and altered ecosystem states	ENSO-driven reorganization of the Humboldt Current; eutrophication regime shift	NAO-driven regime shift and food-web reorganization in the North Sea (late 1980s); eutrophication and subsequent nutrient-reduction-induced food-web reorganization (Dutch coastal North Sea)

Dimension	Category	Key characteristics	What it controls in the food web	Ecological implications	Marine systems	Dutch North Sea examples
	Interaction plasticity	Diet switching, seasonal feeding modes, ontogenetic niche shifts	Temporal rewiring of trophic links	Increases adaptive capacity and resilience , dampens trophic cascades	Ontogenetic diet shifts; seasonal omnivory in coastal/estuarine fish	Habitat and diet shifts of plaice / mullets / whiting (Wadden Sea nursery grounds and North Sea)

4 Food-web indicators to evaluate the ecological status as well as stressors

Research sub-question:

- *How can status/changes in the North Sea at the food-web level be evaluated by using food-web indicators, with respect to EU nature restoration (EU) and national nature improvement and conservation?*

4.1 Applying indicators to observe the status and changes of an ecosystem

The verb “*indicate*” means in modern language to *point to a fact*. This implies that indicating something does not actually prove a fact, and all the circumstances may also not be entirely known or understood. Here, an indicator (Latin *indicātor* “one who points out”) means that it informs us about the environmental condition of the ecosystem, or specific parts of it. Indicators are applied because knowledge says that they connect to certain mechanisms and can therefore signal change caused by impacts on the ecosystem. Indicators can provide coherent ways of measuring and describing status or change, independent of, e.g. species which may differ across habitats or regions. Species-based index approaches alone can fail to reflect interactions between trophic levels, while indicators capturing the functions of species in the food web help evaluate how the ecosystem works.

Within the MSFD, Good Environmental Status is assessed through eleven environmental descriptors. Eight of them are categorized as “**pressure descriptors**” as they relate to human induced pressures. The descriptor “Food webs” (D4) is one of the three “**state descriptors**” for characterizing marine biodiversity, the other two being “Biological diversity” (D1) and “Sea-floor integrity” (D6). The descriptor “Populations of all commercially exploited fish and shellfish” (D3) is both a pressure and a state descriptor as it relates to fishing activity (pressure) as well as, e.g. size distributions and biomass (state).

The overall goal for the descriptor “Food webs” is: “*All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.*” This implies that different ways of looking at food webs are necessary, including complex ways of measuring and describing the state of food webs, at least a conceptual model describing “what eats what” based on expert knowledge, or accompanied with more sophisticated food-web modelling.

4.2 Food-web modelling as a basis for food-web indicators

Food-web modelling is applied for different purposes. First, food-web models have been developed within academic ecosystem research. The goals within academia have been primarily to test ecological theory, to explore ecosystem dynamics and evaluate long-term changes in food web structure, and furthermore to investigate impacts of climate change or other pressures, or for purely advancing modelling techniques. The main purpose of food web modelling within an academic context are to improve explanations of the functions of food webs and to make predictions, but often without explicit management goals.

Second, within the International Council for the Exploration of the Sea (ICES), food-web models are used to adjust stock assessments for advice to fisheries management, to inform precautionary reference points, to evaluate management scenarios, and by that to support ecosystem-based fisheries management. The output of such food-web models then translates into policy-relevant indicators or connect to TACs (Total Allowable

Catches) in advice. One example of models developed within ICES are Multispecies Statistical Models, e.g. the North Sea SMS (ICES, 2024b).

Third, food-web models are used to evaluate and monitor the state of the environment. Within EU and Dutch policy frameworks, food-web indicators derived from these models are used to assess ecosystem status and changes over time by quantifying trophic structure, trophic interactions, and ecosystem functioning. Unlike single-species indicators, they provide information on how species and habitats are connected and how pressures such as fishing, climate change, and habitat alteration together affect the ecosystem. By analysing food-web indicators and tracking trends, managers can evaluate whether the North Sea is moving towards or away from the objectives of EU nature restoration, MSFD Good Environmental Status, and national nature conservation and improvement targets. Food-web modelling therefore supports the translation of broad biodiversity goals into measurable ecosystem-level outcomes.

4.2.1 Food-web modelling and ecosystem indicator tools

Several established approaches are available for the assessment of marine food webs and ecosystem functioning. Among the most widely applied is **Ecopath with Ecosim (EwE)**, a modelling framework that quantifies biomass and energy flows within ecosystems and can evaluate ecosystem responses to pressures such as fishing, environmental change, and management measures (Christensen and Walters, 2004; Heymans et al., 2016). EwE provides both a static mass-balance description of ecosystem structure (Ecopath) and dynamic simulations through time (Ecosim), making it particularly suitable for evaluating management scenarios and ecosystem trade-offs. EwE supports ecosystem-based management by integrating multiple species, trophic interactions, and human pressures within a single analytical framework.

The **ECOIND plug-in** for EwE provides a standardized method for calculating a broad range of ecological and food-web indicators, including biomass-, trophic-, size-, and trait-based metrics that are relevant for ecosystem assessments and MSFD reporting (Coll and Steenbeek, 2017; Keramidas et al., 2023).

Complementary to EwE, **Ecological Network Analysis (ENA)** provides metrics that characterize food-web structure, energy transfer, trophic complexity, recycling processes, and ecosystem resilience. ENA can be applied to both static food-web models and time-series data, enabling the assessment of ecosystem organization and change over time (Schückel 2022; Belgrano & Tomczak, 2025).

EwE, ENA, and ECOIND constitute toolboxes for assessing ecosystem status, food-web functioning, and responses to anthropogenic and environmental pressures. EwE is complementary with ENA, as EwE can generate the flow matrices, and ENA can analyze them. More information on these tools, indicators derived, and examples of applications in European and international marine ecosystems is provided in **Annex 2**.

4.3 Goals for improving status in marine environments

Sub-question:

- *What are the links between applying food-web indicators and the goals of the MFSD, the EU Biodiversity strategy for 2030, the EU Birds and Habitat directives, and Other Effective Area-Based Conservation Measures (OECMs)?*

The Marine Strategy Framework Directive (MSFD; 2008/56/EC) aims to achieve **Good Environmental Status (GES)** in European marine waters while safeguarding the ecological processes that support marine ecosystem services. To assess progress towards GES, Commission Decision 2017/848/EU specifies criteria and indicators for the MSFD descriptors (see section 4.1). For Descriptor 4 (Food Webs), four main criteria with indicators are defined (**Table 4.1**), covering multiple trophic guilds across the food web (European Commission, 2017; Boschetti et al., 2021).

Despite the MFSD requirements, assessment of food-web status remains challenging. Marine food webs span multiple spatial and temporal scales (see sections 3.2, 3.4), while assessment data are often derived from different monitoring programmes and ecosystem components. Integrating these datasets for evaluation of

ecosystem functioning is therefore a persistent challenge (Borja et al., 2013; Tam et al., 2017), particularly where mobile and resident species may respond differently to environmental pressures (OSPAR Commission, 2012).

The MSFD is embedded within a broader policy framework for biodiversity conservation, ecosystem restoration, sustainable resource use, climate adaptation, and regional marine governance (**Table 4.2**). These policies share a common requirement: understanding how human pressures affect ecosystem structure, functioning, and resilience. **Food-web indicators** provide a common ecological language to translate changes in species composition, trophic interactions, and energy flows into measurable indicators of ecosystem condition. **Food-web models** complement these indicators by integrating ecological processes and quantifying how pressures or management measures affect ecosystem functioning, particularly relevant for the EU Biodiversity Strategy for 2030 (European Commission 2021) and the associated Nature Restoration Regulation (2024/1991/EU). This ecosystem perspective is aligned with the Birds and Habitats Directives and the emerging framework for Other Effective Area-Based Conservation Measures (OECMs) (**Table 4.2**). Together, these initiatives aim to halt biodiversity loss, restore degraded ecosystems, and improve the conservation status of protected habitats and species.

Restoration targets focus not only on the presence of species and habitats, but also on the recovery of ecological functioning. Food-web indicators provide the metrics needed to measure ecosystem condition, while food-web models provide the analytical framework to interpret these indicators and evaluate management options, to support coherent marine management. Within the MSFD, food-web indicators also facilitate integration across descriptors by linking changes in ecosystem function observed under other descriptors. Food-web indicators support Descriptor 1 (Biodiversity) by evaluating the functional consequences of biodiversity change, Descriptor 2 (Non-indigenous species) by assessing the impact of non-indigenous species on ecosystem functioning, Descriptor 3 (Commercial Fish and Shellfish) through ecosystem-based fisheries assessments, and Descriptor 5 (Eutrophication) by tracing the effects of nutrient enrichment on plankton production, trophic transfer, hypoxia, and productivity. By connecting pressures, ecosystem processes and outcomes, food-web models and food-web indicators derived from such models can support ecosystem-based approach that underpins the MSFD.

Beyond MSFD, ecosystem-based fisheries management (EBFM) as promoted by ICES, FAO, and NOAA (NOAA, n.d.), similarly relies on an understanding of trophic interactions and ecosystem trade-offs (**Table 4.2**). Food-web models support EBFM by enabling multi-species assessments including indirect effects of harvesting, and identifying ecological thresholds, such as forage fish biomass required to sustain predators. Such applications strengthen the scientific basis for balancing exploitation with ecosystem resilience.

Table 4.1. Criteria with defined goals for the descriptor 'Food webs' (D4) in the EU Marine Strategy Framework Directive, and indicators with links to OSPAR assessments.

Criteria	Goal	Indicator	Description	Common / Candidate	Explanation	OSPAR Food webs Thematic Assessment
C1	The diversity (species composition and their relative abundance) of the trophic guild is not adversely affected due to anthropogenic pressures. (Primary.)	FW5 - PH1	Changes in phyto- and zooplankton	Common	Indices based on plankton abundance or biomass (per species / genera / taxa). Requires definitions of trophic guilds. Indicate climate change and eutrophication .	Changes in Phytoplankton and Zooplankton Communities
C2	The balance of total abundance between the trophic guilds is not adversely affected due to anthropogenic pressures. (Primary.)					
		FW7	Fish biomass and abundance of dietary functional groups (Planktivores, Sub-apex demersal predators, Sub-apex pelagic predators, Apex predators)	Candidate	Currently includes pelagic and demersal fish and elasmobranchs only, will in future include data on higher and lower trophic levels. Tracks the change in biomass and diversity of taxonomic groups that share similar prey items (e.g. planktivores, benthivores and piscivores), i.e. functional groups in the food web. Pressures detected are fisheries and climate change , which may interact to alter energy pathways through the food web.	Pilot Assessment of Feeding Guilds
C3	The size distribution of individuals across the trophic guild is not adversely affected due to anthropogenic pressures. (Secondary.)	FC2	Proportion of large fish (Sub-apex demersal predators)	Common	Biomasses of density of fish in maximum length class to that in minimum length class. Includes many species of demersal fish (including elasmobranchs), summarizes the change in the size structure of the fish community. Has threshold values for the North Sea. Affected by fisheries and, e.g. climate change (cold water species).	Proportion of Large Fish (Large Fish Index)
		FC3	Mean maximum length of fish	Candidate	Mean maximum length is calculated (ICES, 2012), where L_{maxj} is the maximum length obtained by species j , B_j is the biomass of all individuals of species j and B is the total biomass of all individuals, and species are weighted by their ability to grow large. Affected by fisheries and, e.g. climate change .	Pilot Assessment of Mean Maximum Length of Fish
		FW3	Size composition in fish communities	Common	The Typical Length indicator measures the size-structure of feeding assemblages of demersal fish, and detects effects of fisheries , also within spatial sub-divisions.	Size Composition in Fish Communities

Criteria	Goal	Indicator	Description	Common / Candidate	Explanation	OSPAR Food webs Thematic Assessment
C4	The productivity of the trophic guild (i.e. phytoplankton) is not adversely affected due to anthropogenic pressures. (Secondary - to be used in support of criterion D4C2, where necessary.)	FW2	Productivity of phytoplankton	Candidate	Detects climate change and eutrophication (including induced hydrodynamical changes especially in coastal and variable salinity areas). (other examples of productivity indices: Production per unit biomass (ratio Production:Biomass), Primary production required to sustain a fishery.	Pilot Assessment of Primary Productivity
(C2)	The changes in average trophic level of marine consumers is not adversely affected due to anthropogenic pressures.	FW4	Changes in average trophic level of marine consumers	Common	The indicator is based on biomass data and trophic level (TL) of the species, which may be complex to define (separation of stages within species, and information on diet is required). The average trophic level mainly reflects effects of fishing pressure on the structure of food webs; climate change , eutrophication and invasive species can also be of relevance.	Changes in Average Trophic Level of Marine Consumers
(C1-C4)	Ecological Network Analysis (ENA) is a system-ecology oriented approach providing multiple indices for analysing trophic interactions (e.g. flows in energy or carbon) among all compartments of a food web.	FW9	Ecological Network Analysis Indices	Candidate	A multitrophic level indicator including pelagic elements (phytoplankton, zooplankton), benthic elements, fish, seabirds and mammals. ENA and its related indices (FW9) enable assessment of the structure and functioning of food webs based on the analysis of all interactions among food-web compartments . The responses to pressures may be complex to interpret, including possible feedback loops and counteractive effects within the food web. Support from other here listed criteria is required.	Pilot Assessment of Ecological Network Analysis Indices

Table 4.2. International policy contexts, objectives and relevance of food-web analysis, linked to MSFD.

Policy context	Main objective	Relevance of food-web analysis	Content
EBFM (ICES, FAO, NOAA)	Sustainable ecosystem exploitation	Multi-species harvest advice, trade-off analysis	Supports ecosystem-based fisheries management (EBFM) by quantifying species interactions, trophic dependencies, and the ecological consequences of fishing. Helps balance exploitation with ecosystem health; contributes to achieving MSFD Good Environmental Status (GES).
CBD (Global biodiversity framework)	Ecosystem integrity and restoration	Functional indicators/indices, resilience metrics	Assesses ecosystem structure, functioning, and resilience, supporting biodiversity conservation and restoration targets. Food-web indicators help evaluate ecosystem integrity and complement MSFD biodiversity and food-web descriptors.
IPCC climate assessments	Climate risk evaluation	Future productivity and stability projections	Evaluates how climate-driven changes in temperature, productivity, and species distributions affect ecosystem functioning. Supports projections of ecosystem resilience and risks, informing climate adaptation measures relevant to MSFD implementation.
Regional seas conventions (e.g. OSPAR)	Regional ecosystem status	Cumulative impacts, transboundary coordination	Integrates multiple pressures and ecosystem responses across national boundaries, enabling coherent regional assessments. Food-web models support ecosystem status reporting, indicator development under OSPAR, and coordinated measures under MSFD.

4.4 Operational food-web indicators for marine ecosystems

Sub-questions (reformulated):

- Which food-web properties are needed to assess the North Sea, which ecosystem components should be represented, which indicators already provide this information, and where are additional indicators needed?
- How well do current indicators capture food-web properties?
- Which additional indicators are required to provide a more complete basis for ecosystem management and restoration?

4.4.1 Evaluation of existing food-web indicators

To evaluate the suitability of food-web indicators for North Sea assessments, a list of indicators reported at the ICES workshop WKFOODWEB (ICES, 2025a) were reviewed. The 28 indicators were assessed through expert judgement regarding their feasibility, applicability, and relevance to the various pressures recognized by OSPAR (OSPAR, 2023). Indicators were further grouped into categories based on what component of the food web they target, i.e. also capturing increasing ecological complexity (**Table 4.3**; table with details in **Annex 3**). Although sometimes named differently, the indicators overlap, match or are equivalent to those currently applied in OSPAR, i.e. MSFD D4 common and candidate indicators (**Table 4.1**).

Table 4.3. Categories of indicators based on food-web component or feature, that are relevant for a management-oriented assessment, based on the food-web component or feature they target, overlap with existing MFS D food-web indicators (details in **Table 4.1**), as well as the operational status of those within OSPAR, and identified strengths and limitations. (For details on each indicator, scoring of feasibility and relevance for pressure factors, see Annex 3.)

Food-web component / feature	Indicator(s) reported at WKFODWEB (details in Annex 3)	MSFD D4 criterion / food-web indicator	Operational status	Strengths	Limitations
Lower trophic-level dynamics	Zooplankton mean size, zooplankton abundance indicators	C1 – Diversity within trophic guilds (FW5 – PH1); C2 Abundance balance among trophic guilds (FW7)	Operational (OSPAR)	Represents plankton dynamics and bottom-up processes; responsive to eutrophication and climate change	High natural variability; linkage to higher trophic levels can be unclear
Community structure and trophic balance	High trophic level indicator (HTI), apex predator indicator (API), mean trophic level (MTL), marine trophic index (MTI), fishing-in-balance (FiB)	C2 – Abundance balance among trophic guilds (FW7); Average trophic level (FW4)	Operational (OSPAR)	Established methodology; long time series; sensitive to fishing impacts	Simplifies food-web complexity; information on trophic interactions may be limited
Guild composition and biomass balance	Biomass ratios, key species indicators, ECOIND metrics	C2 – Abundance balance of trophic guilds (FW7)	Operational (OSPAR)	Directly linked to ecosystem structure; straightforward interpretation	Dependent on guild definitions; limited mechanistic understanding
Size structure and trophic transfer	Length-based indicators, size composition, Mean Life Span Index, biomass spectra / ratios	C3 – Size distribution of species (FC2, FC3, FW3); partly C2 (FW7)	Operational (OSPAR)	Well-established; sensitive to fishing pressure; extensive monitoring data	Indirect measure of food-web functioning
Productivity and energy transfer	Primary productivity, Ocean Productivity available to Fish (OPFish), marine bird productivity, ICES F_{eco}	C4 – Productivity of phytoplankton (FW2)	Pilot to operational	Directly addresses ecosystem productivity and energy transfer	Attribution of changes to pressures can be difficult; some indicators are model-dependent
Diet-based trophic interactions	Stomach Content Analysis (SCA), Stable Isotope Analysis (SIA)	Mainly C2 (FW4/FW7) and C4 (FW2)	Partially operational	Direct evidence of trophic links and energy pathways	Resource intensive; temporal and spatial coverage may be limited
Integrated trophic assessment	Integrated Trophic Analysis (ITA), other integrated trophic indicators	Combines C1, C2, C3, C4 (FW2, FW3, FW5, FW7, FW4)	Pilot / developing	Integrates multiple ecosystem components; detects broad ecosystem change	Methodologically complex; data hungry
Network structure and resilience	Connectance, omnivory, redundancy, centrality, and other topological indices	Primarily FW9 System Ecology Indices (cross-cutting across C1–C4)	Research / non-operational	Addresses ecosystem organization and resilience explicitly	Requires comprehensive food-web models; no established thresholds
System functioning and ecosystem resilience	Ecological Network Analysis (ENA), cumulative biomass theory (stability / resilience), carbon-flow indicators	FW9 System Ecology Indices (cross-cutting across C1–C4)	Research / pilot	Quantifies activity, organization, resilience, recycling and energy flow	Highly model-dependent; not yet routinely applied in MSFD assessments

The different categories of indicators (**Table 4.3**) are commented below:

Lower trophic-level dynamics indicators target plankton and represents bottom-up processes. One example is the indicator 'Zooplankton mean size' applied as a core indicator within HELCOM (Gorokhova et al., 2013). Overlapping with this category is the indicator *FW5 - PH1* 'Changes in phyto- and zooplankton' which assesses changes in plankton community composition and how this affects energy transfer through the food web.

By evaluating the plankton community structure, where good status is indicated by high abundance of large-bodied zooplankton, effects of climate change, eutrophication, and indirectly the abundance of zooplanktivorous fish in the food web can be assessed. However, because of high natural variability in plankton abundance, especially on the shorter term, the linkage to higher trophic levels can be unclear.

Community structure and trophic balance indicators describe the relative distribution of biomass, abundance, or energy among trophic levels and functional groups in the food web. They are used to assess whether ecosystems maintain a balanced trophic structure or show signs of disturbance, such as a disproportionate loss of higher trophic levels due to fishing pressure. Examples include the OSPAR *FW4* 'Average trophic level' and *FW7* 'Abundance balance among trophic guilds', as well as other widely used fisheries indicators, e.g. Mean Trophic Level (MTL), Marine Trophic Index (MTI), High Trophic Index (HTI), Apex Predator Index (API), and Fishing-in-Balance (FiB) index (**Annex 3**).

These indicators benefit from long-term monitoring datasets, making them valuable for tracking broad ecosystem changes. Also, they are relatively simple to calculate. However, they simplify complex food-web interactions and may not fully capture trophic linkages, species-specific dependencies, or indirect ecosystem effects.

Guild composition and biomass balance indicators assess how biomass or abundance is distributed among trophic guilds (e.g. primary consumers, planktivorous fish, piscivorous fish, benthivores, apex predators) and whether this distribution remains consistent with an ecologically balanced food web. Examples include the OSPAR *FW7* 'Abundance balance among trophic guilds', and other biomass-ratio indicators, key-species indicators, and ecosystem assessment metrics included in the ECOIND software plugin (**Annex 2 and 3**). These indicators are based on the premise that human pressures, particularly fishing, eutrophication, and habitat alteration, can shift biomass from some guilds to others, leading to altered ecosystem functioning.

The principal strength of these indicators is their direct ecological relevance: by quantifying changes in the structure of the ecosystem an intuitive indication of trophic imbalances is provided, e.g. depletion of top predators or the dominance of lower trophic levels. The indicators are mostly derived from monitoring and ecosystem survey data and are relatively straightforward to calculate and communicate to stakeholders. However, most of these indicators are based primarily on fish communities and therefore capture only part of the food web. While they can provide valuable information on trophic structure and fishing-related impacts, they do not adequately represent trophic interactions involving plankton, benthic invertebrates, seabirds, or marine mammals, limiting their suitability as stand-alone indicators for assessing Good Environmental Status under MSFD Descriptor 4.

The interpretation of these indices depends on how the trophic guilds are defined and aggregated. Different species may perform multiple ecological roles, and similar biomass distributions can arise from different ecological processes. Consequently, these indicators provide limited insight into the mechanisms underlying observed changes and generally cannot resolve the strength or complexity of trophic interactions within the food web. However, when used alongside indicators of trophic dynamics and predation pressure, or outputs from ecosystem modelling, these indicators are most informative.

Size structure and trophic transfer indicators describe the distribution of individuals or biomass across body-size classes within an ecosystem. They are based on the fundamental ecological relationship between body size, trophic position, and energy transfer. Because larger organisms generally occupy higher trophic levels and have longer life spans, changes in size structure can provide insight into alterations in food-web

structure and exploitation pressure. Examples include the OSPAR indicators *FC2* 'Large fish index (LFI)', *FC3* 'Mean maximum length of fish', and *FW3* 'Size composition in fish communities'. Other examples include various size- and biomass spectra, length-based indicators, size composition indices, and the Mean Life Span Index (MLSI) (**Annex 3**).

These indicators are supported by extensive monitoring datasets and a strong theoretical foundation and consequently among the most widely applied ecosystem metrics. They are particularly sensitive to fishing pressure, which often selectively removes larger and older individuals, resulting in truncated size distributions and reduced representation of higher trophic levels. Shifts in size structure can thereby provide an early warning of ecosystem change and are relatively easy to assess from routine survey data.

However, size-based indicators measure food-web functioning only indirectly. While changes in size distributions are often associated with altered trophic dynamics, they do not directly quantify predator-prey interactions, energy flows, or trophic linkages. Similar size structures may arise from different ecological mechanisms, and observed changes can also be driven by environmental factors such as temperature, productivity, or species turnover. Therefore, size-based indicators are useful when interpreted alongside complementary indicators of trophic interactions, guild composition, or ecosystem functioning (and vice versa).

Productivity and energy transfer indicators assess the capacity of ecosystems to generate biomass and transfer energy through the food web, from primary producers to higher trophic levels. They are founded on the principle that healthy food webs efficiently convert primary production into secondary production and ultimately support fish, seabirds, and other predators. This category is represented by the OSPAR indicator *FW2* 'Productivity of phytoplankton'. Other examples of indicators are various measures of primary productivity, the Operational Fish Productivity Index (OPFish), marine bird productivity indicators, and ecosystem productivity metrics such as ICES F_{eco} (**Annex 3**).

Indicators in this category have a strong ecological basis because they directly address a central function of food webs: the production and transfer of energy among trophic levels. Changes in productivity can reveal alterations in ecosystem functioning that may not be detectable through abundance or composition metrics alone. As a result, productivity indicators can provide valuable insight in the consequences of pressures such as fishing, eutrophication, climate change, or habitat degradation for ecosystem performance and the capacity to support higher trophic levels.

A key challenge in interpretation is that productivity is influenced by multiple interacting drivers, making it difficult to attribute observed changes to a specific pressure. For example, shifts in fish productivity may result from exploitation, changing prey availability, environmental conditions, or a combination of these factors. In addition, some productivity indicators rely on ecosystem models or estimates of energy flows, introducing uncertainties related to model structure, parameterization, and data availability. Consequently, productivity indicators are often most valuable when interpreted in combination with indicators of community structure, trophic interactions, and environmental conditions (and vice versa).

Diet-based trophic interactions quantify feeding relationships within food webs by examining what organisms consume and how energy moves between trophic levels. Unlike aggregate indicators based on biomass, abundance, or size structure, these indicators provide direct predator-prey linkages and trophic pathways. They therefore offer valuable insights into food-web structure, resource use, trophic niches, and changes in ecosystem functioning. Within MSFD and OSPAR assessments, diet information can contribute to indicators related to *FW4* 'Changes in average trophic level', *FW7* 'Abundance balance among (fish) trophic guilds', and *FW2* 'Productivity of phytoplankton'.

Common examples of applied methods to study trophic interactions include Stomach Content Analysis (SCA) and Stable Isotope Analysis (SIA). SCA identifies recently consumed prey and can reveal species-specific feeding preferences, feeding overlap, and short-term dietary shifts. In contrast, SIA integrates dietary information over longer time scales by measuring the isotopic composition of consumer tissues, allowing estimation of trophic position and the relative importance of different energy sources. Together, these methods provide complementary information on trophic interactions and energy transfer pathways.

The main strength of diet-based indicators is that they provide some of the most direct evidence available for food-web linkages and ecosystem functioning. They can detect changes in predator–prey relationships, identify key forage species, and improve understanding of the mechanisms underlying observed shifts in community structure or productivity. However, these approaches are often resource-intensive and require substantial sampling, laboratory analyses, and taxonomic expertise. As a result, datasets are frequently restricted in spatial and temporal coverage, which can limit their application in large-scale ecosystem assessments. To overcome this, the available data on species diet is often compiled and generalized for larger spatial areas (and later periods), which involves simplifications. Given these limitations, diet-based indicators are often used to complement broader community- and productivity-based indicators rather than as stand-alone measures of food-web status.

Integrated trophic assessment indicators combine information from multiple components of the food web to provide a holistic evaluation of ecosystem structure and functioning. Rather than focusing on single aspects, e.g. biomass, size structure, or productivity, these indicators span over all D4 criteria, i.e. species composition and diversity (C1), trophic guild balance (C2), size structure (C3), and productivity (C4). No single indicator captures food-web functioning comprehensively. For example, *FW2* 'Productivity of phytoplankton' primarily reflects the lower trophic guilds, whereas *FW3* 'Size composition', *FW4* 'Average trophic level', *FW5* 'Changes in phyto- and zooplankton', and *FW7* 'Abundance balance of trophic guilds', as well as frameworks such as Integrated Trophic Analysis (ITA) and integrated trophic indicator suites provide information on trophic structure, community composition and the balance among trophic guilds. (**Annex 3**).

No single indicator captures food-web functioning comprehensively. For example, *FW2* primarily reflects productivity dynamics, whereas *FW3*, *FW4*, *FW5* and *FW7* provide information on trophic structure, community composition and the balance among trophic guilds.

The primary strength of integrated trophic assessment is that it can capture the inherently multidimensional nature of food webs. By combining information from several trophic levels and ecological processes, they can identify ecosystem-wide changes that may not be apparent from individual indicators alone. This approach is particularly valuable for ecosystem-based management as it provides a more comprehensive picture of food-web status, resilience, and functioning. When accounting for interactions among ecosystem components, effects of pressures that may be non-intuitive to interpret, can be evaluated.

However, integrated trophic assessments are methodologically demanding. They typically require extensive datasets spanning multiple trophic levels, consistent monitoring programs, and decisions about indicator selection, weighting, aggregation of feeding guilds, and interpretation. As a result, uncertainty can arise from both data limitations and methodological choices. Because integrated indices combine multiple ecological signals, they may also provide less direct insight into single specific mechanisms driving observed changes. Consequently, they are often used as high-level assessment tools alongside other indicators that help identify the underlying causes of ecosystem change.

Network structure and resilience indicators evaluate food webs as networks of interacting species, focusing on the organization, complexity, and robustness of the ecosystem. Within the OSPAR framework, *FW9* 'Ecological Network Analysis Indices' represent this category of indicators. In the QSR 2023 assessments (OSPAR, 2023), *FW9* is presented to use for evaluating the structure and organization of marine food webs to assess ecosystem-wide structure and functioning, using ecosystem network properties rather than examining individual food-web elements or processes. By integrating information across multiple food-web criteria (C1-C4), these indicators characterize the architecture of the entire food web and its capacity to withstand and recover from disturbances.

Common examples of this category of indicators include metrics such as connectance (the proportion of possible trophic links that occur), omnivory (the extent to which species feed across trophic levels), redundancy (the presence of multiple species performing similar ecological functions), centrality (the importance of species within the network), and other topological indices that describe food-web complexity and organization (**Annex 3**). These metrics also provide insight into ecosystem resilience, as more diverse

and interconnected networks are generally considered better able to absorb perturbations without losing key ecological functions.

The principal strength of network-based indicators is that by explicitly addressing ecosystem organization, trophic interactions, and resilience, they can provide a more mechanistic understanding of food-web functioning than indicators based on abundances, biomasses, size structures, or productivity. Hereby, vulnerabilities in ecosystem structure can be identified by detecting the loss of key species or trophic pathways and assessing potential cascading effects throughout the food web.

However, their application is often constrained by substantial data requirements. Also, reliable estimation of network properties requires comprehensive food-web models, detailed dietary information, and quantitative descriptions of trophic interactions and energy flows across multiple trophic levels. Furthermore, unlike many population- or community-based indicators, widely accepted ecological thresholds for interpreting network metrics in terms of Good Environmental Status are currently lacking. As a result, these indicators remain largely in the pilot and development stage, although they are increasingly recognized as promising tools for ecosystem-based assessment and management.

System functioning and ecosystem resilience indicators have a focus on the flow of biomass and energy through food webs, and assess the overall performance, organization, and stability of marine food webs by quantifying the movement of energy and matter through ecosystems. Hereby they represent yet a step for analysing food webs, following the category 'Network structure and resilience' (see above). As for the previous category (network structure and resilience indicators), this category is represented only by FW9 'Ecological Network Analysis (ENA)' indices, which apply system ecology principles to evaluate how species and trophic groups interact as an integrated network rather than as isolated components. This approach is cross-cutting as it integrates information related to community composition (C1), trophic structure (C2), size structure (C3), and productivity (C4) to provide an ecosystem-wide perspective. Examples include Ecological Network Analysis (ENA) metrics, cumulative biomass theory, carbon-flow indicators, and related measures of ecosystem organization (**Annex 3**).

These indicators quantify properties such as energy flow and flux, recycling efficiency, trophic transfer efficiency, system activity, redundancy, robustness, and resilience. These properties provide insight into the capacity of ecosystems to maintain their structure and functioning under environmental change or anthropogenic pressures. Ecosystems with efficient energy transfer pathways, high levels of recycling, and multiple alternative trophic routes are generally considered more resilient to disturbance.

The principal strength of these indicators is their ability to explicitly address ecosystem functioning rather than solely ecosystem structure. By representing food webs as interacting systems of energy and material flows, they can reveal changes in ecosystem organization, resilience, and functioning that may not be detectable using traditional abundance- or biomass-based indicators. They are therefore among the most holistic approaches currently available for food-web assessment.

However, these methods are highly dependent on ecosystem models and detailed quantitative descriptions of trophic interactions and energy flows. Developing such models requires extensive data on diets, biomass, productivity, and species interactions across multiple trophic levels. Furthermore, the interpretation of many system ecology metrics remains challenging, and ecological thresholds corresponding to Good Environmental Status (GES) remain to be established. Consequently, although FW9 and related system ecology approaches show considerable promise for ecosystem-based management, they are currently applied mainly in pilot assessments and research contexts rather than as routine MSFD assessments.

4.4.2 OSPAR food-web indicators applied for the North Sea

Both FW5/PH1 referring to plankton lifeforms capturing climate change, nutrient availability, and FW2 referring to **primary productivity**, have been assessed in the Greater North Sea (OSPAR, 2023). However, while FW5/PH1 is an operational indicator that contributed directly to food-web assessment, primary productivity is mainly associated with the indicator FW2 'Productivity of phytoplankton' which is under development and has not yet reached the same level of operational implementation.

In order of increasing level of complexity, other indicators which have been applied for the North Sea are *FW3* capturing demersal **fish size composition**, and *FC2*, *FC3* focusing on demersal **trophic guilds**, n.b. only fish, also relevant to MSFD Descriptor 3 ('Commercial fish and shellfish'). The indicator *FW7* also incorporates **multiple feeding guilds** of fish spanning several trophic levels. *FW5/PH1* is intended for capturing (bottom-up) **changes in phytoplankton and zooplankton communities**, while *FW4* captures changes in the **average trophic level of marine consumers**. *FW4* was not applied in the North Sea region during the OSPAR QSR 2023 assessment cycle but was operationally assessed in the Bay of Biscay and Iberian Coast (OSPAR region IV). The lack of implementation of this indicator in the North Sea so far can be attributed to methodological challenges and limited data availability, rather than a lack of ecological relevance or suitability.

For OSPAR Region II (Greater North Sea), the food-web assessment has until now primarily relied on the common metrics *FW3*, *FC2*, and *FW5*, and the candidate metrics *FC3*, and *FW7* (**Table 4.1**). However, the applied indicators mentioned above still do not represent a full food web across multiple trophic levels, including ecosystem interactions. Only the candidate indicator *FW9* explicitly represents the food web as a multitrophic network with whole-food-web-processes (**Table 4.3**). This indicator is to be applied within OSPAR by some of the North Sea countries in a pilot phase during 2027-2028, based on empirical data and modelled food webs in different, mainly coastal areas.

4.4.3 Recommendations for additional indicators for assessment of North Sea food-webs

OSPAR food-web indicators applied in previous assessments capture relatively well fish community structure and size-based responses, for evaluating effects of changes in nutrient input, climate change and exploitation pressure by fisheries (OSPAR, 2023). However, effects of other anthropogenic pressures on the food web, e.g. invasive species, toxicants, as well as indirect effects within the food web (**Annex 3**), are less - or not yet - covered, and have therefore not yet been possible to evaluate fully. Other environmental changes which may affect food webs are, e.g. offshore wind development, shipping, habitat alteration including sand extraction and sediment disposal. Although all environmental changes and pressures may not even have been considered yet, it is evident that a better understanding of food-web functions is crucial to foresee ecosystem effects of single pressures, and more so of pressures in combination (Cabral et al., 2019; Piet et al., 2023, 2021; Torres et al., 2017). Existing indicators are largely based on community composition and size structure and therefore provide limited information on trophic interactions, energy transfer pathways, and spatial dependencies within the food web.

A key feature of the North Sea food web is the strong coupling between the seabed and water column habitats, and the rapid exchanges of energy, organic matter, and nutrients (chapter 3). This **benthic-pelagic coupling** is particularly strong in **shallow and coastal regions**, making these regions are particularly **sensitive to natural variation and anthropogenic disturbances**.

Another important feature is the **spatial openness** of the North Sea and **mobility of key species**. Because these processes depend on trophic interactions and energy flows between habitats and regions, they cannot be adequately assessed using indicators that focus primarily on community composition or size structure. Apart from fulfilling the MFSD requirements to evaluate the progress towards GES for each of the D4 criteria 1-4, food-web indicators should cover these aspects of connectivity across spatial scales within the North Sea food web and make it possible to interpret how key species in the food-web hereby contribute (**Table 4.1**, **Table 4.3**).

Regarding these specific characteristics of the North Sea, it is highly desirable to be able to evaluate effects of pressures and development towards GES with respect to predator-prey interactions (energy flow) including the benthic-pelagic coupling, and the trophic relationships including mobile fish, seabirds, and marine mammals. To be able to evaluate the food-web status, stability and resilience, it is essential to consider this spatial connectivity and how key species function in a spatial context, as well as how the seasonal dynamics might affect the food web. These circumstances motivate a holistic perspective on the North Sea ecosystem, which calls for more complex food-web indicators. Such indicators include capturing

diet information for integrated trophic assessments. Spatio-temporal datasets of empirically derived North Sea food webs can be used to calculate network-based indicators, such as Ecological Network Analysis metrics describing trophic complexity, energy flow, pathway redundancy and ecosystem resilience (Shurety et al., 2026).

FW4 'Average trophic level' provides information on the distribution of biomass across trophic levels and can therefore help detect changes in food-web structure that may result from altered predator–prey relationships, shifts in energy pathways, or cumulative pressure effects. As a start, in coming MFSD assessments of C2 for the North Sea, selected *FW4* indicators (**Annex 3**) could be applied for (defined parts of) the North Sea to complement the previously reported *FW7* 'Abundance balance among trophic guilds'. *FW4* can be implemented based on available biomass survey data from fish and invertebrates, and agreed trophic-level estimates for the species involved (OSPAR Commission, n.d.). To apply *FW4*, species-specific trophic-level estimates are needed, agreements on how those are derived as well as a validated assessment methodology (i.e. a higher methodological burden compared to *FW3* or *FC2*). Also, obtaining reliable trophic-level values often depends on previous food-web work (see section **4.2**).

Whereas *FW4* characterizes the vertical trophic structure of the food web, *FW9* indicators derived from Ecological Network Analysis (ENA) can quantify connectance, energy routing, dependency among compartments, and overall system functioning, thereby addressing aspects of food-web resilience and stability that are not captured by simpler indicators. To capture the connectance of different parts of the food web, modelling the food web and applying indicators for network structure and system function are needed. However, the substantial data and modelling requirements mean that these indicators are currently better suited to supplementary or exploratory assessments than to routine operational assessment. Their wider operational use will depend on whether the required data, monitoring, and modelling capabilities can be delivered realistically, consistently, and cost-effectively over the long term.

5 Elaboration of selected case studies where proposed food-web indicators can be applied

Research sub-question:

- *Based on collected information, how can examples of food webs in the (Dutch) North Sea be categorized regarding their characteristics?*

5.1 Case study – The Dutch Voordelta: Benthic community linked to pelagic habitat and birds

To demonstrate the empirical application and added value of food web indicators through concrete North Sea examples, the Dutch Voordelta system exemplifies a highly connected, cross-shore coastal-marine continuum characterised by strong benthic-pelagic coupling and significant spatial separation between foraging and breeding habitats. It can be categorised across three principal ecological axes:

- (a) **Spatial habitat gradient:** A continuous transition from offshore sandy seabeds and ebb-tidal deltas (Natura 2000 Habitat H1110: Subtidal Sandbanks) to intertidal mudflats (H1140), extending landward to salt marshes (H1330, H1320) and coastal dunes;
- (b) **Trophic pathway interdependence:** Driven primarily by bottom-up energy transfers where lower trophic levels and non-protected species fuel apex predators and Natura 2000 target species; and
- (c) **Functional connectivity:** A system relying heavily on bridge species that couple distinct geographic areas and energy pathways, requiring assessment metrics that look beyond isolated geographic boundaries.

The Voordelta food web is characterised by interacting pathways, categorised by their distinct energy drivers and structural components:

1. Benthic pathway (dominant)

Habitat context: Subtidal sandbanks (H1110) and intertidal flats (H1140)

Dynamics: Primary production → benthic fauna → fish → predators

Management Relevance: Changes in lower trophic levels (e.g. benthos decline) may not be captured by N2000 targets but can strongly affect birds and seals.

2. Pelagic-benthic coupling

Dynamics: Direct biomass and nutrient exchange between the water column (phytoplankton, zooplankton) and seabed (benthos).

Key biological driver: Biogenic oyster reefs (consisting of flat oysters *Ostrea edulis* and Pacific oysters *Magallana gigas*) embedded within the H1110 habitat. Oysters filter pelagic material, transforming it into localised benthic biomass and biodeposits. This channels nutrients directly into higher trophic levels (top predators, such as fish).

Management Relevance: This coupling is central to D4, especially in shallow coastal systems like the Voordelta.

Examples of key food-web elements are oyster reefs consisting of flat oyster (*Ostrea edulis*) and Pacific oyster (*Magallana gigas*), forming reef structures embedded mostly in the H1110 habitat (subtidal sandbanks) in this area. In the Dutch Natura 2000 system, oyster banks are not designated as a separate habitat type. This creates a discrepancy between habitat classification and food-web functioning, highlighting the added value of a food-web-based (D4) assessment for the Voordelta. Oysters filter material from the pelagic zone, convert it into biomass and deposits, and thereby fuel benthic food webs. Benthic organisms are then consumed by fish, birds, and other predators, creating a strong benthic-pelagic coupling. This

bottom-up energy flow from pelagic primary production → oysters → benthic food web → fish → top predators, illustrates how oysters channel pelagic resources, via the benthic food web, into higher trophic levels.

The Natura 2000 designation of the Voordelta primarily targets non-breeding bird populations, as the area functions mainly as an area for foraging, resting and a wintering habitat. The common scoter (*Melanitta nigra*) is a Birds Directive species that regularly uses the Voordelta as a wintering and foraging area, feeding on benthic shellfish within H1110 habitats, providing a strong functional link between benthic communities and higher trophic levels. The common scoter therefore represents a key functional “bridge species” within the food web, directly linking benthic shellfish communities to higher trophic levels, and thereby providing an indicator of benthic habitat quality that is not fully captured within the actual Natura 2000 target species.

Breeding colonies of coastal bird species are largely located in adjacent Natura 2000 sites (e.g. Voornes Duin, the Oosterschelde, Grevelingen), reflecting the spatial separation of ecological functions within the North Sea coastal system. For example, shell banks in the former sea arms of the Delta region provide a suitable breeding habitat for the Arctic tern (*Sterna paradisaea*). During that period, the birds forage in the Voordelta. This spatial separation of ecological functions highlights the importance of considering food-web processes by applying suitable indicators across connected ecosystems rather than within individual Natura 2000 sites alone. Conservation of species in the Delta region depends on maintaining functional connections between habitats across the wider coastal ecosystem (Noordzeeloket, n.d.; Rijkswaterstaat, n.d.).

Highly mobile species such as Arctic terns depend on trophic resources originating from multiple connected ecosystems. Whereas abundance or condition indicators reveal whether a tern population is performing well or poorly, food-web indicators can help determine whether observed changes are linked to alterations in prey availability, trophic transfer, ecosystem productivity, or ecosystem processes across connected habitats. By identifying the ecological mechanisms underlying changes in population status, they can support the identification of management measures, beyond at the breeding sites themselves. Rather than as primary conservation indicators for the species, food-web indicators may offer early warning signals of ecosystem change before effects become apparent in bird population abundance or breeding success, and may be complementary for providing insight into ecosystem functioning and drivers of population change.

The Voordelta has shifted from heavy structural and pollution pressures in the past to a mix of ongoing human use (fisheries, shipping, recreation) and emerging pressures (climate change, energy development), with hydromorphological changes from the Delta Works still shaping the system today. Data from a long-term monitoring project in recent years in the Voordelta could be applied to illustrate the added value of food-web assessment. The PMR-NCV monitoring and research programme covered roughly 14-15 years (2004-2018), including pre-monitoring and two main phases:

- Baseline measurements: 2004-2007
- Phase 1 monitoring: 2009-2015
- Phase 2 monitoring: 2016-2018

The final syntheses and reporting were compiled at the end of Phase 2 in 2018, with the final scientific report published in 2020 (Prins et al., 2020). The extensive monitoring programme was structured around several key organism groups, ecological components, and environmental themes. These were grouped into the following distinct monitoring modules ('percelen'):

Benthic invertebrates

Monitoring of bottom-living invertebrate communities (benthic fauna) are related to sediment characteristics, which are a key part of habitat function and food availability. Benthic data were collected repeatedly across the project period to assess changes relative to baseline conditions.

Fish

Fish assemblages and community structure were surveyed to assess effects of habitat changes and nature compensatory measures. Reported results include studies on fish distribution and abundance following protection measures. Data on fish diet is available for part of the monitoring period.

Birds

Bird fieldwork was conducted annually, with a specific dataset on sea ducks from 2016-2020. Monitoring included a range of bird species, with particular attention to common scoter (*Melanitta nigra*), sandwich tern (*Thalasseus sandvicensis*) and common tern (*Sterna hirundo*).

Abiotic environment

Environmental and physical data such as salinity, water temperature, river discharge, sediment characteristics and other abiotic factors were collected. These data were important for relating to biological changes and to differentiate between natural variability and effects of compensatory measures.

Human and ecological use

Human usage patterns, e.g. fishing intensity and recreational usage was monitored. This includes data from fishing vessel monitoring and assessments of habitat interactions.

Advantages of applying food-web indicators to this system

The area of the proposed system is limited in space where a large amount of data covering a broad range of the marine coastal food web has recently been collected, and some of which is being collected in current monitoring programmes. Most data are directly available, although they need to be retrieved and made ready for use. Other data, e.g. zooplankton, can be inferred from other data sources.

For the criterion C3 (i.e. size distributions within guilds) indicators including the guilds planktivores, sub-apex pelagic predators, and apex predators (FW7) was applied across all survey strata in the Greater North Sea, but did not specifically report numerical results from coastal areas in the previous QSR (OSPAR, 2023). Applying indicators including guild diets within this coastal system would enable a link between the benthic and the pelagic habitats for reporting of ecological status in relation to pressures, and recovery following management measures. Another advantage is that the system studied has undergone changes during the monitoring period, which may point to the suitability of specific food-web indicators to detect these changes.

Proposed food-web indicators

- C2-FW7 - **Fish biomass and abundance of dietary functional groups** (Planktivores, Sub-apex demersal predators, Sub-apex pelagic predators, Apex predators) (candidate)
- C2-FW4 - **Changes in average trophic level of marine consumers** - (separation of stages within species, and information on diet is required)
- C3-FW3 - **Size composition in fish communities**
- C3-FC2 - **Proportion of large fish** (Sub-apex demersal predators)
- C3-FC3 - **Mean maximum length of fish**

With support from selected indicators (above), it is proposed to use data from the proposed system for developing an integrated system-ecology approach to analyze trophic interactions by:

- C1-C4-FW9 **Ecological Network Analysis (ENA)** Indices – to capture the benthic part of the food-web and the benthic-pelagic coupling

Furthermore, aligned with the second proposed example (see section 5.2), it can also be proposed to include D1 - **Predator productivity** (support indicator) – Breeding productivity of seabirds (e.g. chicks fledged annually per breeding pair, clutch or nest within defined areas) and reproductive success of marine mammals (e.g. seal pup production), potentially complemented by abundance assessments. While these are biodiversity indicators under Descriptor 1, they can provide evidence of food-web conditions and prey availability (OSPAR 2023).

As the Voordelta is a limited coastal area of its own, calculating the suggested indicators based on the data available from the more detailed PMR monitoring would likely result in different outcomes compared to what has been reported for the North Sea as a whole. Examples of such differences are for the indicators: Fish biomass and abundance of dietary functional groups, size composition in fish communities, proportion of large fish, and mean maximum length of fish. Also, the average trophic level of consumers may be different.

To consider

The Dutch delta area has a strong connection to the North Sea. Therefore, direct abiotic as well as direct and indirect biotic influences from the North Sea to the delta ought to be considered when food-web indices are chosen and being evaluated.

Table 5.1. The example of a 'Benthic community linked to pelagic habitat and birds' (Dutch Voordelta) showing connections between key habitats (Janssen et al. 2014), species groups and their trophic roles with examples of species, their relevance in connection to Natura 2000, their role in the food web, and potentially relevant (OSPAR, or other) food-web indicators.

Key habitats (H)	Species group	Trophic role	Species (examples)	N2000 relevance (species)	Food-web role	Potential D4 indicators
H1110	Marine mammals	Apex predators	Harbour seal (<i>Phoca vitulina</i>), Harbour porpoise (<i>Phocoena phocoena</i>)	Yes (Habitats Directive)	Integrate whole food web	Other descriptor - D1, FW9
H1110 (oyster/mussel beds)	Shellfish-eating birds	Predator on molluscs	Common eider (<i>Somateria mollissima</i>)	(Yes - but not primarily in the Voordelta)	Link: biogenic habitats ↔ birds	Other descriptor - D1, FW9
H1110	Benthic-feeding (bridge species)	Specialist mollusc predator	Common scoter (<i>Melanitta nigra</i>)	Yes (Birds Directive)	Direct indicator of benthic prey availability	Other descriptor - D1, FW9
H1110	Seabirds (fish-eating)	Piscivores	Common tern (<i>Sterna hirundo</i>), Sandwich tern (<i>Thalasseus sandvicensis</i>)	Yes (core)	Indicators of fish availability	Other descriptor - D1, FW9
H1140	Wading birds	Predators (benthos)	Eurasian oystercatcher (<i>Haematopus ostralegus</i>), Red knot (<i>Calidris canutus</i>)	Yes (core)	Top-down control on benthos	Other descriptor - D1, FW9
H1110	Sub-apex predators	Predators on (small) fish and crustaceans	Whiting (<i>Merlangius merlangus</i>), Seabass (<i>Dicentrarchus labrax</i>)	Indirect	Top-down control	FW7, FC2
H1110	Demersal fish	Benthivores	Plaice (<i>Pleuronectes platessa</i>), Sole (<i>Solea solea</i>)	Indirect	Link: benthos → higher trophic levels	FW7, FC2
H1110 (water column)	Pelagic fish	Zooplanktivores	Herring (<i>Clupea harengus</i>), Sprat (<i>Sprattus sprattus</i>)	Indirect	Link: plankton → birds/mammals	FW2, FW7, FC2, FW4
H1110 (reef structures)	Biogenic engineers	Filter feeders / habitat formers	Flat oyster (<i>Ostrea edulis</i>), Pacific oyster (<i>Magallana gigas</i>)	No (in Voordelta)	Enhance pelagic-benthic coupling	FW5, FW9

Key habitats (H)	Species group	Trophic role	Species (examples)	N2000 relevance (species)	Food-web role	Potential D4 indicators
H1110, H1140	Benthic invertebrates	Primary consumers / prey	Sandworm (<i>Arenicola marina</i>), Baltic clam (<i>Macoma balthica</i>), Razor clams (<i>Ensis</i> spp.), Brown shrimp (<i>Crangon crangon</i>)	No	Key energy transfer (benthos → fish/birds)	FW9
H1110, H1140	Detritus	Secondary production		No	Supports benthic production → fish → birds + other predators	FW9
H1110, H1140	Primary producers	Primary production	Phytoplankton, microphytobenthos	No	Base of all energy flow	FW5, FW9

5.2 Case study – The Dutch coastal zone and the greater North Sea: Pelagic food web, fish guilds, and breeding birds

The Dutch coastal zone forms a highly connected ecological interface between the Greater North Sea and the estuarine and intertidal systems of the Wadden Sea and the Delta. Primary production by phytoplankton and microphytobenthos supports a diverse assemblage of zooplankton, benthic invertebrates, and fish within coastal areas (ICES, 2023; Rijkswaterstaat, 2023). Variability in prey quality is influenced by climate driven changes in plankton communities, fishing pressure, and habitat conditions on offshore sandbanks (OSPAR, 2023). On the local scale within coastal and estuarine habitats, benthic invertebrates (e.g. bivalves, polychaetes, and crustaceans) form the primary food source for waders and sea ducks (SOVON, 2023; WSQSR, 2022). These prey species vary seasonally in abundance, energy content, and accessibility (van Gils et al., 2006; van Roomen et al., 2018). This in turn affects the diet composition of predator bird species such as knot (*Calidris canutus*), bar-tailed godwit (*Limosa lapponica*), and common eider (*Somateria mollissima*) (SOVON, 2023; van der Meer et al., 2001). However, several of these bird species do not breed along the Dutch coast (but further north in Scandinavia or Siberia).

Forage fish species such as sandeel (*Ammodytes marinus*), sprat (*Sprattus sprattus*), and herring (*Clupea harengus*) are key prey for seabirds and marine mammals, and their availability strongly influences predator diet composition and prey quality (ICES, 2023; Piersma and van Gils, 2011; van Gils et al., 2005). Research that connects the underwater marine world with the 'above water' marine world, and also connects the coastal zone with offshore areas on a larger spatial scale, focuses on how prey fish for seabirds can affect their demography. This brings the marine ecosystem together with the partly terrestrial lifestyle of birds breeding along the coast. A recent review on this topic describes these relationships for some seabirds (terns and gulls) that breed in the Netherlands (Van Donk et al., 2025; Schekkerman et al., 2025). One species that is dependent on the marine environment for breeding is the Sandwich tern (*Thalasseus sandvicensis*). All published studies of Sandwich terns on relationships between demographic rates and food resources come from the Netherlands, and nearly all concern breeding performance, not adult or juvenile survival (Schekkerman et al., 2025). Although survival may be influenced by food availability, no studies have yet examined this directly (Van Donk et al., 2025).

Diet composition and prey quality

During the breeding season, Sandwich tern chicks are mainly fed with sandeel (*Ammodytidae*) and clupeids, i.e. herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) (Stienen and Brenninkmeijer, 2002a; Fijn et al., 2018; Courtens et al., 2022). Clupeids are thought to be a higher quality prey because they contain more energy per unit size than sandeels. Prey loss to competing black-headed gulls can substantially reduce food delivery to chicks. Black-headed gulls were in one study reported to steal larger sandeels more frequently than herring, i.e. prey size was more important than energy content. As a result of gulls stealing prey ('kleptoparasitism'), Sandwich tern adults may be unable to deliver enough food to their chicks, and chicks fed predominantly on sandeel may receive insufficient energy for successful fledging (Stienen and Brenninkmeijer, 2002b). Because chick energy demands increase as they grow, adults should supply more clupeids later in development, but this shift was not observed on Griend, indicating limitation of clupeid availability. In years when sandeel prey was dominating, parents increased foraging effort and left older chicks unattended more often, potentially decreasing survival (Stienen and Brenninkmeijer, 2002a, b). This example illustrates how changes in the abundance and size composition of prey fish can propagate through the food web and ultimately influence the reproductive success of coastal seabirds.

Effects on breeding productivity

Breeding productivity of seabirds is tightly linked to the availability, accessibility, and quality of prey during the breeding season (ICES, 2023; van der Meer and Leopold, 1995).

Pelagic predators such as terns (*Sterna* spp.), gulls (*Larus* spp.), guillemots (*Uria aalge*), and razorbills (*Alca torda*) rely heavily on small pelagic fish. Prey quality, particularly lipid content and size structure, plays a

critical role in chick provisioning and adult condition (ICES, 2023; Piersma and van Gils, 2011; van der Meer and Leopold, 1995). Evidence suggests that availability of high-quality prey (clupeids) affects breeding success. Sandwich tern (*Thalasseus sandvicensis*) and common tern (*Sterna hirundo*) show reduced breeding success in years with low sandeel or sprat abundance (ICES, 2023). Similarly, lesser black-backed gulls (*Larus fuscus*) and herring gulls (*Larus argentatus*) exhibit shifts in diet and reduced chick growth when forage fish availability declines (Piersma and van Gils, 2011; SOVON, 2023). However, many studies lack direct measurements of fish abundance near colonies, i.e. an area extending to the North Sea coastal zone above the central Wadden islands. A comparison of long-term breeding data with clupeid abundance (IBTS survey) found no clear relationship with clutch size or chick productivity. However, they found a strong correlation between clupeid abundance and the number of adults settling to breed in the Wadden Sea, but not in the Delta area (Stienen, 2006). This suggests that prey availability influences settlement decisions and breeding propensity, rather than breeding success *per se*. (However, the same pattern was for unknown reasons not seen in the Delta region.)

A study in the northern Delta area used chick diet as proxy for food supply (Fijn et al. 2018). Chick survival and fledgling condition improved when larger clupeids (a proxy for prey quality) were delivered and frequent deliveries of herring (a proxy for abundance) increased fledging success. However, no such relationships were found for sandeel. Clupeids thus drive chick quality and fledging success, whereas sandeel functions as a secondary fallback prey. Sandeel was nevertheless the main food for adults in early breeding season. In the Western Scheldt, chicks were fed mostly small herring and sandeel, but in this colony this resulted nevertheless in high breeding productivity probably because small fish were abundant close to the colony, enabling efficient foraging.

For benthic-feeding birds breeding in Dutch coastal areas, breeding productivity and adult survival depend on the condition of intertidal flats (H1140) and estuaries (H1130). Declines in bivalve stocks or changes in sediment dynamics can reduce food availability for waders and sea ducks (Kraan et al., 2009; van der Meer et al., 2001), affecting both local breeding populations and migratory species using the Dutch coast as a staging area (van Roomen et al., 2018; WSQSR, 2022). However, in the present food-web example, we are focusing on the coastal area with breeding marine bird species (i.e. terns and gulls), that during the breeding season forage on pelagic forage fish species, thereby bridging coastal with offshore areas.

Potential datasets

To start with food-web calculations on fish and birds, several datasets are interesting. The DFS (coastal) and IBTS and BTS (offshore) fish survey data could be used to calculate fish abundance and species distribution in relation to breeding areas. Under the 'Nature Strengthening and Species Protection Monitoring Survey' (MONS) program, pelagic fish are being monitored along the coast twice a year (Van Hal et al., 2025). In 2026, bird counts from the ship are done at the same time as other monitoring. These data could also be used for future calculations.

Cross-habitat linkage: connecting marine, terrestrial, and aerial ecosystems

The Dutch North Sea is characterized by a mosaic of offshore marine, coastal, estuarine, deltaic and intertidal ecosystems that are connected through ecological processes across the marine-terrestrial transition zone (Bogaart et al., 2023). The strong spatial coupling between offshore, coastal, estuarine, and intertidal habitats is mediated by mobile predators, especially seabirds and fish, which move energy and nutrients across habitat boundaries (ICES, 2023; OSPAR, 2023). Migratory waders depend on intertidal flats for feeding but roost on saltmarshes, dunes, and agricultural land (Piersma, 2007; van Gils et al., 2016). Breeding seabirds nest in terrestrial habitats but forage at sea, creating strong cross-habitat energy flows (ICES, 2023; SOVON, 2023). Through these processes, birds create a biological bridge between marine, coastal, and terrestrial systems, making them essential indicators for the MSFD Descriptor 4 and Natura 2000 conservation objectives.

Advantages of applying food-web indicators to this system

Sandwich terns are listed in Annex I of the EU Birds Directive, with specific conservation objectives in N2000 areas, reflecting the protected status of this species. Applying indicators to, e.g. connect breeding success of Sandwich terns within the proposed system is directly related to their food and would provide a link between the breeding area and the marine habitat on different (chosen) spatial scales. The system is also relatively

well investigated. Most of the data are directly available (although they would need to be retrieved and made ready for use).

Under the EU Birds Directive (Directive 2009/147/EC), Special Protection Areas (SPAs) are designated to protect habitats essential for threatened or vulnerable bird species (Annex I, Birds Directive), or regular migratory bird species. SPAs form part of the Natura 2000 network, alongside SACs (Special Areas of Conservation) designated under the Habitats Directive. SPAs along the Dutch coast (e.g., Wadden Sea, Delta, Voordelta, North Sea coastal zone) protect breeding colonies of gulls, terns, cormorants, and provide wintering and staging areas for waders, sea ducks, and geese. The offshore foraging zones for seabirds anchor the biological “nodes” that connect coastal habitats, offshore sandbanks, estuaries, and the wider Greater North Sea ecosystem.

Proposed food-web indicators

Simple indicators, e.g. seabird breeding success or fish size structure, are valuable but limited as they do not reveal trophic bottlenecks such as forage fish shortages or benthic-pelagic decoupling (van Roomen et al., 2018). They also cannot quantify energy transfer efficiency, functional redundancy, or keystone roles (Bijleveld et al., 2012; Piersma and van Gils, 2011). To obtain a more integrated food-web perspective, indicators of bird breeding success can then be directly compared with abundances of clupeids and sandeels (as ‘guilds’) obtained from monitoring data, or indicators reflecting forage fish and the fish community.

Using complex food-web indicators (e.g. Ecopath/Ecosim outputs, ENA network metrics, benthic-pelagic coupling indices) can help system-level understanding by showing food sources with varying quality, how energy flows through the ecosystem, identifying keystone species and critical habitats, and quantifying trophic efficiency (Bijleveld et al., 2012; ICES, 2023). Because pressures propagate across habitats, a food-web approach is essential for ecosystem-based management under the MSFD. In **Table 5.2**, connections are shown between key habitats and species groups and their trophic roles in this system, their role in the food web, and MSFD/OSPAR and other particular food-web indicators that would be relevant to apply in combination with complex food-web indicators (i.e. FW9 Ecological Network Analysis Indices).

To consider

The Dutch N2000 coastal areas have a strong connection to the North Sea. Therefore, direct and indirect biotic influences from the greater North Sea ought to be considered when food-web indices directly reflecting coastal parts of the food web are chosen and being evaluated. Furthermore, the breeding success of birds should be supported with information on their abundance on a larger scale also outside the breeding season in the studied area, as well as considerations of other factors other than food availability which may influence breeding success.

Table 5.2. The example 'Dutch coastal zone and the greater North Sea' (pelagic food web, fish guilds, and breeding birds) showing connections between key habitats (Janssen et al. 2014), species groups and their trophic roles with examples of species, their relevance in connection to Natura 2000, their role in the food web, and potentially relevant (MSFD/OSPAR, and other) food -web indicators.

Key habitats (H)	Species group	Trophic role	Species (examples)	N2000 relevance (species)	Food -web role	Potential food -web (D4) indicators
H1110 (water column)	Forage fish	Mid-trophic prey	Sandeel (<i>Ammodytes marinus</i>), sprat (<i>Sprattus sprattus</i>), Atlantic herring (<i>Clupea harengus</i>), whiting (<i>Merlangius merlangus</i>), juvenile cod (<i>Gadus morhua</i>)	Critical for SPA foraging	Major energy conduit from plankton to predators	Forage fish biomass; fish functional groups and size structures (C2-FW7, C3-FW3)
	Piscivorous seabirds	Top predators	Lesser black-backed gull (<i>Larus fuscus</i>), herring gull (<i>Larus argentatus</i>), Sandwich tern (<i>Thalasseus sandvicensis</i>)	SPA breeding colonies depend on sandbank prey	Mobile link between offshore and coast	(Other descriptor - D1 Seabird breeding success)
	Marine mammals	Top predators	Harbour porpoise (<i>Phocoena phocoena</i>), harbour seal (<i>Phoca vitulina</i>), grey seal (<i>Halichoerus grypus</i>)	Annex II species	Control forage fish	(Other descriptor - D1)
H1130 – Estuaries (Eems-Dollard, Westerschelde)	Estuarine fish & crustaceans	Mid-trophic consumers	European flounder (<i>Platichthys flesus</i>), European smelt (<i>Osmerus eperlanus</i>), mullet spp. (<i>Chelon</i> spp.), brown shrimp (<i>Crangon crangon</i>), shore crab (<i>Carcinus maenas</i>)	Key nursery areas	Export of juveniles to coastal food webs	Fish functional groups and size structures (C2-FW7, C3-FW3); (Fish condition)
	Cormorants & terns	Top predators	common tern (<i>Sterna hirundo</i>), Great cormorant (<i>Phalacrocorax carbo</i>)	SPA breeding/roosting	Strong benthic-pelagic coupling	(Other descriptor - D1 Seabird breeding success)
H1150 – Coastal lagoons (limited in NL)	Juvenile fish	Nursery role	Three-spined stickleback (<i>Gasterosteus aculeatus</i>), mullet spp. (<i>Chelon</i> spp.)	Local N2000 sites	Export of juveniles to coastal waters	Nursery productivity indicators; fish functional groups and size structures (C2-FW7, C3-FW3)

(Continued on next page.)

Table 5.2. *Continued.*

Key habitats (H)	Species group	Trophic role	Species (examples)	N2000 relevance (species)	Food -web role	Potential food -web (D4) indicators
H1160 – Large shallow inlets & bays (Wadden Sea basins, Delta waters)	Pelagic fish	Mid-trophic prey	Atlantic herring (<i>Clupea harengus</i>), sprat (<i>Sprattus sprattus</i>), juvenile whiting (<i>Merlangius merlangus</i>)	Key foraging areas/habitats for protected bird species	Seasonal energy transfer	Forage fish biomass; fish functional groups and size structures (C2-FW7, C3-FW3)
	Terns & gulls	Top predators	Common tern (<i>Sterna hirundo</i>), Arctic tern (<i>Sterna paradisaea</i>), black-headed gull (<i>Chroicocephalus ridibundus</i>)	Key areas for breeding colonies of protected birds	Sensitive to small fish availability	(Other descriptor - D1 Seabird breeding success)
* H1140 – Intertidal mudflats & sandflats (Wadden Sea, Delta)	Benthic invertebrates	Primary consumers	Common cockle (<i>Cerastoderma edule</i>), blue mussel (<i>Mytilus edulis</i>), lugworm (<i>Arenicola marina</i>), ragworm (<i>Hediste diversicolor</i>)	Core N2000 habitat	Base of benthic food web	Benthic biomass
	Waders & shorebirds	Benthic predators	Red knot (<i>Calidris canutus</i>), bar-tailed godwit (<i>Limosa lapponica</i>), Eurasian oystercatcher (<i>Haematopus ostralegus</i>), dunlin (<i>Calidris alpina</i>)	Internationally important flyway populations	Transfer benthic energy to higher trophic levels	Wintering bird abundance
	Diving ducks	Benthic predators	Common eider (<i>Somateria mollissima</i>), common scoter (<i>Melanitta nigra</i>)	SPA wintering concentrations	Sensitive to shellfish availability	Diving duck abundance
* H1170 – Reefs (natural + artificial: wrecks, wind farms)	Reef-associate d fish & invertebrates	Mid-trophic consumers	Goldsinny wrasse (<i>Ctenolabrus rupestris</i>), gobies (<i>Pomatoschistus</i> spp.), edible crab (<i>Cancer pagurus</i>)	Artificial reefs enhance N2000 connectivity	Local hotspots for predators	Fish functional groups and size structures (C2-FW7, C3-FW3)
	Diving seabirds	Top predators	Common guillemot (<i>Uria aalge</i>), razorbill (<i>Alca torda</i>), European shag (<i>Gulosus aristotelis</i>)	Offshore SPA foraging	Link pelagic and reef systems	Seabird at-sea distribution
* H1310-H1330 – Saltmarshes	Herbivores & detritivores	Low-trophic consumers	Dark-bellied brent goose (<i>Branta bernicla bernicla</i>), barnacle goose (<i>Branta leucopsis</i>), common shelduck (<i>Tadorna tadorna</i>)	Key N2000 habitat	Export of detritus to coastal waters	Cross-habitat coupling indicators
	Waders	Benthic predators	Common redshank (<i>Tringa totanus</i>), Eurasian curlew (<i>Numenius arquata</i>)	SPA roosting/feeding	Link terrestrial–marine interface	Wintering bird abundance

* Associated habitat; not primarily in focus for the proposed case study.

6 Discussion

Food-web topology and context-dependent usefulness (Chapter 1)

How can food webs be described in relation to topology, including characteristics such as spatial or temporal context, resilience, shape, complexity, level of detail, or other characters, e.g. related to species traits and ecological function?

Can food-web-category-dependent conclusions be made regarding the usefulness of a food-web perspective to evaluate, e.g. effects of climate change or other stressors?

Food webs represent ecosystems as networks of trophic interactions, where nodes (species or functional groups) are linked through energy transfer. Their topology, characterized by connectance and trophic structure, strongly influences ecosystem stability and resilience (Dunne et al., 2002; Thébault and Fontaine, 2010). In the North Sea, these properties vary between subsystems, where pelagic food webs tend to be highly dynamic and bottom-up connected, while benthic systems are often more segmental and spatially structured in defined habitat types.

Temporal dynamics together with species traits (e.g. thermal preferences, phenology) influence food-web structure and function. A key example is the North Sea plankton-fish food web, where climate-driven shifts in zooplankton composition have altered trophic linkages. Changes in the abundance of *Calanus finmarchicus*, a key copepod zooplankton species in the North Sea, have been linked to reduced recruitment of cod (*Gadus morhua*) due to trophic mismatch (Beaugrand et al., 2003). **Spatial context** is equally important. Coastal zones of the Dutch North Sea are characterized by strong benthic-pelagic coupling and nutrient enrichment, whereas pelagic-dominated offshore systems are mostly influenced by large-scale circulation (Christiansen et al., 2023; Desmit et al., 2024; Neumann et al., 2021; Otero et al., 2023). Thereby coastal and offshore food webs are differently influenced in their energy pathways, with effects on their resilience to disturbance.

The level of detail in food-web construction also determines its usefulness. High-resolution, species-based food webs capture trait-mediated biotic interactions that are valuable for understanding, e.g. climate change impacts. Size-based food-web approaches are more directly suitable for fisheries management (Shin et al., 2005). For instance, size-spectra of fish communities have been widely applied in the North Sea to evaluate fishing pressure on trophic structure (Blanchard et al., 2014; Jennings et al., 2002).

Overall, the usefulness of a food-web perspective is category-dependent. taxonomic or trait-based webs can better capture climate change impacts, while size-based or trophic-level indicators can be used to more effectively assess impacts of fishing on the food web. Furthermore, habitat-specific pressures (e.g., eutrophication) require spatially explicit, benthic-pelagic frameworks.

Food-web indicators for observing ecological change (Chapter 2)

How can changes in ecosystem functioning be detected using food-web indicators?

Clarification: Which indicators are expected to respond to changes in ecosystem functions such as primary production, trophic transfer, nutrient cycling, or benthic-pelagic coupling?

How can information regarding food-web indicators be compiled on logical spatial scales for use in assessment?

Clarification: Which spatial scales apply for assessment? If chosen food-web indicators are applied, is there an overlap or non-overlap in the spatial scales?

Based on collected information, how can examples of food webs in the (Dutch) North Sea be categorized regarding their characteristics?

Food-web indicators provide measurable proxies for ecosystem function and can reveal changes in response to environmental pressures. In the North Sea, widely used indicators include mean trophic level, large fish indicator (LFI), predator-prey biomass ratios, and primary production to biomass transfer efficiency (Shannon et al., 2014). A well-documented case is the decline in mean trophic level due to “fishing down the food web” where intensive fishing shifts the system toward lower trophic levels by reducing large predatory fish (Pauly et al., 1998).

Food-web information is already used operationally in fisheries management. Examples include recruitment analyses that account for prey availability and predation on cod early life stages (Neumann et al., 2014), capelin management that considers predator dependence on forage fish (Layton-Matthews et al., 2026; Singh et al., 2025), multispecies assessment models that incorporate predator-prey interactions (Karp et al., 2023; Pope, 1991), and ecosystem models that evaluate management scenarios within an ecosystem-based fisheries management framework (Rodriguez-Perez et al., 2023).

In the North Sea, increases in smaller fish and invertebrates have been observed, altering energy pathways and ecosystem functioning (Jennings et al., 2002). Another example is the increase of gelatinous zooplankton and small pelagic species under warming conditions, which can reduce trophic transfer efficiency to higher predators (Brodeur et al., 2019; Heneghan et al., 2023). Such changes may not directly alter biomass-based indicators but can significantly affect ecosystem function, highlighting the need for complementary and more complex food-web indicators.

Spatial scale considerations in North Sea food webs

North Sea food webs can be categorized as 1) pelagic food webs, i.e. phytoplankton-zooplankton-fish dominated, highly dynamic, and climate-sensitive; 2) benthic food webs, i.e. detritus-based, spatially structured, influenced by sediment and nutrient inputs; and 3) coupled benthic-pelagic systems, especially in coastal zones, with strong feedbacks between compartments. These categories differ in resilience, complexity, and sensitivity to stressors, reinforcing the need for tailored collections of indicators.

Food-web indicators operate across different spatial scales. Within the MSFD framework, assessments are commonly organized around eco-hydrographic sub-areas (variable-salinity, coastal, shelf, and oceanic waters), which represent ecologically meaningful units that differ in environmental conditions, community composition, and dominant food-web processes. On a local scale (e.g. estuaries, coastal habitats, sandbanks, or Oyster Grounds), interaction-specific indicators may be most appropriate, for example indicators describing benthic community structure and trophic transfer to fish. At the scale of eco-hydrographic sub-areas or larger regions of the Dutch North Sea, indicators describing aggregated biomass, trophic guilds, size structure, and trophic levels become increasingly informative. At the basin scale (the wider North Sea), assessment may focus on large-scale patterns in productivity, species distributions, and connectivity among food-web components. This largely aligns with current MSFD practice, but a stronger food-web perspective would require greater emphasis on ecological connectivity across habitats and assessment units, rather than evaluating ecosystem components in isolation.

There is often partial overlap between different spatial scales which may need to be considered regarding the interpretation of indicator outcomes. For example, the Large Fish Indicator (LFI) is applied regionally, but may both directly and indirectly reflect processes occurring at smaller spatial scales. In contrast, plankton indicators are often basin-wide due to hydrodynamic connectivity. Mismatches in scale can therefore complicate interpretation, particularly in highly open systems like the North Sea. Consequently, future food-web assessments are likely to benefit from combining indicators across multiple spatial scales, including the MSFD eco-hydrographic sub-areas, to better capture trophic interactions and ecosystem connectivity.

Food-web indicators in policy and ecosystem assessment (Chapter 3)

How can status/changes in the North Sea at the food-web level be evaluated by using food-web indicators, with respect to EU nature restoration (EU) and national nature improvement and conservation (Figure 2.1)?

Food-web indicators play an important role in evaluating ecosystem status under European and national policy frameworks. Within the Marine Strategy Framework Directive (MSFD), Descriptor 4 ('Food webs') explicitly requires assessment of trophic relationships and energy flow. Indicators reflecting trophic level (C2-FW-7), LFI (Large Fish Indicator; C3-FC2), and productivity (i.e. C4-FW2) encompass the food web in supporting the evaluation of Good Environmental Status (Borja et al., 2013; European Commission, 2008).

The effectiveness of food-web indicators within the MSFD ultimately depends on their translation into management actions. While the Directive has the potential to serve as a powerful instrument for ecosystem-based marine governance, realizing this potential will require more ambitious national implementation and stronger enforcement at the EU level (Puharinen, 2023). Similarly, the EU Biodiversity Strategy for 2030 and the Birds and Habitats Directives emphasize ecosystem integrity and species conservation, which are inherently linked to food-web structure. For example, declines in forage fish can directly affect seabird populations, demonstrating the connection between trophic dynamics and conservation targets (Cook et al., 2014; Cury et al., 2011; Searle et al., 2023; Votier et al., 2023).

Other Effective Area-Based Conservation Measures (OECMs) also benefit from food-web indicators by assessing whether protected (i.e. MPAs) or managed areas maintain functional trophic interactions, rather than only by considering presence and abundance of particular species (Fulton et al., 2011; IUCN, 2019).

Bridging science and management

A key challenge in striving for a food-web perspective is the discrepancy between academic food-web research and management applications. Scientific studies often focus on complex, high-resolution networks, whereas policy often requires simplified, standardized indicators with clear thresholds (Jennings, 2005). This necessitates defining food-web boundaries and selecting appropriate levels of aggregation.

The application of food-web indicators within MSFD Descriptor 4 has the potential to improve the ecological coherence and interpretability of regional assessments. By explicitly accounting for trophic interactions, cross-scale dynamics, and pressure-response relationships, such indicators can help bridge the gap between fragmented datasets and the overarching goal of achieving Good Environmental Status in the North Sea (Borja et al., 2013; Tam et al., 2017). Within the MSFD and OSPAR assessment frameworks, food-web condition is primarily evaluated using simplified, standardized indicators intended to support comparability, trend analysis, and threshold-based decision-making (MSFD Descriptor 4; OSPAR ecosystem component assessments). The application of such indicators requires clear choices regarding food-web boundaries, spatial assessment units, and levels of trophic or functional aggregation. Definitions of the above are critical, as they determine whether indicators are sensitive to pressures affecting trophic functioning, or merely reflect changes in species presence or abundance.

More complex food-web approaches, including Ecological Network Analysis (ENA) and ecosystem modelling, provide an explicit analytical basis for informing these choices under MSFD Food-Web criteria (e.g. MSFD FW9). By quantifying whole-system properties such as energy and biomass flows, trophic dependencies, redundancy, and indirect interactions, these more complex approaches allow systematic evaluation of, e.g. alternative boundary definitions and food-web components. This also enables the identification of key functional groups, trophic pathways, or interaction strengths that must be retained for a specific indicator to meaningfully reflect food-web structure and functioning. Complex food-web indicators do not replace more straightforward operational OSPAR indicators, but will rather provide supporting analyses especially in underpinning the relevance and further development of ecologically grounded and policy-tailored simplified indicators (Coll et al., 2016; Heymans et al., 2016; Shin and Shannon, 2010).

Cross-habitat food-web indicators can further support MSFD and OSPAR objectives by indicating trophic connectivity, e.g. benthic-pelagic coupling or coastal-offshore energy transfers, which are not always captured within fixed assessment units. This is particularly relevant for area-based management instruments,

including MPAs and OECMs, where achieving GES depends on functional trophic interactions that may extend beyond designated boundaries. By identifying ecologically meaningful linkages between habitats, cross-habitat indicators provide a scientifically robust basis for defining assessment units, aggregation levels, and management scales that are consistent with MSFD ecosystem-based management principles rather than administrative convenience (De Jonge et al., 2012).

However, application of more complex food-web indicators typically requires substantially greater data integration, monitoring coverage, and modelling effort than currently operational indicators. As a result, the above-described approaches can currently be concluded to be better suited to supplementary and exploratory analyses than to routine assessments, and a potentially wide operational use in the future will depend on whether such requirements can be met realistically, consistently, and cost-effectively over the long term.

Interpreting changes and uncertainties

How should food webs be defined and limited to determine status and changes?

Why may certain perceived changes not be manifested in certain food-web indicators?

Regarding ambiguity about observed changes (or not), how may this be related to food-web resilience, level of detail, inherent dynamics, time, and space, or the degree of isolation vs. openness of the food web?

What knowledge gaps can be defined?

While regulatory frameworks such as the Marine Strategy Framework Directive (MSFD) necessarily rely on simplified, standardised indicators with clear thresholds, the results presented in this report show that apparent stability in food-web indicators does not always mean that the ecosystem functioning is unchanged. For example, despite pronounced shifts in North Sea species composition, trophic-level indicators showed little net change, suggesting compensatory species turnover that maintained overall trophic structure (Coll et al., 2016). Such apparent stability may arise from e.g. compensatory dynamics, where ecosystem functions are maintained despite changes in species composition (Folke et al., 2004), from time-lagged responses linked to long-lived species or slow ecosystem processes (Scheffer et al., 2009), from spatial connectivity allowing immigration to compensate for local declines (Loreau et al., 2003), or from the way indicators aggregate species or trophic groups, which can hide changes in predator-prey interactions and energy pathways (Shin and Shannon, 2010). Against this background, the selected case studies (see chapter 5) provide an effective way to demonstrate when and why the application of more complex food-web indicators is both informative and operationally relevant.

Case studies highlighting the relevance of complex food-web indicators for assessing environmental status and recovery (Chapter 4)

The Dutch Voordelta as a first illustrative example, represents a system in which benthic communities are tightly linked to pelagic habitats and higher trophic levels such as seabirds. In this coastal area, energy transfer across the benthic-pelagic interface underpins key ecosystem functions, including prey availability for foraging birds and fish. Changes in benthic community composition, sediment characteristics, or benthic productivity can therefore propagate upwards through the food web, even when bird abundance or simple community indicators appear stable. Such stability may reflect functional redundancy or compensatory dynamics within benthic communities rather than preserved ecosystem structure (Folke et al., 2004). One key food-web element consisting of oyster reefs in the area also highlight an intricate pathway, where oysters provide a link from pelagic resources, via the benthic food web, into higher trophic levels. This also points to the added value of a food-web-based assessment for the Voordelta. More complex food-web indicators would be able to detect shifts in benthic-pelagic coupling, energy pathways, and functional roles that are not captured by aggregated metrics. Thereby, a more ecologically grounded interpretation of management impacts would be supported, including those associated with spatial protection, restoration measures, or multiple-use pressures.

The second example focuses on the Dutch coastal zone and the wider North Sea, where the food web is predominantly pelagic and structured around fish guilds and their links to breeding seabirds. This large, open system is characterised by high mobility of organisms and strong spatial connectivity, with redistribution

processes and immigration potentially able to buffer local declines (Loreau et al., 2003). Consequently, trophic food-web indicators may remain relatively stable despite marked changes in species composition, size structure, or predator-prey relationships. Evidence from the North Sea shows that such stability can result from compensatory dynamics within the food web rather than from an absence of ecological change (Coll et al., 2016). Applying more complex food-web indicators in this system would therefore help to distinguish between genuine resilience and apparent stability driven by spatial averaging or aggregation effects, addressing known limitations of conventional indicator approaches (Shin et al., 2010).

Together, the two case studies demonstrate that complex food-web indicators are not intended to replace simplified policy metrics, but to complement them by providing mechanistic insight into ecosystem functioning. By deliberately contrasting a benthic-dominated, spatially constrained system (the Voordelta) with a highly connected pelagic system (the Dutch coastal zone and greater North Sea), the examples illustrate how food-web complexity, spatial openness, and functional redundancy can influence outcomes of applied indicators (Folke et al., 2004; Loreau et al., 2003). This targeted application of complex food-web indicators could enhance the interpretation of observed trends and strengthen the scientific basis for ecosystem-based management decisions consistent with MSFD food-web objectives. Both case studies illustrate that key ecological processes are driven by food-web linkages that span habitats, trophic levels, and spatial scales. This underlines the value of developing a comprehensive ecosystem model capable of assessing food-web activity, organisation, and resilience at the scale of the wider North Sea ecosystem.

Key knowledge gaps

The two proposed case studies provide complementary and policy-relevant examples for illustrating how more complex food-web indicators can help address several persistent knowledge gaps in ecosystem-based marine management. First, **limited availability of long-term, high-resolution trophic interaction data** is often identified as a major constraint for assessing food-web structure and functioning. In both selected case studies, this gap is comparatively well covered due to sustained monitoring of benthic communities, pelagic fish assemblages, and seabirds, as well as the availability of diet, trait, and functional information. This makes these systems particularly suitable for applying and testing more complex food-web indicators, as they allow trophic interactions and energy pathways to be analysed in greater detail than is possible in many other regions.

Second, **uncertainty in interaction strengths and the role of non-trophic interactions**, combined with the **difficulty of integrating spatial dynamics and climate-driven redistribution of species**, remains a central challenge for interpreting food-web indicators. The two case studies highlight different aspects of this challenge. In the Voordelta, benthic–pelagic coupling and habitat-mediated interactions play a key role, whereas in the Dutch coastal zone and the wider North Sea, high mobility and spatial openness allow compensatory dynamics and redistribution to mask local change. In both contexts, more complex food-web indicators are particularly valuable for identifying changes in interaction strength, indirect effects, and shifting trophic roles that are not captured by simplified, aggregated indicators.

Third, the case studies also illustrate **limited alignment between ecological indicators and policy thresholds**. While overarching management objectives are well aligned with international and EU-level policy frameworks, such as the MSFD, the translation of these objectives into clear, spatially explicit national goals remains challenging. The Voordelta and Dutch coastal/North Sea examples provide concrete contexts in which the application of complex food-web indicators could support the development of more operational, area-specific objectives that are better linked to underlying ecosystem processes and pressures.

A key consideration for future food-web assessment is the **trade-off between ecological realism and operational feasibility**. Some approaches, particularly ecosystem models and network-based indicators, can provide detailed insight into food-web structure, connectivity, and ecosystem functioning, but often depend on extensive long-term datasets and high monitoring coverage. As a result, their application may be restricted to relatively well-studied areas where sufficient data are available, but leaves possibilities for upscaling uncertain. This raises the question of how readily such approaches can be scaled up to larger parts of the North Sea.

An alternative strategy, which has not been treated specifically in this report, is to prioritise indicators and assessment approaches that can be applied consistently across broader spatial areas using existing monitoring programmes. Such approaches may provide less detailed information on food-web processes, but upscaling by this strategy can offer greater spatial coverage, comparability, and operational robustness. It is also more likely to support routine assessments within the practical constraints of monitoring budgets and reporting cycles. In essence, this is to a substantial extent, what is currently being done already within OSPAR (see section 4.4.2). However, it could be beneficial to compile an inventory of existing datasets and to evaluate the potential to aggregate these, to develop combined indicators across eco-hydrographic sub-areas (variable-salinity, coastal, shelf, and oceanic waters) *or* otherwise defined habitats or systems. Such potential aggregations could provide novel opportunities for developing integrated North Sea food-web assessments that are not yet applied.

In practice, a tiered approach may be most effective. Data-intensive methods can be used in selected case-study areas to improve ecological understanding and test novel indicators, while simpler and more widely applicable indicators provide operational assessment at larger spatial scales. The main challenge is to ensure that simplified indicators remain sufficiently representative of underlying food-web dynamics, particularly in regions where detailed validation data are lacking.

7 Conclusions

Addressing key knowledge gaps in food-web assessment will depend on integrating monitoring, modelling, and trait-based approaches, enabling both improved ecological understanding and stronger links between science and policy. In this way, complex food-web indicators can play a targeted but important role in complementing single metrics and more simple food-web indicators, supporting the interpretation of observed trends, and strengthening ecosystem-based management at regional and national scales. Addressing these gaps will require integrating monitoring, modelling, and trait-based approaches to improve both ecological understanding and policy relevance.

Continued investment in long-term, high-resolution monitoring of trophic interactions, particularly diet, functional traits, and habitat coupling, should be prioritised. Examples of systems where these properties pose challenges for food-web assessment are the Dutch Voordelta, and the Dutch coastal and offshore waters, where collected data already provide a strong foundation. To reduce uncertainty in interaction strengths and account for indirect and non-trophic effects, complex food-web indicators and models should be applied selectively to quantify energy flows, interaction asymmetries, and compensatory dynamics across trophic levels. At the same time, spatially explicit analyses are needed to better integrate species mobility and climate-driven redistribution into food-web assessments, especially for open systems like the North Sea. Finally, closer alignment between ecological indicators and policy thresholds would benefit from using concrete case studies to translate international objectives into clearer, spatially defined national targets. Together, these steps can improve both ecological understanding and the practical relevance of food-web indicators for ecosystem-based management.

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Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system, certified since February 27, 2001 by DNV. ISO 9001 is an international standard for quality management, focused on the continuous improvement of processes and ensuring customer satisfaction.

The quality of all test methods used at the chemical and benthos laboratory of Wageningen Marine Research is guaranteed in various ways:

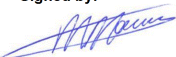
- First-line control: Control samples are taken with each series of measurements to immediately verify correctness and accuracy.
- Second-line control: An independent internal check is carried out by a colleague to provide additional assurance of calculations, input, and plausibility.
- Third-line control: The accuracy of analysis methods is regularly tested externally through participation in interlaboratory tests or proficiency tests.

Information on the performance characteristics of analytical methods are available from the laboratory upon request. In the event of uncontrolled quality, appropriate corrective measures will be taken.

Justification

Report: C064/26
Project Number: 4318100479

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

Approved:	Ralf van Hal Researcher
Signature:	<div><div>Signed by:</div><div></div><div>F03A265A9CBA46C...</div></div>
Date:	25 September 2026
Approved:	A.M. Mouissie, PhD Business Manager Projects
Signature:	<div><div>Signed by:</div><div></div><div>291E7A4CA7DB419...</div></div>
Date:	25 September 2026

Annex 1 – Article 5: Restoration of marine ecosystems

From: Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 (Text with EEA relevance) (<https://eur-lex.europa.eu/eli/reg/2024/1991>)

1. Member States shall put in place the restoration measures that are necessary to improve to good condition areas of habitat types listed in Annex II which are not in good condition. Such restoration measures shall be put in place:

(a)

by 2030, on at least 30 % of the total area of groups 1 to 6 of the habitat types listed in Annex II that is not in good condition, as quantified in the national restoration plan referred to in Article 15;

(b)

by 2040, on at least 60 % and, by 2050, on at least 90 % of the area of each of the groups 1 to 6 of the habitat types listed in Annex II that is not in good condition, as quantified in the national restoration plan referred to in Article 15;

(c)

by 2040, on at least two thirds of the percentage referred to in point (d) of this paragraph of the area of group 7 of the habitat types listed in Annex II that is not in good condition, as quantified in the national restoration plan referred to in Article 15; and

(d)

by 2050, on a percentage, identified in accordance with Article 14(3), of the area of group 7 of the habitat types listed in Annex II that is not in good condition, as quantified in the national restoration plan referred to in Article 15.

The percentage referred to in the first subparagraph, point (d), of this Article shall be set so as not to prevent good environmental status, as determined pursuant to Article 9(1) of Directive 2008/56/EC, from being achieved or maintained.

2. Member States shall put in place the restoration measures that are necessary to re-establish the habitat types in groups 1 to 6 listed in Annex II in areas where those habitat types do not occur, with the aim of reaching the favourable reference area for those habitat types. Such measures shall be in place on areas representing at least 30 % of the additional surface needed to reach the favourable reference area for each group of habitat types, as quantified in the national restoration plan referred to in Article 15, by 2030, on areas representing at least 60 % of that surface by 2040, and on 100 % of that surface by 2050.

3. By way of derogation from paragraph 2 of this Article, if a Member State considers that it is not possible to put in place restoration measures by 2050 that are necessary to reach the favourable reference area for a specific habitat type on 100 % of the surface, the Member State concerned may set a lower percentage at a level between 90 % and 100 % in its national restoration plan as referred to in Article 15 and provide adequate justification. In such a case, the Member State shall gradually put in place restoration measures that are necessary to achieve that lower percentage by 2050. By 2030, those restoration measures shall cover at least 30 % of the additional surface needed to achieve such lower percentage by 2050, and by 2040, they shall cover at least 60 % of the additional surface needed to achieve such lower percentage by 2050.

4. If a Member State applies the derogation pursuant to paragraph 3 to specific habitat types, the obligation set out in paragraph 2 shall apply to the remaining additional surface needed to reach the favourable reference area of each group of habitat types listed in Annex II to which those specific habitat types belong.

5. Member States shall put in place restoration measures for the marine habitats of species listed in Annex III to this Regulation and in Annexes II, IV and V to Directive 92/43/EEC and for the marine habitats of wild birds falling within the scope of Directive 2009/147/EC that are, in addition to the restoration measures referred to in paragraphs 1 and 2 of this Article, necessary to improve the quality and quantity of those habitats, including by re-establishing them, and to enhance connectivity, until sufficient quality and quantity of those habitats is achieved.

6. The determination of the most suitable areas for restoration measures in accordance with paragraphs 1, 2 and 5 of this Article shall be based on the best available knowledge and the latest technical and scientific progress in determining the condition of the habitat types listed in Annex II to this Regulation and the quality and quantity of the habitats of the species referred to in paragraph 5 of this Article, making use of information reported under Article 17 of Directive 92/43/EEC, Article 12 of Directive 2009/147/EC and Article 17 of Directive 2008/56/EC.

7. Member States shall ensure that the condition is known of the following areas:

(a)

by 2030, for at least 50 % of the area distributed over all habitat types in groups 1 to 6 listed in Annex II;

(b)

by 2040, for all areas of the habitat types in groups 1 to 6 listed in Annex II;

(c)

by 2040, for at least 50 % of the area distributed over all habitat types in group 7 listed in Annex II;

(d)

by 2050, for all areas of the habitat types in group 7 listed in Annex II.

8. The restoration measures referred to in paragraphs 1 and 2 shall consider the need for improved ecological coherence and connectivity between the habitat types listed in Annex II and take into account the ecological requirements of the species referred to in paragraph 5 that occur in those habitat types.

9. Member States shall put in place measures which shall aim to ensure that the areas that are subject to restoration measures in accordance with paragraphs 1, 2 and 5 show a continuous improvement in the condition of the habitat types listed in Annex II until good condition is reached, and a continuous improvement of the quality of the habitats of the species referred to in paragraph 5, until the sufficient quality of those habitats is reached.

Without prejudice to Directive 92/43/EEC, Member States shall put in place measures which shall aim to ensure that areas in which good condition has been reached, and in which the sufficient quality of the habitats of the species has been reached, do not significantly deteriorate.

10. Without prejudice to Directive 92/43/EEC, Member States shall, by the date of publication of their national restoration plans in accordance with Article 17(6) of this Regulation, endeavour to put in place necessary measures with the aim of preventing significant deterioration of areas where the habitat types listed in Annex II to this Regulation occur and which are in good condition or are necessary to meet the restoration targets set out in paragraph 14 of this Article.

11. Outside Natura 2000 sites, the obligation set out in paragraph 9 shall not apply to deterioration caused by:

(a)

force majeure, including natural disasters;

(b)

unavoidable habitat transformations which are directly caused by climate change;

(c)

a plan or project of overriding public interest for which no less damaging alternative solutions are available, to be determined on a case by case basis; or

(d)

action or inaction by third countries for which the Member State concerned is not responsible.

12. Outside Natura 2000 sites, the obligation set out in paragraph 10 shall not apply to deterioration caused by:

- (a)
force majeure, including natural disasters;
- (b)
unavoidable habitat transformations which are directly caused by climate change;
- (c)
a plan or project of overriding public interest, for which no less damaging alternative solutions are available;
or
- (d)
action or inaction by third countries for which the Member State concerned is not responsible.

13. Within Natura 2000 sites, the non-fulfilment of the obligations set out in paragraphs 9 and 10 is justified if it is caused by:

- (a)
force majeure, including natural disasters;
- (b)
unavoidable habitat transformations which are directly caused by climate change; or
- (c)
a plan or project authorised in accordance with Article 6(4) of Directive 92/43/EEC.

14. Member States shall ensure that there is:

- (a)
an increase of the area in good condition for habitat types of groups 1 to 6 of the habitat types listed in Annex II until at least 90 % is in good condition and until the favourable reference area for each habitat type in each biogeographic region of the Member State concerned is reached;
- (b)
an increase of the area in good condition for habitat types of group 7 of the habitat types listed in Annex II until at least the percentage, referred to in paragraph 1, first subparagraph, point (d), is in good condition and until the favourable reference area for each habitat type in each biogeographical region of the Member State concerned is reached;
- (c)
an increasing trend towards the sufficient quality and quantity of the marine habitats of the species listed in Annex III to this Regulation and in Annexes II, IV and V to Directive 92/43/EEC and of the species falling within the scope of Directive 2009/147/EC.

Annex 2 – Modelling frameworks for marine food webs

A widely used ecosystem modelling framework for studying food webs is **Ecopath with Ecosim (EwE)**. This tool can quantify energy and biomass flows within marine food webs and simulate their dynamics under different pressures. It combines a mass-balance “snapshot” model (Ecopath) with time-dynamic simulations (Ecosim), which allows for testing scenarios such as changes in fishing pressure, nutrient inputs, species recovery, or climate forcing. Its main usefulness lies in supporting ecosystem-based management by helping to evaluate trade-offs between fisheries yield and biodiversity conservation, assess indirect trophic effects, estimate ecosystem overfishing, and derive food-web indicators relevant to policies such as the EU Marine Strategy Framework Directive (Christensen and Walters, 2004; Heymans et al., 2016). EwE is particularly valuable as a decision-support tool because it integrates multiple species and pressures into a coherent system framework, enabling risk-based advice rather than single-species assessments alone.

EwE has an available plug-in called ECOIND (Ecological Indicators) that standardizes the calculation of many ecological and food-web indicators directly from EwE models (Coll and Steenbeek, 2017). It has been applied in a number of peer-reviewed studies to derive quantitative indicators of ecosystem structure and function. The Indicators derived by ECOIND are directly relevant for assessments of food webs for MSFD (Keramidas et al., 2023).

EwE applied in the Southern Bight of the North Sea

A food-web model of the Southern Bight of the North Sea was developed based on the year 1991, including 43 functional groups and commercial as well as recreational fisheries fleets (Pint et al., 2024). Although MSFD indicators are not mentioned explicitly, ecological and fishing indicators that are commonly used for ecosystem assessment are discussed.

Among the ecological food-web indicators used are Total System Throughput (TST; sum of all flow rates of energy or material in units of mass or energy per area per time, thereby a measure of the “energetic size” or “metabolic rate” of the food web), Primary production/TST (PP/TST), Mean Trophic Level of the Community (mTLco; used in OSPAR assessments), Finn’s Cycling Index (FCI; gives a fraction of the total flow of energy that is recycled), and System Omnivory Index (SOI; average variability of trophic levels in a food web where higher values indicate complex, food webs with many feeding interactions, and low values suggest linear, less resilient systems).

Ecological Network Analysis (ENA) is a set of analytical metrics applied to flow networks (often food-web models) to understand system structure, organization, and cycling.

ENA can provide multiple indices to quantify core properties of ecosystems (Schückel 2022; Belgrano & Tomczak, 2025). EwE is therefore complementary with ENA, as EwE can generate the flow matrices, and ENA can analyze them. One group of food-web indicators obtained by ENA depend on time series data, i.e. that the data in the matrix of the food web with connections of nodes is available for many time steps (often year by year), so that indicators capturing change and (in/)stability of the food web can be obtained. Although ENA is often used by applying time series data to track how such network properties change over time, ENA does not necessarily require time series and can, as EwE, be applied to a single steady-state snapshot relevant for a subset of the indicators.

ENA applications

Ecological Network Analysis (ENA) was applied to reconstruct and compare historical food webs of intertidal benthic communities in Jade Bay (German Wadden Sea), showing how ecosystem structure, energy flows, and organization changed in response to long-term climatic variability and human pressures. Results showed

that while the system increased in size and internal 'energy efficiency' over time, the reduction in parallel trophic pathways suggested a loss of trophic diversity and buffering capacity, reducing the ability of the food web to withstand disturbances despite apparent gains in organization (Schückel et al., 2015).

In a study of the Baltic Sea a food-web model and ENA were used to examine how climate change and fishing pressure drove a major regime shift in the central Baltic Sea after the 1970s, marked by a reorganization of energy flows through the ecosystem. Results showed that from the late 1980s the food web became more linear and less resilient, indicating a reduced ability to buffer the impacts of environmental variability and disturbances, despite that the system remained in an alternative ecological state (Tomczak et al., 2013).

In a recent example a combination of EwE and ENA is applied for a heavily utilized temperate marine embayment (Cockburn Sound, Australia), to help understand ecosystem processes for evaluating future development, impacts, and climate change effects (Hector et al., 2025). An EwE/Ecosim food-web model was developed, and ENA was used to characterize trophic structure and identify keystone species. The analyses produced 35 indicators across five categories (biomass-based, ecosystem-level, energy use, fisheries, and conservation) that quantify the state and functioning of the food web. Thereby the food-web model and ENA outputs provided quantitative tools for assessing ecosystem responses to anthropogenic pressures which effectively could support ecosystem-based management decisions. Key ENA-generated indicators from this study were Total System Throughput (TST), Transfer efficiencies (enables comparison of energy flow patterns for different trophic levels), Keystone indices (critical species like small sharks and sea lions), and Mixed Trophic Impacts (quantifies indirect effects, e.g. how large sharks positively affect small pelagics by controlling their predators). When comparing outcomes of ENA indicators across different Australian systems revealed that Cockburn Sound had the highest System Omnivory Index (SOI; average variability of trophic levels in a food web) indicating a higher complex trophic organization (Hector et al., 2025).

The **ECOIND plug-in** for Ecopath with Ecosim was developed to calculate standardized ecological indicators from food-web models and has been applied in both temporal and spatial ecosystem assessments (Coll and Steenbeek, 2017). It can calculate a wide suite of food-web and ecosystem indicators, grouped into biomass-based indicators (e.g. demersal/pelagic partitioning), trophic indicators, size-based indicators, and species-based indicators (e.g. IUCN-listed species), and vulnerability and trait-based indicators linking species traits to fishing pressure and ecosystem sensitivity. A 2023 review of Ecotrophic perspectives in European marine ecosystems also lists several applications of ECOIND in EU Seas (e.g., Mediterranean, North Sea, Bay of Biscay) and shows how its indicators have been used in both static and spatio-temporal analyses of food webs.

Annex 3 – Detailed table of categorized indicators (WKFOODWEB)

The Table A3.1. contains indicators presented at WKFOODWEB (ICES, 2025a); whether used for reporting to management (or not; marked in grey), corresponding national research institutes working on them, and links to the MSFD food-web criteria with related indicators and relevance/feasibility for showing different pressures (1 = low → 4 = high). In columns “Complex → Simple (1-4)” to “Other” (left to right), the numbers 1-4 are also illustrated by colours (red, orange, yellow, green) in a gradient from 1=red to 4=green.

Table A3.1. Indicators presented at WKFOODWEB (ICES, 2025a); whether used for reporting to management (or not; marked in grey), corresponding national research institutes working on them, and links to the MSFD food-web criteria with related indicators and relevance/feasibility for showing different pressures (1 = low - → 4 = high).

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)	Data difficult → easily available (1-4)	Number of trophic levels included (few to more 1-4)	Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
Y	Zooplankton mean size	Evaluates the zooplankton community structure (including GES). Good status = large-bodied zooplankton (older stages of calanoid copepods and adult cladocerans) are abundant. Reflects eutrophication and food-web interactions (abundance of planktivores).	C1	C2			C1-FW5 Diversity (plankton) C2-FW7 Abundance balance (guilds)	C1 & C2: Yes (OSPAR) - International North Sea 1960-2019.	FW5: Trends related to pressures FW7: Trends (OSPAR).	3	2	2	4	3	4	4	4	1	1	2		
Y	Kinneret Sustainability Index	Measures Divergence to desired state	C1	C2			C1-FW5 Diversity (plankton) C2-FW7 Abundance balance (guilds)	(Irrelevant - used for one freshwater system.)	System specific (defined desired state)	2	2	2	2	2	4	4	4	1	1	1		
Y	Zooplankton indicators	Changes in phytoplankton biomass and zooplankton abundance	C1	C2			C1-FW5 Diversity (plankton) [C2-FW7 Abundance balance (guilds)]	C1 & C2: Yes (OSPAR) - Int. North Sea 1960-2019.	FW5: Trends related to pressures FW7: Trends (OSPAR).	3	3	2	4	3	4	1	4	1	1	2		

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)	Data difficult → easily available (1-4)	Number of trophic levels included (few to more 1-4)	Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
N	Trophic indicator: high trophic level indicator (HTI) and the apex predator indicator (API)	Proportion of predators within the food web <i>and</i> proportion of apex predators among predators		C2			C2-FW7 Abundance balance (guilds)	C2: Yes (OSPAR) - Int. North Sea 1997-2020.	FW7: Trends (OSPAR).	4	3	2	4	3	4	4	2	1	1	3		
N	Ocean Productivity available to Fish (OPFish)	Zooplankton relative production, Potential fish production, relative energy flow along marine food webs comparable in space and time. Remote sensing of ocean colour, frequency and intensity of horizon gradients of chlorophyll-a weighted by relative day length.	C1			C4	C1-FW5 Diversity (plankton) C4-FW2 Productivity of phytoplankton	C1: Yes (OSPAR) - Int. North Sea 1960-2019. C4: So far pilot. Int. North Sea 2015-2019.	FW5: Trends related to pressures FW2: Trends (OSPAR).	2	1	4	2	2	4	2	4	1	1	2		
Y	Stomach content analysis (SCA)	Biomass of prey (fish and cephalopods) eaten by cetaceans	(C1)	C2	(C3)	(C4)	C2-FW7 Abundance balance (guilds) (C2)-FW4 Average trophic level (C1-C4)-FW9 System-ecology indices (e.g. carbon flows)	C2: Yes (OSPAR) - Int. North Sea 1997-2020.	FW7: Trends (OSPAR). FW4: - FW9: -	4	1	3	4	3	4	4	4	4	1	3		

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)	Data difficult → easily available (1-4)	Number of trophic levels included (few to more 1-4)	Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
Y	ITA (Integrated Trophic Analysis - whole system)	Integrated trend analysis - analyses how the relative abundance between and within trophic guilds/groups change over time. Can identify state changes and direction of change.		C2		C4	C2-FW7 Abundance balance (guilds) C4-FW2 Productivity of phytoplankton	C2: Yes (OSPAR) - Int. North Sea 1997-2020. C4: So far pilot. Int. North Sea 2015-2019.	FW7: Trend analyses (OSPAR). FW2: Trend (OSPAR).	2	2	3	2	2	4	4	4	1	1	3		
N	Integrated trophic indicators	Primary productivity, Biomass distribution among trophic levels, (Functional groups within trophic levels), Functionally important species and biophysical structures, (Landscape-ecological patterns), Biological diversity, Abiotic factors.	C1	C2	C3	C4	C1-FW5 Diversity (plankton) C2-FW7 Abundance balance (guilds) C3-FC2, FC3, FW3 Size distribution (C2)-FW4 Average trophic level C4-FW2 Productivity of phytoplankton	C1 & C2: Yes (OSPAR) - Int. North Sea 1960-2019. C3: Yes (OSPAR) - Int. North Sea 1996 / 2016-2020. C4: So far pilot (OSPAR) - Int. North Sea 2015-2019.	FW5: Trends related to pressures. FC2: (LFI) Threshold. FC3, FW2, FW3, FW4, FW7: Trends (OSPAR).	1	1	4	1	2	4	4	4	2	2	4		
Y	ICES F _{eco}	Ecosystem based fishing reference point		C2		C4	C2-FW7 Abundance balance (guilds) C4-FW2 Productivity of phytoplankton	C2: Yes (OSPAR) - Int. North Sea 1997-2020. C4: So far pilot. Int. North Sea 2015-2019.	FW7: Trends (OSPAR). FW2: Trends (OSPAR).	4	2	3	3	3	4	4	3	1	1	3		

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)	Data difficult → easily available (1-4)	Number of trophic levels included (few to more 1-4)	Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
N	Ecological indicators included in ECOIND	Biomass, catch and ratios of specific groups (e.g., pelagic/demersal, fish/invertebrates, predator/forage fish)	C2			C4	C2-FW7 Abundance balance (guilds) C4-FW2 Productivity of phytoplankton	C2: Yes (OSPAR) - Int. North Sea 1997-2020. C4: So far pilot. Int. North Sea 2015-2019.	FW7: Trends (OSPAR). FW2: Trends (OSPAR).	4	3	3	3	3	4	4	4	2	1	4		
Y	Trophic indices	Mean trophic level (MTL) of the community, Mean trophic index (MTL of community of species with TL >3.25)	C2				C2-FW7 Abundance balance (guilds) (C2)-FW4 Average trophic level	C2: Yes (OSPAR) - Int. North Sea 1997-2020.	FW7: Trends (OSPAR). FW4: -	2	2	3	3	3	4	4	4	4	1	3		
N	Mean Life Span index	Mean maximum age of the community. This is a proxy for mean turnover rate of species and communities			C3	(C4)	Variant C3-FC2, FC3, FW3 Size distribution Proxy (partial) for C4-FW2 Productivity of phytoplankton	C3: <i>Indirectly by length</i> (OSPAR) - Int. North Sea 1997-2020.	FC2: (LFI) Threshold. FC3, FW3 & FW2: Trends (OSPAR).	4	3	3	3	3	4	4	4	1	1	2		
Y	Length-based indicators (LBI)	Express changes in size of fish across the community as a measure of impact on the overall community			C3		C3-FC2, FC3, FW3 Size distribution	C3: Yes (OSPAR) - Int. North Sea 1997-2020.	FC2: (LFI) Threshold. FC3, FW3: Trends (OSPAR).	4	4	3	3	4	4	4	2	1	1	2		
Y	Size composition	Mean size and/or size distribution in fish communities			C3		C3-FC2, FC3, FW3 Size distribution	C3: Yes (OSPAR) - Int. North Sea 1997-2020.	FC2: (LFI) Threshold. FC3, FW3: Trends (OSPAR).	4	4	3	4	4	4	4	3	1	1	3		

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)	Data difficult → easily available (1-4)	Number of trophic levels included (few to more 1-4)	Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
N	Biomass spectrum	Continuous integrated biomass across trophic levels		C2	C3		C2-FW7 Abundance balance (guilds) C3-FC2, FC3, FW3 Size distribution	C2 & C3: Yes (OSPAR) - Int. North Sea 1997-2020.	FW7: Trend analyses (OSPAR). FC2: (LFI) Threshold. FC3, FW3: Trends (OSPAR).	2	2	4	3	3	4	4	2	1	1	2		
Y	Status and trends of key species	Biomass of e.g. key-stone spp, important predators etc.		C2			C2-FW7 Abundance balance (guilds)	C2: Yes (OSPAR) - Int. North Sea 1997-2020.	FW7: Trend analyses (OSPAR).	4	3	1	4	3	4	4	2	1	1	4		
Y	Biomass ratios	Ratios of biomass between key compartments of the ecosystem (pelagic/demersal, fish/invertebrates, predator/forage fish)		C2			C2-FW7 Abundance balance (guilds)	C2: Yes (OSPAR) - Int. North Sea 1997-2020.	FW7: Trend analyses (OSPAR).	3	2	3	3	3	4	4	2	1	1	2		
N	Productivity of seabirds (or other charismatic megafauna)	How many chicks are fledged annually, per pair, clutch or nest; complement to assessment of marine bird abundance; see OSPAR QSR 2023.				C4	C4-FW2 Productivity of phytoplankton	Assessed under D1 (Biodiversity) as Marine Bird Breeding Productivity (D1C3-B3).	Species-specific threshold values.	3	1	2	3	2	3	3	3	3	1	3	3	e.g. Breeding habitat (D1C5-D7)
N	Marine bird abundance	Numbers of adult birds in the non-breeding season or pairs at breeding colonies				C4	C4-FW2 Productivity of phytoplankton	Assessed under D1 (Biodiversity) as Marine bird abundance (D1C3-B1).	Trends.	4	2	2	4	3	2	3	3	3	1	3	3	e.g. Breeding habitat (D1C5-D7)

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)		Data difficult → easily available (1-4)		Number of trophic levels included (few to more 1-4)		Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
Y	Primary productivity					C4	C4-FW2 Productivity of phytoplankton	C4: So far pilot (OSPAR) - Int. North Sea 2015-2019.	(Trends.)	3	3	1	4	3	4	2	4	1	1	2					
N	Trophic level and source of carbon by stable isotopes analysis (SIA)	d15N and d13C estimates indicate trophic level of a species, its source of carbon (terrestrial vs. marine, benthic vs. pelagic) but also habitat use (coastal vs. offshore)		(C2)		C4	(C2)-FW4 Average trophic level C4-FW2 Productivity of phytoplankton			1	1	4	2	2	4	4	4	4	1	3					
Y	Fishing-in-Balance (FIB) index	FIB: Increasing if catches increase faster than predicted by trophic level declines, and decreasing if increasing catches fail to compensate for a decrease in trophic level. Useful to evaluate environmental status by combining descriptors.		(C2)			(C2)-FW4 Average trophic level			3	2	3	2	3	4	4	4	4	1	3					
Y	Stable isotopes analysis	Analysis of the trophic chain to estimate the realized food assimilation		(C2)			(C2)-FW4 Average trophic level	No. (Possibly for reporting Q1 2028.)		2	1	4	2	2	4	4	4	4	1	3					
N	Cumulative biomass theory (indicators related to	Cumulative biomass response to increasing trophic levels describes a specific s-shape, which respond	(C1)	(C2)	(C3)	(C4)	(C1-C4)-FW9 System-ecology indices (e.g. carbon flows)			1	1	4	2	2	4	1	4	1	1	4					

Directly used in management Y/N	Indicator	Description	MSFD Criteria represented				Corresponds to MFSD D4 Criteria (C1-C4) & food-web indicator FW no.	Already assessment of Dutch part of the North Sea (Yes / No)	GES – Threshold value / Trends	Complex → Simple (1-4)	Data difficult → easily available (1-4)	Number of trophic levels included (few to more 1-4)	Easy to grasp (1-4)	Average score	Climate change	Fisheries	Eutrophication	Invasive species	Toxicants	Indirect via food-web interactions	Other	Specified
	stability and resilience)	to perturbation in a repeatable way						No	No													
N	Topological/centrality indices (e.g., node degree, weighted importance, trophic level etc.)	Indicate the position and importance of a node in a network (i.e. the importance of a species or trophic guild) for the structural integrity of the network	(C1)	(C2)	(C3)	(C4)	(C1-C4)-FW9 System-ecology indices (e.g. carbon flows)			1	1	3	1	2	4	1	4	1	1	4		
(Y)	"Ecological Network Analyses (ENA) indicators"	Indicators of energy flow, structure, function, and evolution of ecosystems	(C1)	(C2)	(C3)	(C4)	(C1-C4)-FW9 System-ecology indices (e.g. carbon flows)			1	1	4	2	2	4	1	4	1	1	4		
Y	Topological indicators based on community biomasses	For example, mean trophic level of the community	(C1)	(C2)	(C3)	(C4)	(C1-C4)-FW9 System-ecology indices (e.g. carbon flows)			3	2	3	2	3	4	1	4	1	1	4		
N	Topological indicators based on binary networks	Represent the structure of the community based on the binary network of connections. They can be calculated at the community level or at the node level	(C1)	(C2)	(C3)	(C4)	(C1-C4)-FW9 System-ecology indices (e.g. carbon flows)			1	1	3	1	2	4	1	4	1	1	4		

To explore
the potential
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improve the
quality of life



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