Witteveen + Bos



Explorative study of changes on higher trophic levels

Ecological numerical modelling of how changing primary production patterns caused by offshore windfarms may affect the North Sea ecosystem

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1

Introduction

1.1 Background

Following the ambitious targets set by the Dutch government for the development of offshore wind farms (henceforth: OWFs), it is essential to have a clear understanding of the environmental effect of OWFs on protected species and the ecosystem. Wozep (acronym for the Dutch program: *Wind op zee ecologisch programma)* is an integrated research program which aims to resolve some of these knowledge gaps. As part of Wozep, multiple numerical modelling studies investigated how the development of OWFs in the international North Sea may lead to change in abiotic (e.g. temperature stratification, suspended matter) and biotic conditions (e.g. primary production) (van Duren et al., 2021; Zijl et al. 2023; 2024; all executed by Deltares). Knowledge of Wozep feeds into KEC (Framework for Ecology and Cumulation) that provides an assessment tool for calculating cumulative ecological effects of existing and planned OWFs on protected species in the North Sea. Specifically, the introduction of wind turbines alters flow patterns and wave dynamics, which causes abiotic and biotic change, both locally and regionally. For example, the Dutch Continental Shelf model-flexible mesh (DCSM-FM) model shows changes in primary production, chlorophyll-a concentration and plankton biomass, where the degree and direction of change (increase or decrease) varies for different OWF locations on the Dutch North Sea (e.g. Zijl et al. 2024). Yet, the ecological implications of these changes on the functioning of the food web, and specifically populations of protected species, remain largely unknown.

Primary production is seen as the base of any food web. Change in primary production may therefore alter production in other parts of the food web, too. The effects on the food web could translate into effects at the population level of species protected under the Environmental and Planning Act and the Birds and Habitat Directives. Additionally, whilst OWFs will not be developed in Natura 2000 areas, their effects on the food web may affect (the protected species of) Natura 2000 areas.

The intricate interactions within a food web ask for sophisticated conceptual and numerical models that aid in our understanding of the food web. This is especially true for dynamic, open and complex ecosystems such as the North Sea. To pinpoint the extent of an impact, detailed modelling studies are required, which may take up to several years to develop, calibrate and validate. Meanwhile, there is a pressing need in KEC to indicate whether the Deltares results are meaningful in terms of protected species. Whilst it is scientifically an oversimplification to translate the Deltares results directly to effects on higher trophic levels, some models are available that can be used, under certain boundary conditions, to explore this translation.

1.2 Aim

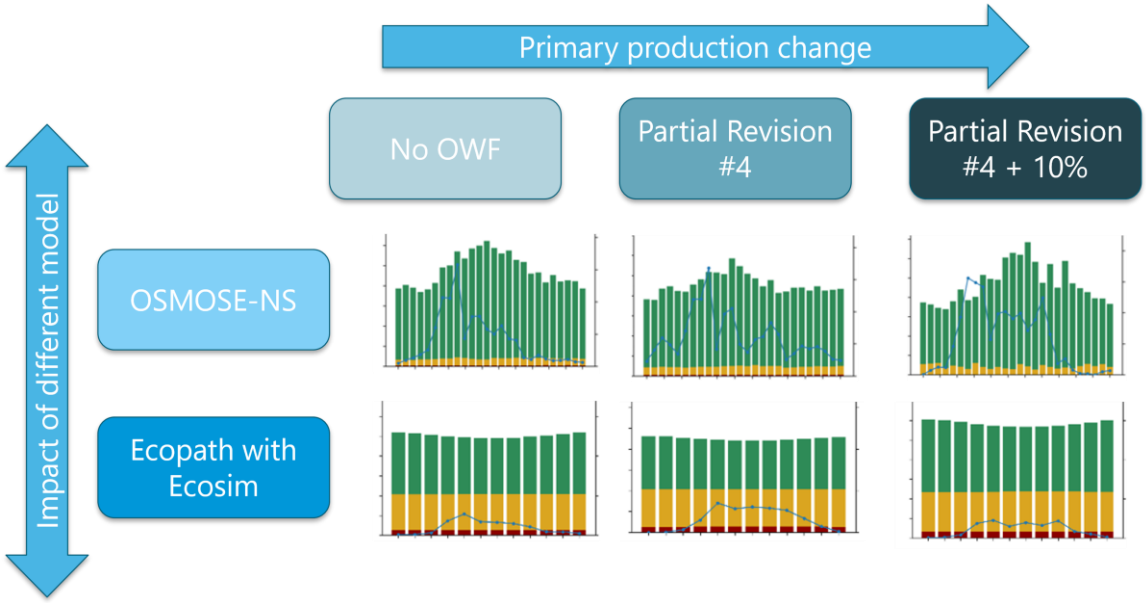
The aim of this modelling study is mainly to determine a first-order bandwidth of ecosystem effects of abiotic change due to offshore wind farms on higher trophic levels, with a focus on (pelagic) fish, and secondary to explore the feasibility of existing models to provide such insights. To this end, two publicly available ecological numerical models were used that had been calibrated and validated for the North Sea in previous studies: Object-Oriented Simulator of Marine Ecosystems (OSMOSE) and Ecopath with Ecosim (EwE). Abiotic changes, altering primary production patterns, as modelled by Deltares, form the input data to this study.

1.3 Scope

This modelling study is the second phase of a two-phase project, limited to exploring the bandwidth of how OWF-driven abiotic change may propagate through the food web to higher trophic levels, with an emphasis on fish. The study does not aim to provide an assessment on the (cumulative) impact of OWFs on protected species in relation to regulatory thresholds. Moreover, this study does not include validation or parameter calibration based on new monitoring data. Model assumptions about e.g. recruitment, growth, diet, migration and mortality were adopted from the existing models already calibrated and validated for the North Sea (Binch et al., 2026; Mackinson & Daskalov, 2007).

This explorative study applies an ensemble approach, in which the combined predictions from multiple models may produce a more accurate and robust result than a single model. A total of three scenarios were investigated, exploring the impact of different changes in primary production on the model results. This study set-up is illustrated in Figure 1.1.

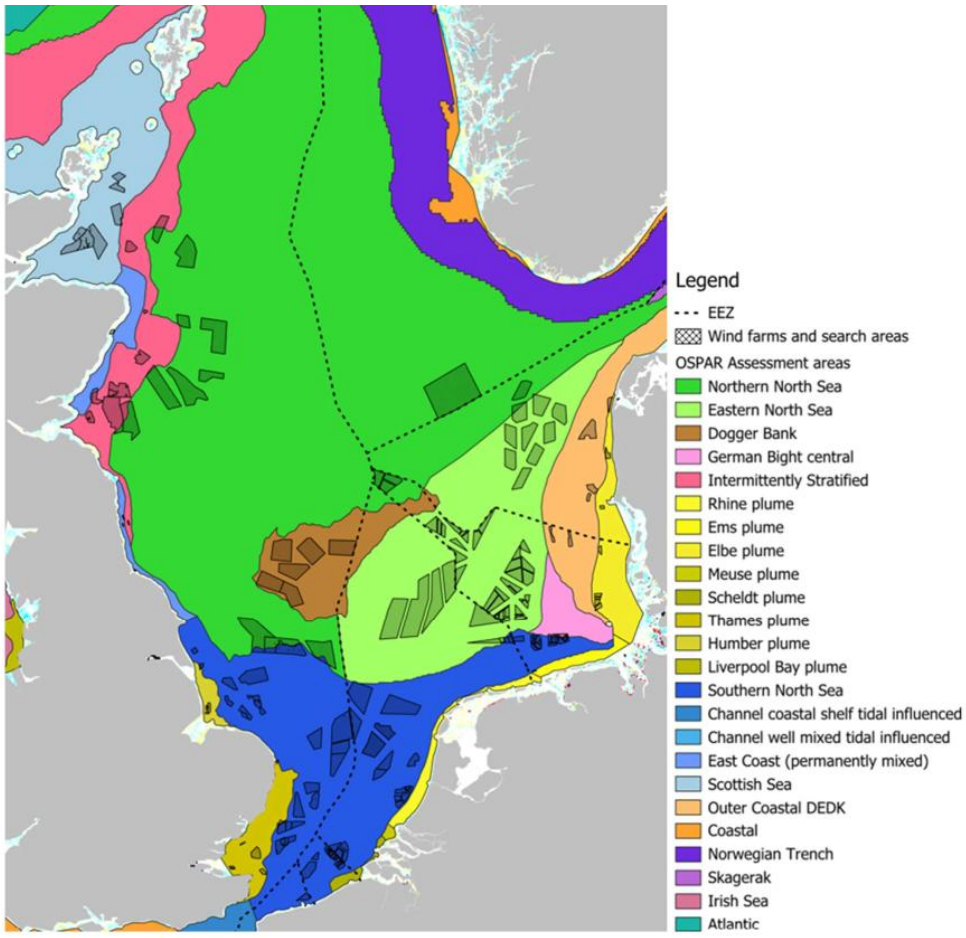
Figure 1.1 Overview of study set-up, with different models (ensemble approach) on the vertical axis and the different scenarios on horizontal axis. Methodology is further detailed in chapter 2. Graphs indicate examples of results. In chapter 3, the model results are provided



Effect areas

OWFs have been developed and are under development on the North Sea. The introduction of these artificial structures has affected and is going to keep affecting the hydrodynamics and primary production patterns on the North Sea. For example, enhanced turbidity due to OWFs may affect nutrient availability and light availability and so, influence primary production. The direction and magnitude of change differ per site, and these changes may propagate further up the food chain. Therefore, this study will aggregate and analyse the propagating effects to higher trophic levels per effect area (Van Duren et al., 2025). In chapter 3, results from the German Bight central, Northern and Southern North Sea are highlighted, as these areas provide distinctive results (Figure 1.2).

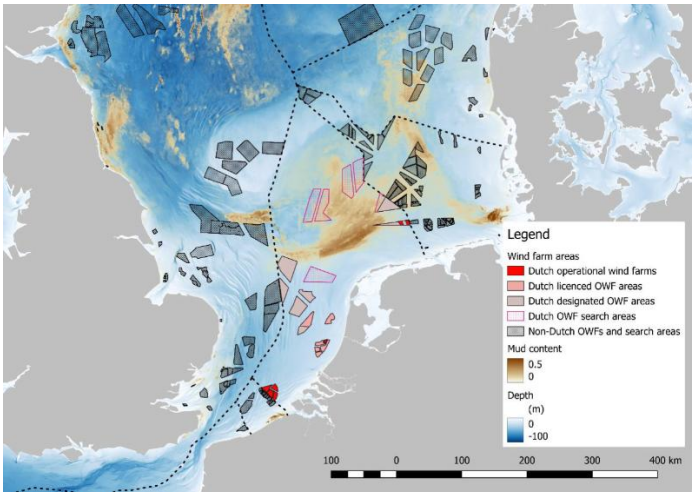
Figure 1.2 The effect areas as defined by Van Duren et al. (2025). These areas have their distinct environmental conditions in terms of hydrodynamics, freshwater influence and sediment composition. Therefore, OWFs will impact the (a)biotic conditions differently



North Sea Program 2022-2027 and the *Partial Revision*

In 2022, the North Sea Program 2022-2027 (in Dutch: Programma Noordzee) came into effect (Ministerie van Infrastructuur en Waterstaat, 2022). This program established, among other aspects, the allocation of offshore energy areas with a total capacity of 10.7 GW to be realised by 2033. However, this does not fulfil the lastest ambition of the Dutch government to develop a total capacity of 23 GW (Routekaart Wind op Zee, version May 2026). Under the *Partial Revision* (in Dutch: Partiële Herziening) of the North Sea Program 2022-2027, additional energy areas were allocated (Ministerie van Infrastructuur en Waterstaat, 2025). A number of studies was conducted as part of the revision process, including a Deltares study (Zijl et al., 2024). They simulated five offshore wind scenarios, with varying total capacity, turbine capacity and spatial layout. Based on present-day market conditions and governmental ambitions, this explorative study assumes scenario 4 (24 GW total capacity, Figure 1.3). For additional background, the reader is referred to Zijl et al. (2024).

Figure 1.3 Layout offshore windfarms of the scenario Partial Revision 4, with bathometry and mud content as background. The status of wind farms and search areas outside the Netherlands is not differentiated (Zijl et al., 2024)



1.4 Reading guide

Chapter 2 describes the functionality of the two ecological numerical models that were used in this study, presents the necessary preprocessing steps of the Deltares data and ends with an overview of modelled scenarios (based on a baseline without OWF and the *Partial Revision 4*). Chapter 3 presents the main model results. This report wraps up with a discussion (chapter 4) on (*i*) the ecological implications of the model outcomes of the two models, and; (*ii*) their usefulness in determining a bandwidth of effects of how changes in primary production may propagate to higher trophic levels.

2

Methodology

2.1 Introduction

This chapter introduces the two ecological numerical models that were used to assess the potential effects of offshore wind farms (OWFs) on higher trophic levels (section 2.2). This includes a brief explanation of how these two models differ in their simulation of the behaviour of individual species and the food web dynamics, the model scenarios are listed in section 2.4. Appendix I presents the preprocessing steps that were taken to prepare the Deltares output (Zijl et al., 2024) as suitable input files for both models.

2.2 Ecological models

This study used two ecological numerical models to find a bandwidth of effects of how changes in primary production patterns due to OWFs translates to the spatial distribution and biomass of higher trophic levels on the North Sea. These models are:

- Object-oriented Simulator of Marine Ecosystems (OSMOSE), and;
- Ecopath with Ecosim (EwE).

For both models, an existing calibrated and validated model was adopted from scientific literature for the extent of the North Sea (suffix: '-NS'). Section 2.2.1 details the functionality of OSMOSE-NS (by Binch et al., 2026). Section 2.2.2 presents the functionality of EwE-NS (by Mackinson & Daskalov, 2007). Key similarities and differences between these models are listed in section 2.2.3.

2.2.1 OSMOSE-NS

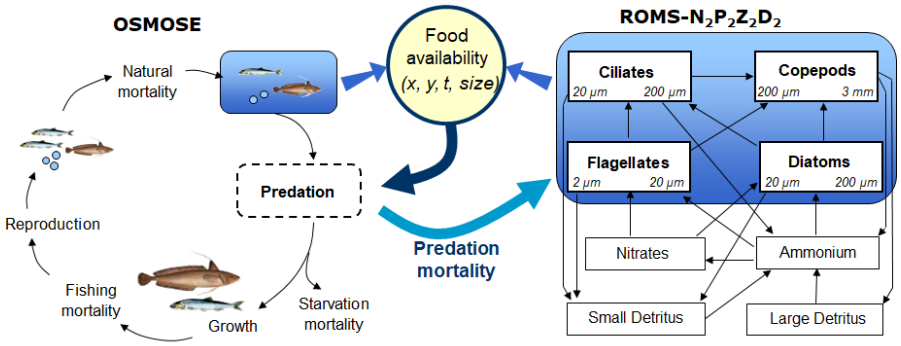
What is OSMOSE?

OSMOSE is a multispecies and individual-based (IBM) spatial model that is based on opportunistic predation (Figure 2.1). The model was ordinally developed in 2001 to investigate the dynamics of exploited marine fish communities (Shin & Cury, 2001). It models the full life cycle of multiple species, encompassing development from the egg stage, growth, reproduction and migration to mortality (predation, starvation, other natural circumstances and fishing). The basic unit of this model is a **super-individual** representing a school of organisms of the same length, weight and age and belonging to the same species (Scheffer et al., 1995). These schools feed on lower trophic levels and on other fish through opportunistic predation, based on spatio-temporal co-occurrence and size adequacy between a predator and its prey. Because of this opportunism, no a priori food web or diet matrix is set, but they emerge from local trophic interactions.

OSMOSE requires input on biomass of five lower trophic level (LTL) groups: microzooplankton, mesozooplankton, meiofauna, suspension feeders and deposit feeders. OSMOSE does not explicitly simulate the dynamics of these LTL groups or the environmental processes that determine food availability. Instead, it relies on external forcing from coupled biogeochemical or lower trophic level models to represent the availability of resources. These coupled models can include physical and biogeochemical processes such as hydrodynamics, nutrient cycling, primary production, and plankton dynamics.

Examples include hydrodynamic–biogeochemical models such as ROMS-based systems or the European Regional Seas Ecosystem Model (ERSEM) (Butenschön et al., 2016), which simulate processes such as nutrient availability (e.g., nitrogen and ammonium), phytoplankton growth, zooplankton production, microbial processes, and the distribution of lower trophic organisms such as ciliates and other plankton groups. For this study, the Deltares data of phytoplankton production was taken as input for OSMOSE, thus replacing the input that was previously provided by the ERSEM model (see section 2.3).

Figure 2.1 Schematic representation of the OSMOSE model (left part) (source: OSMOSE 2026)



Model specification

Spatial and temporal settings

The model OSMOSE-NS by Binch et al. (2026) is a validated model of the North Sea, which was built upon in this study. OSMOSE-NS adopts a grid format where cells correspond to 1/9 of an ICES Statistical Rectangle (ISR). This translates to grid cells ranging approximately 20 km longitude by 18.5 km latitude. The grid is 63 cells high (51°N to 61.5°N) by 39 cells wide (4°W to 9°E). The default model operates with a two-week timestep for a total of 26 timesteps per year.

Species

A total of fourteen fish species is included in OSMOSE-NS, each with individual-specific properties, including: growth, mortality, food constraints, reproduction, distribution map and fishery interactions. In addition, general information is given on food web interactions. This is a crucial element in OSMOSE-NS, which includes a diet matrix that prescribes which species act as a food source for a particular species. The diet matrix only prescribes who may be eaten by whom, but actual predation only occurs if size adequacy between predator and prey is met in the same grid cell. This study adopts the parameter settings used in OSMOSE-NS (Binch et al., 2026). This includes assumptions on the accessibility of lower trophic levels to fish, i.e. the ratio of plankton biomass per grid cell that is accessible to the different fish species. In OSMOSE-NS, micro- and mesozooplankton form one group, and deposit feeders, suspension feeders and meiofauna form another group.

Modelled behaviour of a super-individual

A list of key functions of the model are provided below (Shin & Cury, 2001; Van De Wolfshaar et al., 2021; Von Bertalanffy, 1957):

- *mortality of a super-individual* occurs when the number of individuals belonging to that super-individual has dropped to zero due to mortality processes;
- *recruitment* is the introduction of new super-individuals following species-specific spawning events, where the number of new recruits depends on the total weight of mature biomass;
- *movement of super-individuals* follows a random walk to a neighbouring cell that fits within the life-stage-specific spatial range of the species;
- *interaction of super-individuals* happens if multiple super-individuals are present in the same cell;
- *opportunistic predation* occurs when the size range of the other species is suitable for consumption;
- *growth of super-individuals* follows if sufficient energy was obtained from predation. Insufficient gain of energy by predation limits growth to zero and may cause starvation;

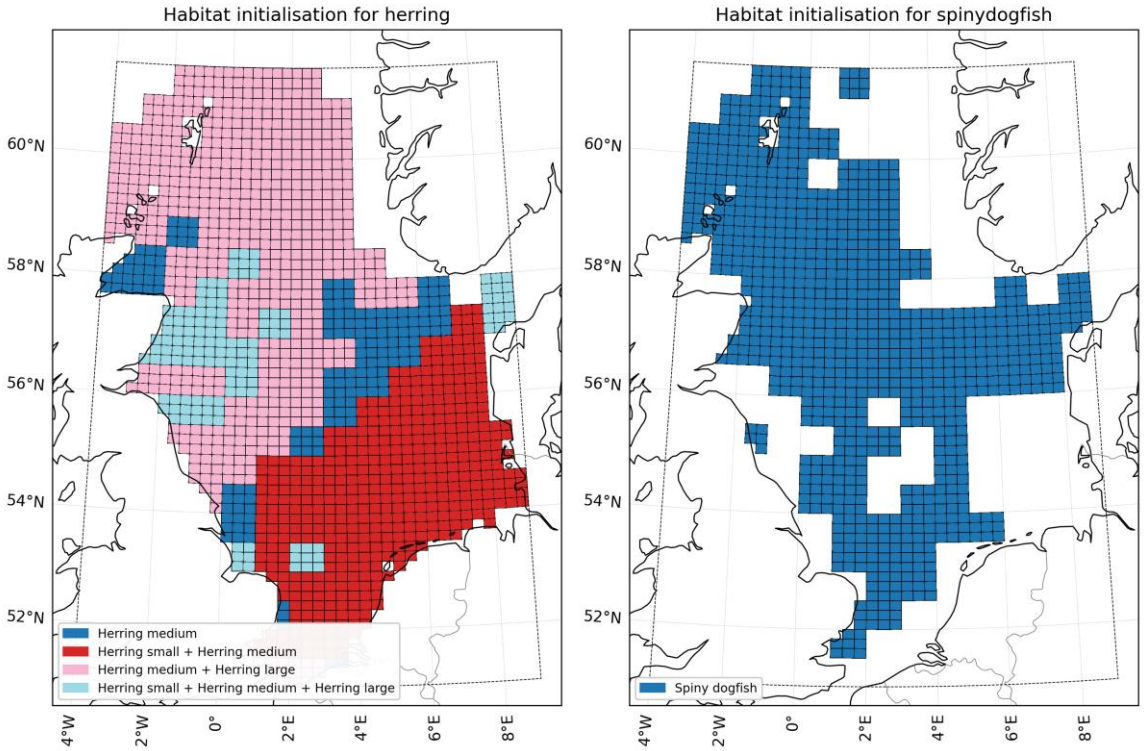
- *lower trophic level (LTL)* resources, representing plankton and macroinvertebrates, are not modelled dynamically within OSMOSE-NS. Instead, they are provided through a one-way coupling with an LTL model and updated each time step.

Model input requirements

The main model inputs to OSMOSE-NS are:

- species-specific biological parameters (see 'modelled behaviour of a super-individual');
- predation parameters (see 'modelled behaviour of a super-individual');
- spatial distribution maps, including an initial distribution map per species. Figure 2.2 shows two examples of the habitat initialisation. For this study, the OSMOSE-NS configuration of Binch et al. (2026) is applied;
- plankton biomass fields as base of the food web. These can come from a biogeochemical model such as ROMS that then forces the lower trophic level input to OSMOSE-NS. OSMOSE-NS does not allow for direct implementation of phytoplankton biomass (see appendix I.4);
- fishing mortality / catch scenarios per species.

Figure 2.2 Examples of habitat initialisation maps, which forms input for the OSMOSE-NS models, based on (Binch et al., 2026). Left; herring (in different size classes), right; spiny dogfish. Note that initialisation is on a discrete scale, where a coloured cell means 'species can be initialised here' and a white cell means 'species cannot be initialised here'



2.2.2 Ecopath with Ecosim (EwE-NS)

What is EwE?

The Ecopath with Ecosim (EwE) suite combines three software modules (Christensen & Walters, 2004). **Ecopath** is a module that provides a static, mass balance snapshot of an ecosystem's trophic interactions at a specific point in time, which was first released in 1992 (Christensen & Pauly, 1992). It ensures that the production of one group is balanced by the consumption of its predators, fishery catches and other forms of mortality, effectively serving as a mass balance filter for ecosystem data. **Ecosim** is a time-dynamic simulation module that uses the mass-balanced state from Ecopath to explore how the ecosystem might change over time.

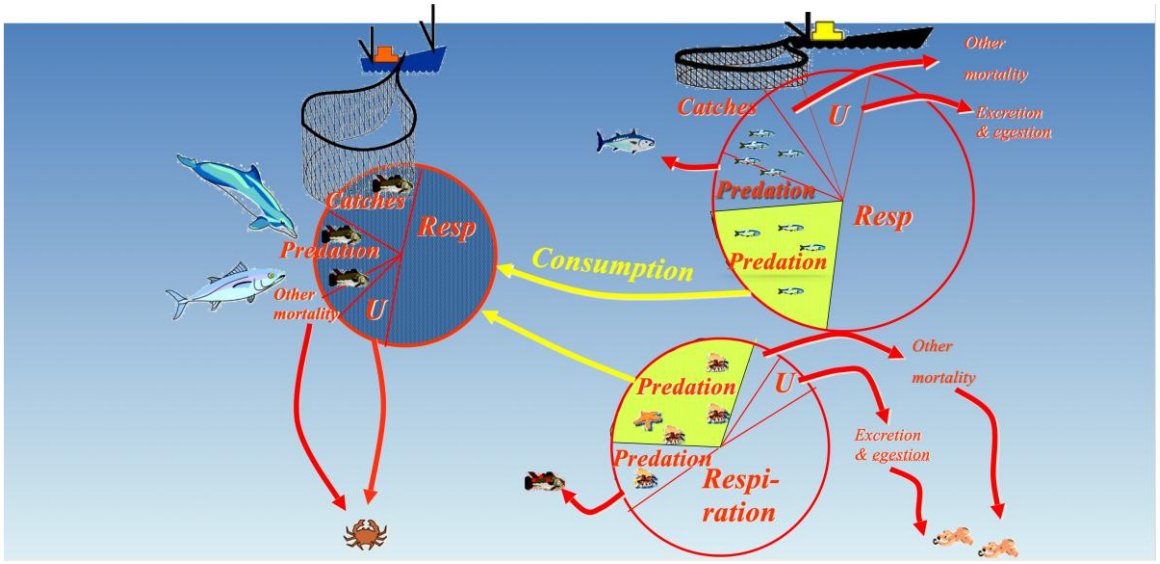
This allows the research of impacts of abiotic and biotic processes (Walters et al., 1997). Finally, **Ecospace** is a module that incorporates a spatial map grid to explore how biomass is distributed across an area (Sinnickson et al., 2021).

The mass balance is governed by two master equations: one for production (balancing between groups) and one for energy balance (balancing within groups). Production describes how the total production of each group is distributed within the system. It is expressed as: Production = Fishery catch + Predation mortality + Net migration + Biomass accumulation + Other mortality. This ensures that 'energy loss' for a prey relates to 'energy gain' for its predators. Once production is balanced between groups, Ecopath ensures that energy is balanced within each individual group using the following equation: Consumption = Production + Respiration + Unassimilated food (Figure 2.3).

Ecopath requires input of three of the following four parameters: biomass, production/biomass ratio (or total mortality), consumption/biomass ratio and ectotrophic efficiency for each of the functional groups in a model. The remaining parameter is then computed by the model.

Ecopath includes tools to address uncertainty during the mass balance process. 'Pedigree Routine' allows users to flag the origin of their data (e.g. direct field measurement or guestimate), based on which Ecopath will assign a confidence interval to help evaluate model quality. 'Ecoranger' is a Monte Carlo resampling routine that draws random variables from user-defined probability distributions to find the most likely balanced state. 'Automated Mass-Balance' is a routine that iteratively perturbs parameters within their confidence intervals to find a balanced state with minimal changes to the most reliable data.

Figure 2.3 Schematic representation of the EwE mass-balance (Christensen & Walters, 2004)



Model specification

Spatial and temporal settings

As a starting point, the balanced North Sea Ecopath model developed by Mackinson and Daskalov (2007) was adopted, which represents the North Sea ecosystem for the reference year 1991. To incorporate temporal dynamics, the Ecopath model was converted into an Ecosim model. The Ecosim model was fitted using historical observations extending from roughly 1973 to 2006 and vulnerability parameters were adjusted until the predicted biomasses matched the observed historical trends. The spatial component was implemented using Ecospace, which extends Ecosim by explicitly representing species distributions and fishing activity across a spatial grid. The model domain encompassed the North Sea (ICES Area IV), covering approximately 570,000 km^2. Habitat maps and species habitat preferences followed the parameterisation of Mackinson and Daskalov (2007).

Before conducting scenario simulations, the Ecospace model was allowed to reach spatial equilibrium so that biomass distributions were consistent with the calibrated Ecosim dynamics and trophic relationships. This initialization produced equilibrium distributions that broadly reflected the long-term spatial patterns of species and fishing activity described by Mackinson and Daskalov (2007).

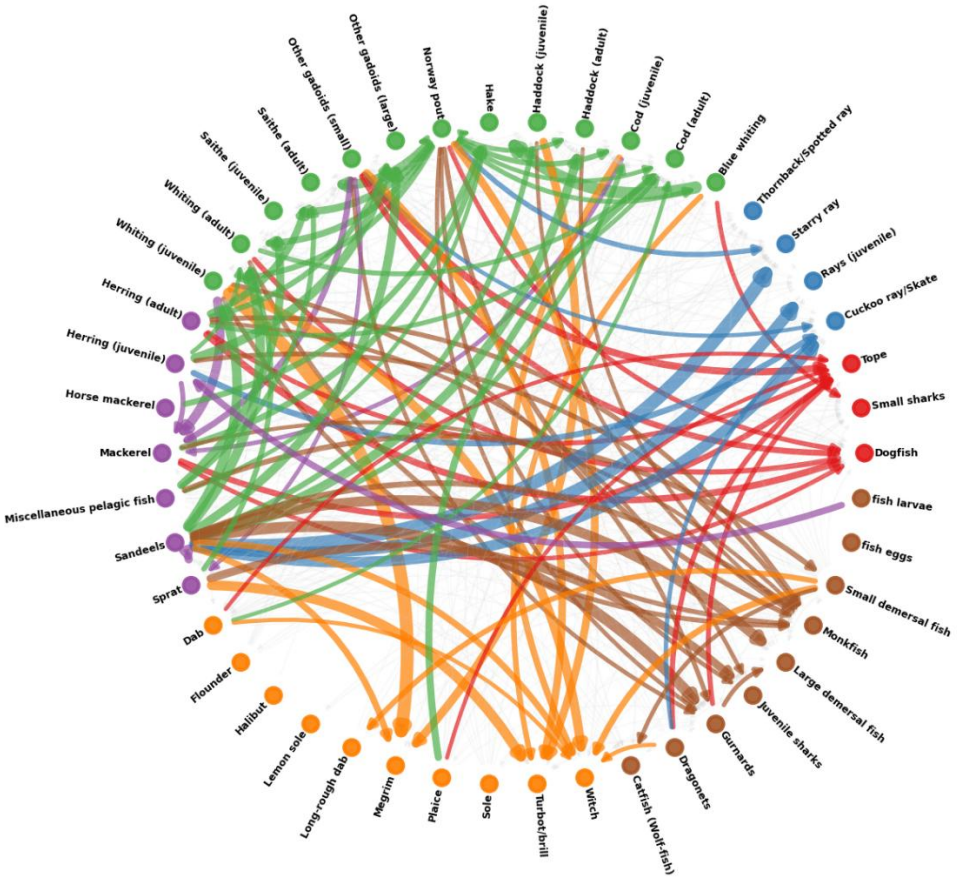
Species

A total of 47 fish groups is included in EwE-NS, including a distinction between juvenile and adult life stages of commercially important target fish species (e.g. cod, herring, saithe, whiting). Different species either constitute their own single groups or are aggregated into clusters of species based on their abundance, diet and commercial or functional importance. Each fish group has their set of biological properties, including growth, mortality, food constraints, reproduction, distribution map, and fishery interactions, amongst others. A diet matrix was developed using the year 1991 stomach data and literature sources (Mackinson & Daskalov, 2007) (Figure 2.4).

Modelled behaviour of the fish groups

Fish groups are represented as aggregated biomass pools, with behaviour described at the population level through mass-balance equations rather than individual processes. Mortality is partitioned into predation mortality (consumption by other functional groups, governed by the diet composition matrix), fishing mortality (from the fleet catch inputs) and other/residual natural mortality (a background term calibrated to close the mass balance). Biomass dynamics follow a production-driven differential equation, where any net surplus contributes to growth and 'recruitment' into the standing stock, rather than recruitment being modelled as a distinct spawning event for most groups. Where age structure matters, multi-stanza groups can be used, splitting a population into juvenile and adult stanzas.

Figure 2.4 Food web of the fish groups in EwE-NS. The colour of the arrow corresponds to the predator. Red: sharks; blue: rays; green: gadoids; purple: pelagic fish; orange: flatfish; brown: other. The size of the arrow corresponds to the relative importance of the food diet of the predator group. Arrows with a relative importance less than 5 % are shown in thin light grey. Based on data collated by Mackinson and Daskalov (2007)



The juvenile and adult stanzas are linked through a von Bertalanffy growth function, which allows reproductive output from adult biomass to propagate to juvenile stanzas with a time lag. Species spatial distribution enters through Ecospace, where groups are assigned to habitat or depth strata and can move between cells based on habitat suitability and foraging arena parameters, with swim rate varying between fish groups. Predation is prescribed through the diet composition matrix, which fixes the proportional contribution of each prey group to each predator's diet. Consumption rates are constrained by the foraging arena concept, which limits prey availability to prevent unrealistic top-down control. Lower trophic level groups, including phytoplankton and detritus, are represented dynamically within the EwE mass-balance framework alongside fish groups. However, their parameterization differs from consumer groups: phytoplankton are driven by primary production and grazing losses, whereas detritus represents a non-living biomass pool governed by inputs and consumption by detritivores.

Model input requirements

The main model inputs to EwE-NS are:

- functional groups, each with initial biomass (B) or ecotrophic efficiency (EE);
- production/biomass (P/B) and consumption/biomass (Q/B) per group;
- diet composition matrix that describes who eats whom, as fractions (Figure 2.4);
- fishery data with landings and discards per group and fleet;
- optional extras such as biomass accumulation, migration, and for Ecosim: timeseries of biomass, catch and fishing effort, plus vulnerability settings.

2.2.3 Comparison

The following remarks can be made on the main differences between OSMOSE and EwE:

- *predation*: OSMOSE allows predator-prey interactions to emerge from size and spatial overlap, making it better suited to examining how changes in e.g. primary production propagate through realistic, dynamic food web relationships. EwE's fixed diet matrices are more static and less flexible when simulating structural changes in the food web. Ecospace allows for spatial heterogeneity in the realisation of fixed diet proportions, but the underlying principle of the fixed diet matrix remains in place;
- *spatial resolution*: OSMOSE is inherently spatially explicit, making it more suitable for questions about area-specific effects (e.g., Dogger Bank, Frisian Front). EwE has a spatial module (Ecospace), but this is an add-on rather than a core component. In this study, the spatial module will be used, too;
- *individual variation*: OSMOSE simulates size and age structure within populations, allowing effects on juvenile vs. adult life stages (relevant to e.g. nursery function) to be captured more accurately. EwE typically works with aggregated biomass per group, without internal age/size structure (unless supplemented with Ecosim's multi-stanza groups). In EwE-NS, multi-stanza groups had been added for a selected number of fish species that are commercially of interest;
- *data and parameter requirements*: OSMOSE requires detailed input on growth, mortality and spatial distribution per species, which is data-intensive and computationally demanding to set up. EwE requires a mass-balanced diet matrix and biomass estimates, which is often quicker to set up but sensitive to assumptions in the diet data. As this study adopts existing validated models, there is no distinct difference between setup time. Assumptions related to e.g. the life cycle of fishes, diet data and fishing mortality are also adopted;
- *scenario testing*: OSMOSE is stronger for testing mechanistic hypotheses (e.g. 'how does predator-prey spatial overlap change under a shift in primary production'). EwE is stronger for management scenarios such as fisheries management, as it can rapidly run different exploitation scenarios at the ecosystem level.

While the models differ in their capacity to answer research questions in relation to OWF-induced primary production changes and the ecosystem response to such changes, both models are included in this study in accordance with ensemble approach. The underlying idea of the ensample approach is that applying different models may provide a more accurate estimation of the ecosystem response than a single model.

Fisheries

On a more specific note related to fisheries, there are some differences between OSMOSE and EwE. In EwE, fisheries are handled in Ecopath as a predefined table of fleet types. For each fleet, the catch of each species group is specified as a fixed weight (tonnes/km^2/year), along with a total catch per fleet and discards specified in the same way. These fixed values are entered into the model and accounted for in the mass balance. In Ecosim, fishing effort can then be varied over time (full or partial effort), with the default set homogeneously (effort = 1) across all time steps. In Ecospace, Marine Protected Areas can be defined (including seasonally), and fishing effort can be linked to habitat characteristics (e.g., depth), allowing spatial heterogeneity in fishing pressure. If left unspecified, fishing distribution is homogeneous by default.

In OSMOSE, fourteen (14) fleet types are defined as input, each with a yearly effort specified in number of fishing days. The proportion of effort per quarter is also defined per fleet, introducing temporal heterogeneity. Fleet maps then define where each fleet is active on the spatial grid. Rather than being prescribed, catch is an emergent output of the model, arising from the interaction between fleet distribution, effort and fish availability. This setup is calibrated against métier-specific fishing effort and landings data (STECF, 2024) for the years 2016–2020.

Biomass propagation from phytoplankton via zooplankton to fish

Both models were designed to result in a nonlinear propagation of biomass from the lower trophic levels to the higher trophic levels. However, OSMOSE and EwE handle this differently. In OSMOSE this is mainly governed by emergence based on overlap of species. So, if lower trophic species and higher trophic species occur in the same grid cell, predation occurs. The amount of predation depends on the accessibility factor of each particular lower trophic level species, which varies per fish species. In EwE, the diet matrix is fixed and the propagation of biomass to fish can be varied from donor-controlled (near-linear propagation of biomass) to top-down controlled (strongly nonlinear propagation of biomass) using a vulnerability factor. Ecosim uses a vulnerability (υ) scale from 1 to infinity, where $\upsilon = 2$ is mixed control, $\upsilon < 2$ is bottom-up control, and $\upsilon > 2$ is top-down control. So, the higher the value, the stronger the predator's top-down effect on that prey. The default settings of EwE-NS were adopted in this study (Mackinson & Daskalov, 2007).

2.3 Preprocessing the Deltares data

Phytoplankton biomass output from the Deltares model was used as the lowest trophic level forcing in both ecosystem models. The way it was incorporated differed, because the two models represent the base of the food web differently. In EwE-NS, phytoplankton is already a functional group in the food web. The Deltares phytoplankton biomass could therefore be implemented directly as the biomass of this group, without further conversion.

In OSMOSE-NS, the lower trophic levels are not simulated but provided as external plankton biomass fields (spatially and seasonally explicit), which serve as prey for fish schools. These fields are not defined at the phytoplankton level but at the level of the plankton groups that fish actually feed on (i.e. micro- and mesozooplankton, deposit and suspension feeders and meiofauna). The Deltares phytoplankton biomass was therefore first translated to the next lowest trophic levels (see elaboration in Appendix I) after which the resulting biomass fields were mapped onto the OSMOSE grid and time steps. These fields then served as the food base for the modelled fish and invertebrate species. Hence, the Deltares output replace input that would otherwise come from models such as ROMS. Also, as the Deltares output passes through an additional conversion step in OSMOSE-NS compared to EwE-NS, differences between the model results may therefore partly reflect the assumptions made in this translation, in addition to differences in model structure.

! Note on mass balance handling of EwE-NS using the Deltares output

The model EwE-NS has been validated and calibrated (Mackinson & Daskalov, 2007). The mass balance depends on the biomass and production levels of all functional groups, including phytoplankton, being mutually consistent.

The new primary production data by Deltares do not necessarily match in absolute magnitude to the mass balance the model EwE-NS was calibrated on. Or in other words, using the absolute data as direct input would risk disturbing the mass balance (pers. comm. EwE support team). Therefore, the phytoplankton data derived from the Deltares study were rescaled to match the level of the validated model, while its spatial and temporal pattern was retained. Ergo, the mass balance of the original model was preserved, but the locations and timings of relative peaks and lows in primary production on the North Sea follow from the Deltares output.

This has **one important implication for interpretation**: results of the model EwE-NS should be read as relative changes (e.g. between seasons and between scenarios), not as absolute predictions of primary production or biomass, nor as a quantification of effect-size. An absolute comparison with the results of OSMOSE-NS is therefore inherently flawed and should not be made. In the discussion (chapter 4) a relative comparison of modelling outcome is presented.

2.4 Scenarios

A total of three scenarios were run using both OSMOSE-NS and EwE-NS. These scenarios are as follows:

- *baseline*: this included the default parameter settings of OSMOSE-NS and EwE-NS with as altered input the preprocessed primary production (EwE-NS) and LTL group data (OSMOSE-NS) of the Deltares scenario *No OWF*s (Zijl et al., 2024);
- *partial revision #4*: this included the default parameter settings of OSMOSE-NS and EwE-NS with as altered input the pre-processed primary production (EwE-NS) and LTL group data (OSMOSE-NS) of the Deltares scenario 4 of the *Partial Revision* (Zijl et al., 2024).;
- *partial revision #4 +10 %*: this was similar to the scenario *Partial Revision* #4, with changes relative to the baseline scenario exaggerated by 10 %. Ergo, areas with an increase in primary production relative to the baseline scenario will see a further 10 % increase. Vice versa, areas with a decrease in primary production relative to the baseline scenario will see a further 10 % decrease. Accordingly, spatial gradients in primary production become larger.

The simulations were run until a stable food web had developed, repeating the primary production signal (a single year) every year without any stochasticity. EwE-NS simulations were run for 80 years. The OSMOSE-NS simulations were run for 30 year. For both models, the output of the final modelling year is presented in Chapter 3.

2.5 Postprocessing

To analyse the outcomes of both ecological models, data on biomass of fish were grouped into their trophic level and species group (e.g. gadoids, flatfish). These data were then amalgamated on the level of the effect areas (Figure 1.2). Below, a table is shown of the characteristics of all fish species that were included in the postprocessing. In case of multi-stanza groups (only relevant in EwE-NS), all juveniles were considered prey fish (Table 2.1). A visual representation of the data reduction steps during postprocessing is included Figure 2.5 Although the models can produce graphic output mapped over the North Sea, results are presented per effect area. This 'higher level' representation was selected given the uncertainty of the models outcomes of this explorative study.

Figure 2.5 Data reduction steps during postprocessing, where spatial distribution of biomass was aggregated to the different effect areas. These data were first plotted for the scenario *No OWF* as cumulative stacked bars, showing the temporal trend in total biomass in comparison to the primary production signal in the same effect area. Finally, the three scenarios (baseline and two scenarios based on *Partial Revision* 4) were plotted per group (either trophic level or, as in the example below, species group). In the main report, only the latter two figures are included per ecological model and per biomass aggregation (trophic level and species group)

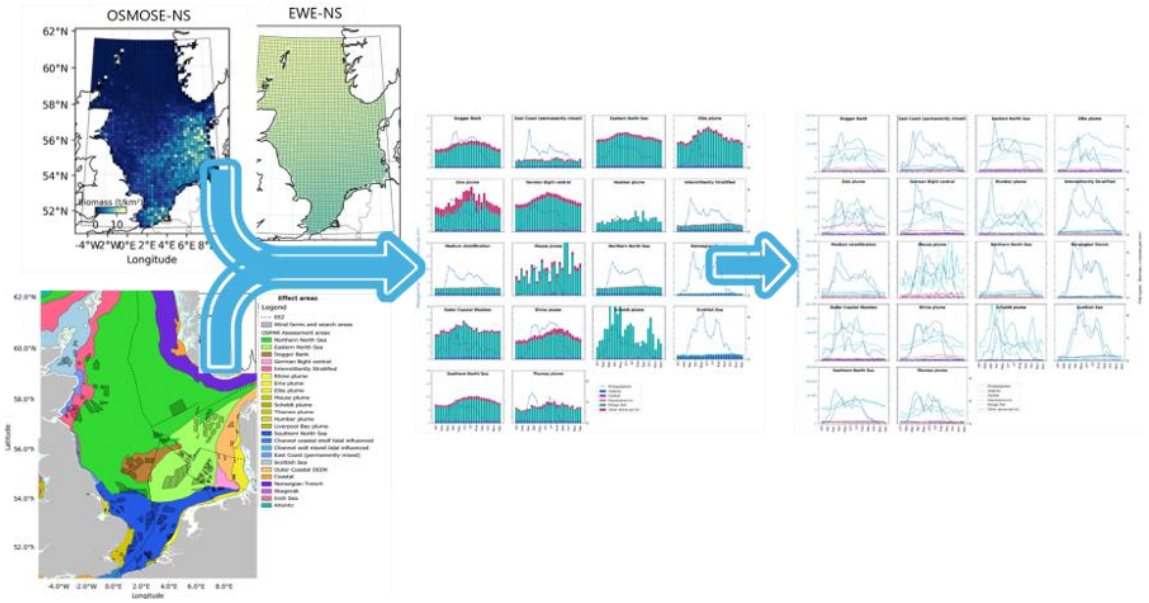


Table 2.1 Trophic level and species group of fish species. Trophic levels are based on Yang (1982). (A) and (J) denote multi-stanza groups (adult - juvenile) in EwE-NS. All species are included in the postprocessing of EwE-NS. The fourteen fish species that are included in OSMOSE-NS, are denoted with a stamp (#)

Fish species	Trophic level	Species group	Fish species	Trophic level	Species group
Cod (A)#	Apex	Gadoids	Lemon sole	Mid-range	Flatfish
Hake	Apex	Gadoids	Plaice#	Mid-range	Flatfish
Halibut	Apex	Flatfish	Rays (A)	Mid-range	Elasmobranchs
Large demersal fish	Apex	Other demersal fish	Small sharks	Mid-range	Elasmobranchs
Large sharks	Apex	Elasmobranchs	Sole#	Mid-range	Flatfish
Megrim	Apex	Flatfish	Thornback ray#	Mid-range	Elasmobranchs
Monkfish	Apex	Other demersal fish	Witch	Mid-range	Flatfish
Other gadoids	Apex	Gadoids	Cod (J)	Prey	Gadoids
Starry ray	Apex	Elasmobranchs	Dragonets	Prey	Other demersal fish
Saithe (A) #	Apex	Gadoids	Haddock (J)	Prey	Gadoids
Spiny dogfish#	Apex	Elasmobranchs	Herring (A) #	Prey	Pelagic fish
Spurdog	Apex	Elasmobranchs	Herring (J)	Prey	Pelagic fish
Toothed whales	Apex	Marine mammals	Horse mackerel	Prey	Pelagic fish
Turbot and brill	Apex	Flatfish	Mackerel	Prey	Pelagic fish
Whiting (A) #	Apex	Gadoids	Norway pout#	Prey	Gadoids
Baleen whales	Mid-range	Marine mammals	rays (J)	Prey	Elasmobranchs
Blue whiting	Mid-range	Gadoids	Saithe (J)	Prey	Gadoids

Fish species	Trophic level	Species group	Fish species	Trophic level	Species group
Catfish	Mid-range	Other demersal fish	Sandeel[#]	Prey	Other demersal fish
Dab[#]	Mid-range	Flatfish	Sharks (J)	Prey	Elasmobranchs
Flounder	Mid-range	Flatfish	Small demersal fish	Prey	Other demersal fish
(Grey) gurnard[#]	Mid-range	Other demersal fish	Sprat[#]	Prey	Pelagic fish
Haddock (A) [#]	Mid-range	Gadoids	Whiting (J)	Prey	Gadoids

3

Model results

3.1 Introduction

This chapter outlines the main model results of the two models OSMOSE-NS (section 3.2) and EwE-NS (section 3.3). This includes responses of biomass of fish for the different effect areas in the North Sea, where fish are aggregated to their place in the food web (apex predator, mid-level predator, prey) and type (rays, flatfish, pelagic fish, gadoids, other). The results of the two models are presented separately and with minimal ecological interpretation. The ecological interpretation of the individual models (e.g. can the results be explained and to what extent are the model outcomes logical and/or do they match our current understanding of the marine ecosystem?) and a comparison between OSMOSE-NS and EwE-NS are given in chapter 4. Additional data output can be found in appendix II.

It should be noted that the trends in primary production as presented in this chapter follow from the Deltares modelling study and not in-situ measurements. For example, the Deltares output of primary production prescribe low or absent primary production during winter time in most effect areas, yet validation data show this is incorrect. Therefore, the findings in this chapter give an estimate of how the models respond to the Deltares output but may not be a valid representation of what truly happens on the North Sea.

3.2 OSMOSE-NS

Below, the effects of the three scenarios of primary production variability are first described on biomass of the three trophic levels (apex and mid-range predators and prey) (section 3.2.1). This is followed by the effects on biomass of the fish types (section 3.2.2). OSMOSE-NS included fourteen fish species that were grouped into: gadoids, flatfish, elasmobranchs, pelagic fish, marine mammals and other demersal fish.

3.2.1 Trophic levels

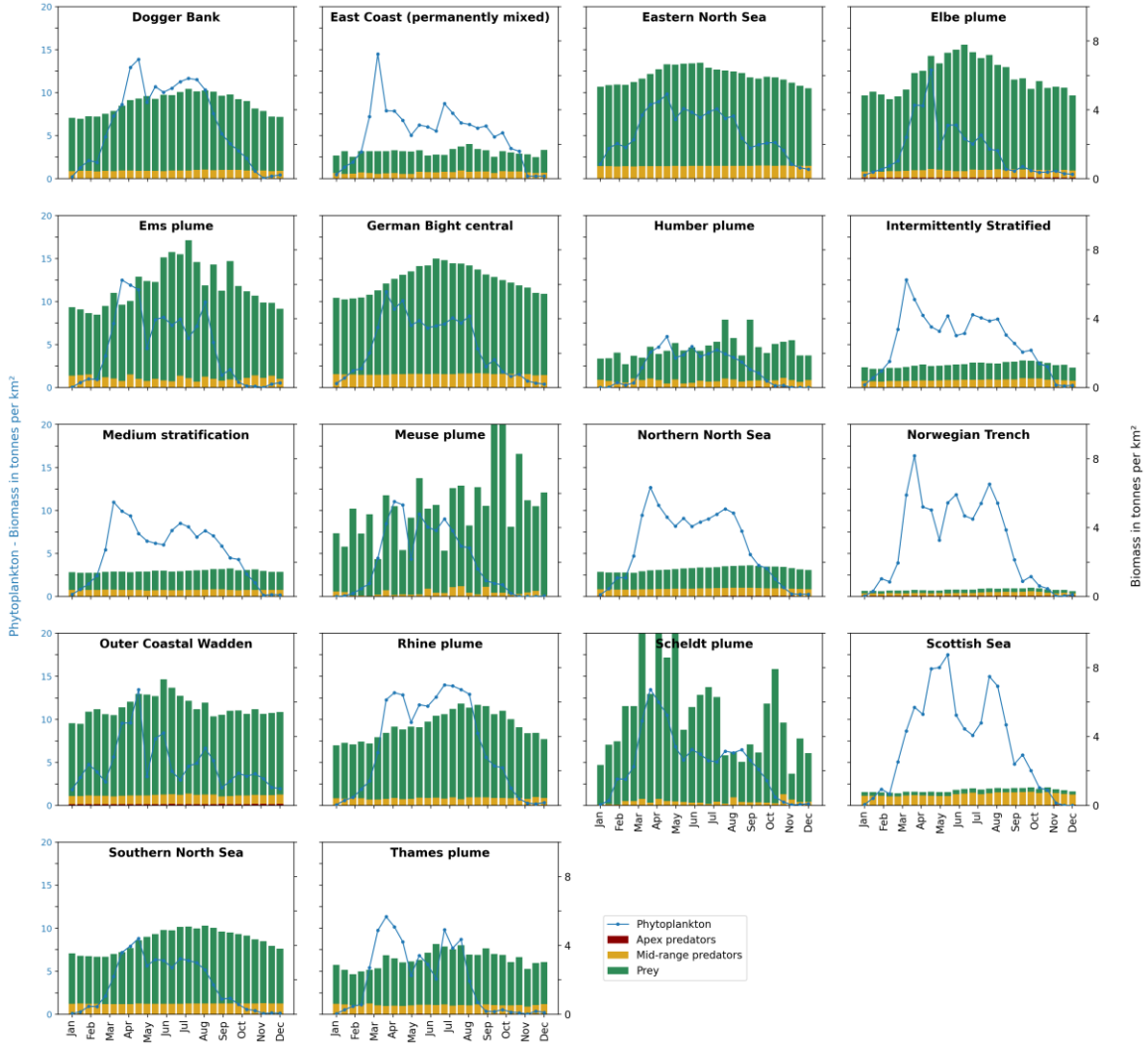
First, the spatial and temporal development of biomass in the base scenario *No OWF* is explained. This is followed by a comparison with and between the scenarios *Partial Revision #4* and *Partial Revision #4 +10%*.

Scenario *No OWF*

The simulated biomass of the three trophic levels in the scenario *No OWF* (Figure 3.1) shows a clear zonation of where which trophic level is dominantly present. Apex predators are predominantly found in the northern effect areas of the North Sea and along the southeastern coast of the United Kingdom (see Figure 1.2 for the location of effect areas). Mid-range predators are omnipresent in the North Sea, with a weak prevalence for the effect areas at and around the German Bight central. Biomass of prey fish is over a magnitude larger than that of apex predators and is concentrated west of Denmark and towards the English Channel. Whilst the biomass of apex predators and prey fish is largely concentrated in certain regions on the North Sea, the biomass of mid-range predators is much more equally distributed on the North Sea.

Throughout the year, all trophic levels show an oscillation in biomass, with peaks in (late) summer and early autumn and lows in early spring (Figure 3.1). In absolute terms, the gain in biomass of prey fish is largest. For example, the biomass gain of prey fish in the German Bight central and Elbe plume is about 40 % and in the Ems plume up to 100 %. The Meuse plume and Scheldt plume show a more irregular pattern with even larger increases, but note that these are based on very few grid cell outputs and therefore more susceptible to large changes if superindividuals migrate in and out of the effect area.

Figure 3.1 Temporal development of biomass of phytoplankton (line; left vertical axis as model input) and of the three trophic levels of fish (stacked bars; right vertical axis as model output) for the different effect (Figure 1.2) areas in the North Sea for the scenario *No OWF*. Model: OSMOSE-NS. Apex predators biomass is marginal and thus barely visible



The primary production seems to govern where prey fish thrive in the simulation. The coast west of Denmark exhibits year-round primary production (e.g. effect areas Outer Coastal Wadden and Eastern North Sea). These are the main (and nearly only) effect areas in the Deltares output where primary production also occurs during winter. On a larger-scale, there is a weak relationship between primary production and biomass of prey fish in the effect areas in the southern half of the North Sea. However, peaks in primary production in the northern half of the North Sea typically do not result in strong net gains of prey fish. As these waters are inhibited by more (biomass of) apex predators, their diet may be one of the contributors limiting the net gain in prey biomass (i.e. many juvenile prey gets eaten).

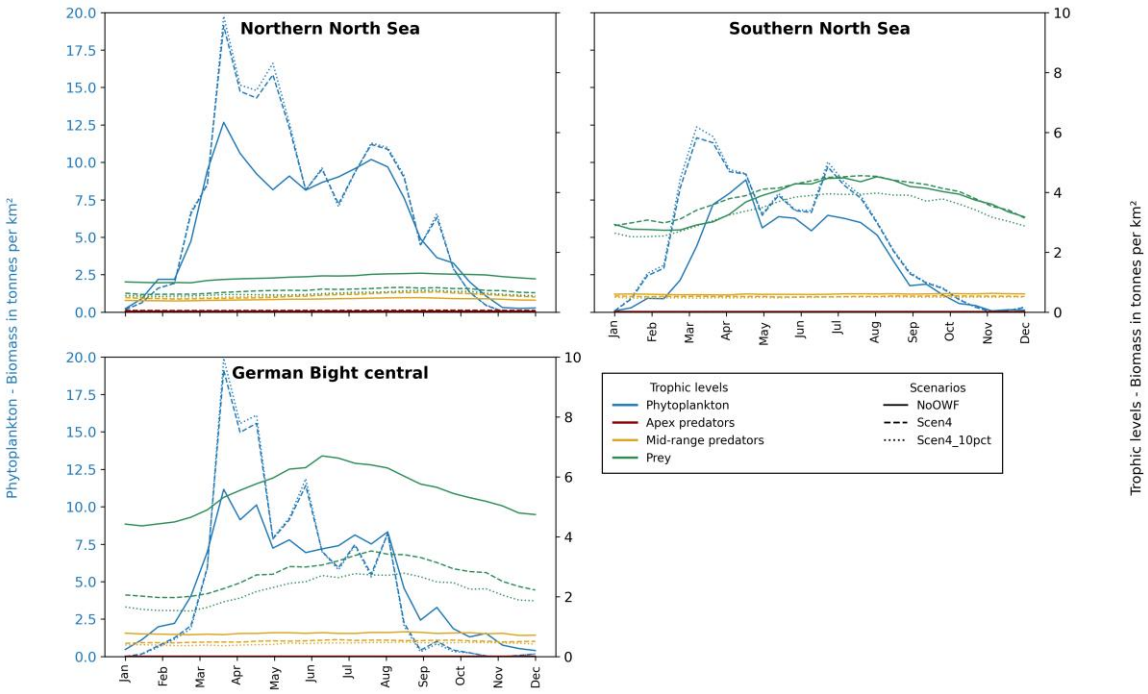
Mid-range predators are only dominant in biomass in the effect areas Norwegian Trench and Scottish Sea. Apex predators are dominant in none of the effect areas in terms of biomass. The gain and loss in biomass of apex and mid-range predators throughout the year is generally in the range of only 5-10 %, while phytoplankton biomass extend from 0 tonnes/km^2 up to 18 tonnes/km^2.

Comparison with *Partial Revision* scenarios

The *Partial Revision* scenarios show similar trends as the baseline scenario *No OWF*, with peak biomass of particularly prey fish occurring in (late) summer and early autumn. However, the total biomass of fish in the North Sea decreases from the scenario *No OWF* to the *Partial Revision* scenarios (Figure 3.2) Especially the eastern part of the North Sea (e.g. Outer Coastal Wadden, German Bight central, Eastern North Sea and the Elbe and Ems plumes) shows a strong decrease in prey fish up to 50 % in the scenario *#4* of the *Partial Revision* and up to 60 % in the scenario *#4 +10 %* (see Figure 1.2 for the location of effect areas). This decrease is not in proportion to the phytoplankton biomass, which is actually increasing in the aforementioned effect areas. At the same time, response in the southern North see to changes in primary production changes is fairly limited (figure 3.2), where the *No OWF* scenario follows the *#4 scenario*.

Mid-range predators also show a decline in biomass in the (south)eastern North Sea (up to about 30 %) but exhibit a net increase in all effect areas north of Dogger Bank, up to about 20 % (e.g. Medium Stratification and Intermittently Stratified). Apex predators appear least affected by the changes in primary production, showing a negligible decline in the southern half of the North Sea and an incremental increase of about 5 to 10 % in the northern half of the North Sea (see appendix II.2 for additional figures).

Figure 3.2 Temporal development of biomass of phytoplankton (blue; left vertical axis as model input) and of the three trophic levels of fish (brown, amber and green lines; right vertical axis as model output) for three different effect areas in the North Sea for the scenario *No OWF* (continuous line), *Partial Revision #4* (dashed line) and *Partial Revision #4 +10%* (dotted line). Model: OSMOSE-NS



Differences between the two *Partial Revision* scenarios are predominantly seen for the prey fish and mid-range predators; apex predators do not exhibit a significant change in biomass (Figure 3.2) As for prey fish, there is a further reduction in biomass in the German Bight and Eastern North Sea region. Strongest local changes are found along the southeastern coasts of the United Kingdom.

The net result is an additional 5 to 10 %-point reduction in the Thames plume and an additional increase of up to 200 %-point at the Humber plume in the scenario #4 +10 % (see appendix II.2 for additional figures).

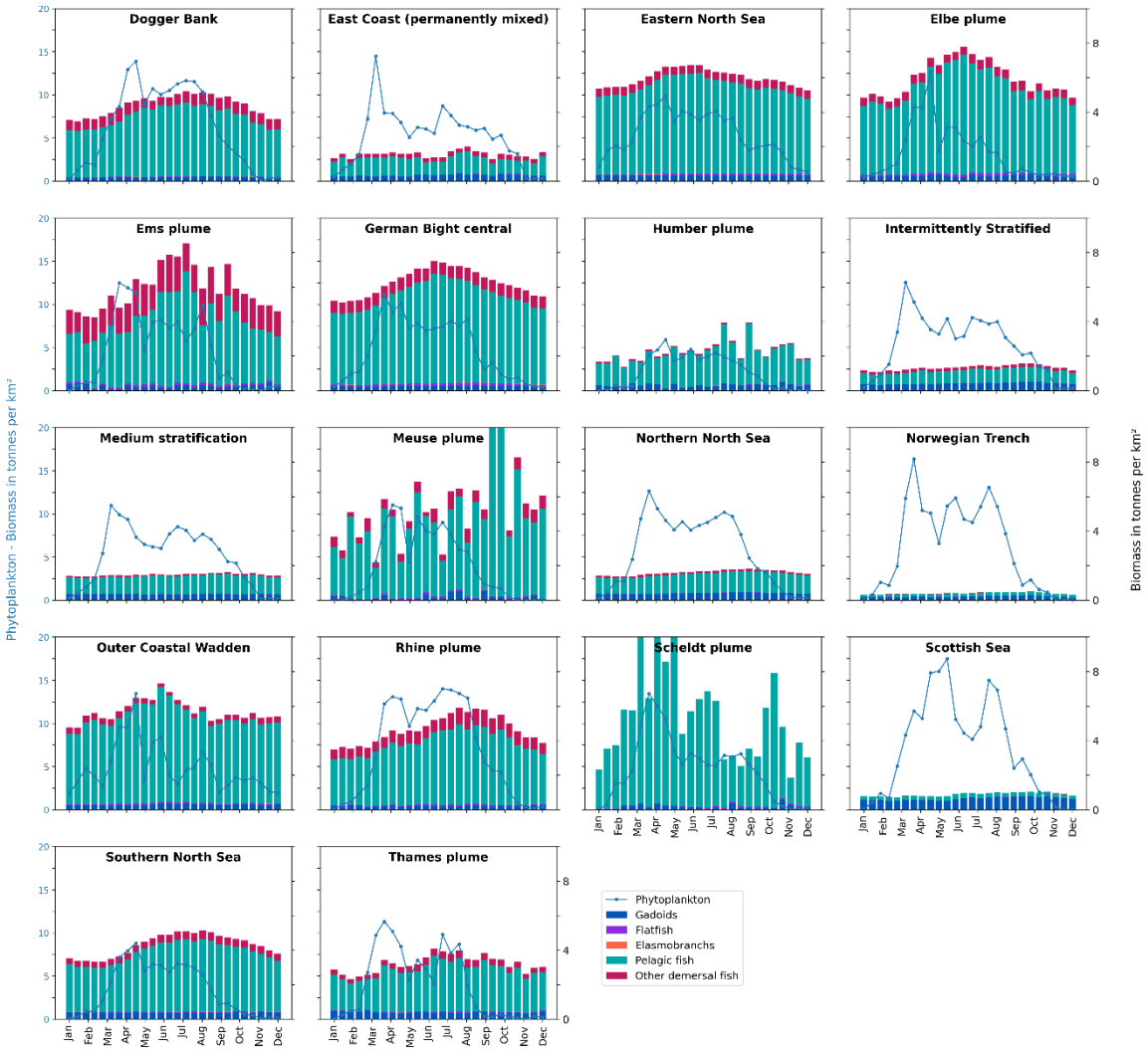
3.2.2 Species groups

First, the spatial and temporal development of biomass in the base scenario *No OWF* is explained. This is followed by a comparison with and between the scenarios *Partial Revision #4* and *Partial Revision #4 +10 %*.

Scenario *No OWF*

There is a clear zonation of the simulated fish groups on the North Sea. Gadoids are predominantly found in the northern half of the North Sea with a fairly low biomass density (rarely above 2.5 tonnes/km^2). All other fish groups are mostly found in the southern half of the North Sea. Albeit with very low biomass density (<0.01 tonnes/km^2), elasmobranch are clustered between the offshore waters between the Netherlands and the United Kingdom. Flatfish are most prevalent west of Denmark and up to the English Channel. Pelagic fish have the highest biomass density of all fish groups, ranging up to nearly 10 tonnes/km^2, and predominantly occur in the coastal and offshore waters along southeastern United Kingdom (see Figure 1.2 for the location of effect areas). Other demersal fish are somewhat clustered in the waters between the Netherlands and the United Kingdom, and in the region near the German Bight.

Figure 3.3 Temporal development of biomass of phytoplankton (line; left vertical axis as model input) and of the five fish types (stacked bars; right vertical axis as model output) for the different effect areas in the North Sea for the scenario *No OWF*. Model: OSMOSE-NS

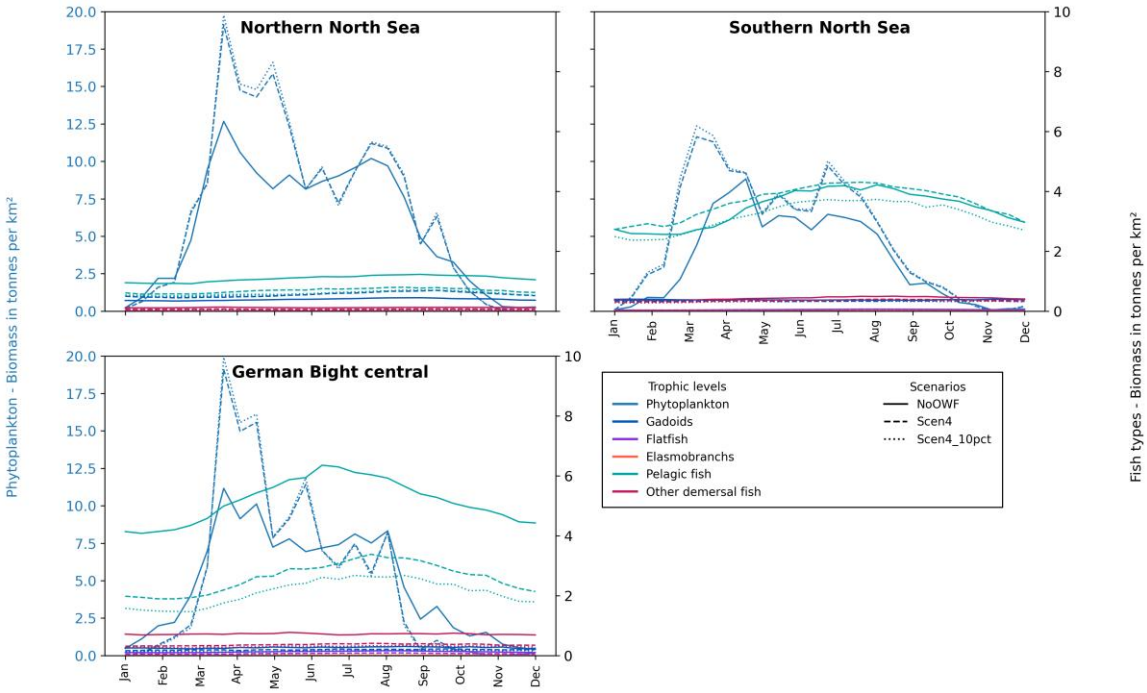


Throughout the year, it is mainly the biomass of pelagic fish that increases in (late) summer and early autumn. The most significant increases in biomass density of pelagic fish include the Rhine plume (about +80 %) and the German Bight central (about + 40 %), disregarding the Humber plume and Scheldt plume, which both are based on only a very limited number of cells. Gadoids also show a weak increase in biomass towards late autumn, especially in effect areas in the northern half of the North Sea. For example, their biomass increases by about 40 % in Intermittently Stratified and to a lesser extent also in Northern North Sea and Scottish Sea. The biomass of gadoids in the effect area East Coast appears more erratic with sudden highs and lows that do not necessarily coincide with biomass changes of other fish groups.

Comparison with *Partial Revision* scenarios

From the baseline scenario *No OWF* to the two *Partial Revision* scenarios, there is a strong decrease particularly in pelagic fish. The species group response to the different scenarios is similar to the response on the different trophic levels (Figure 3.4 and Figure 3.2, respectively). This amounts up to about 50 % in German Bight central and Outer Coastal Wadden in the *scenario #4* and up to about 60 % in the *scenario #4 +10 %* (see Figure 1.2 for the location of effect areas). Only in the Southern North Sea is there a weak increase in pelagic fish (~5-10 %) in *scenario #4*, yet a ~5-10 % decrease in *scenario #4 + 10* %. Other demersal fish have less biomass compared to the baseline scenario. The smallest decrease seems to occur in Meuse plume (note that this is based on a very limited number of cells). In contrast, gadoids tend to have slightly more biomass (order: 5-10 %) in the effect areas in the northern half of the North Sea. In most effect areas, the scenario #4 +10 % shows a stronger difference with the baseline scenario than scenario #4.

Figure 3.4 Temporal development of biomass of phytoplankton (blue; left vertical axis as model input) and of the five fish types (colours correspond to Figure 3.3; right vertical axis as model output) for three different effect areas in the North Sea for the scenario *No OWF* (continuous line), *Partial Revision #4* (dashed line) and *Partial Revision #4 +10 %* (dotted line). Model: OSMOSE-NS



3.3 EwE-NS

Below, the effects of the three scenarios of primary production variability are first described on biomass of the three trophic levels (apex and mid-range predators and prey) (section 3.3.1). This is followed by the effects on biomass of the fish types (section 3.3.2).

As EwE-NS includes a considerably larger set of fish species, more fish groups were distinguished than in OSMOSE-NS. These include: gadoids, flatfish, elasmobranchs, pelagic fish, marine mammals and other demersal fish.

3.3.1 Trophic levels

First, the spatial and temporal development of biomass in the base scenario *No OWF* is explained. This is followed by a comparison with the scenarios *Partial Revision #4* and *Partial Revision #4 +10 %*.

Scenario *No OWF*

The simulated biomass fields of the three trophic levels in the scenario *No OWF* result in a spatially smooth distribution, with no pronounced local maxima and sharp transitions. For all three trophic levels, the north to northwestern parts of the North Sea generally harbour the most biomass. The least biomass is found towards the English Channel, especially so for prey fish (Figure 3.5). Mid-range predators tend to be the most homogeneous of the three trophic levels in the North Sea. Note that water depth is typically not included in EwE simulations, so an apparent correlation with water depth (slightly more biomass for deeper regions on the North Sea) cannot be drawn based on these simulations.

Figure 3.5 Temporal development of biomass of phytoplankton (line; left vertical axis as model input) and of the three trophic levels of fish (stacked bars; right vertical axis as model output) for the different effect areas in the North Sea for the scenario *No OWF*. Model: EwE-NS



Aside from the smooth gradients over space, there is also little variation in biomass allocation of the three trophic levels over the year (Figure 3.5). Biomass of apex and mid-range predators appear near-constant throughout the year, whilst prey fish show a weak decline in the summer months. Closer inspection of the individual fish species shows that most species, also apex and mid-range predators oscillate in biomass over the year (For just a handful of particularly prey species, however, their oscillation is substantial (i.e. more than 5 % around their yearly averaged biomass). The herring exhibits the largest oscillation in biomass.

Comparison of the stacked bars (i.e. biomass of the three trophic levels) and phytoplankton biomass shows there is no clear correlation. Peaks in phytoplankton biomass in late spring and summer seem to coincide with a slight decrease prey fish biomass, but the peak height does not dictate the magnitude of decrease in prey fish biomass. This suggests that local peaks in primary production are 'smoothed' across the effect areas on the North Sea, especially so towards the higher trophic levels.

Comparison with *Partial Revision* scenarios

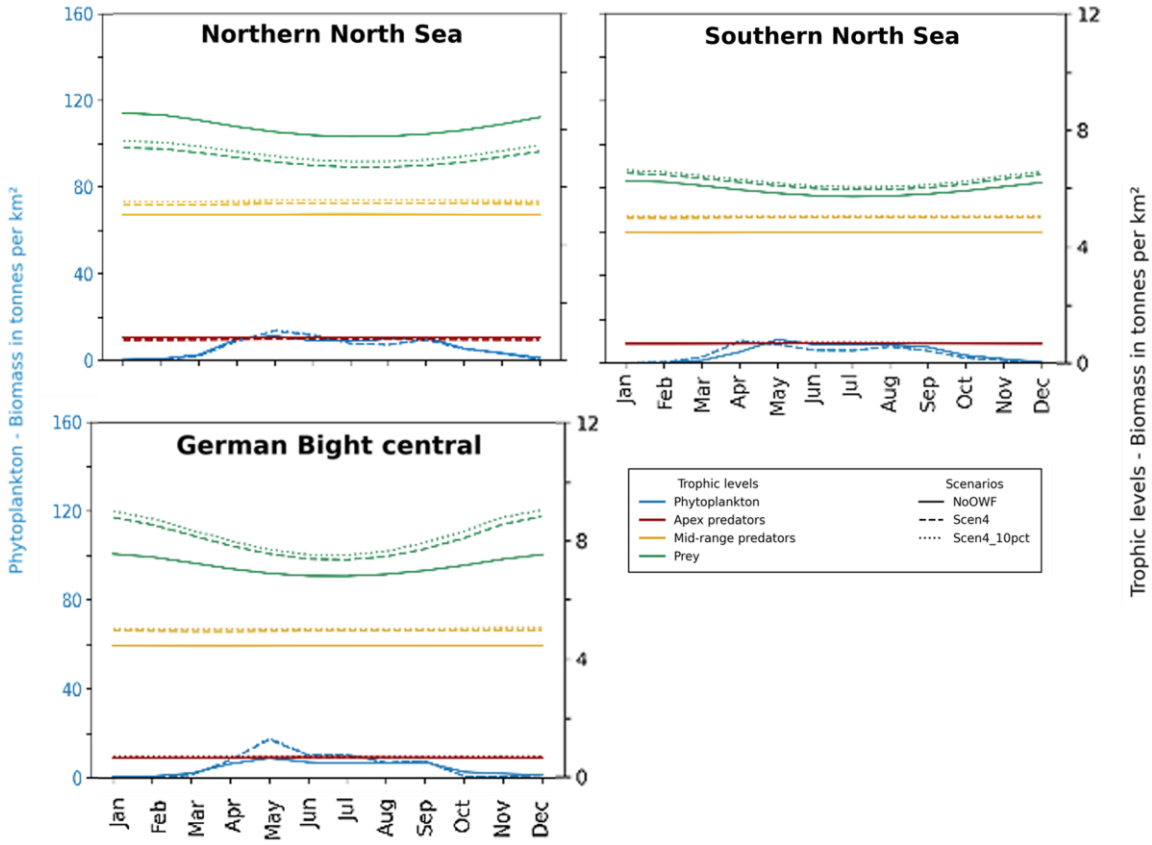
Similar to the base scenario *No OWF*, both *Partial Revision* scenarios also exhibit smooth spatial and temporal gradients in biomass. There are a few key findings and differences between the three scenarios that can be distilled from Figure 3.6. Note that the response of prey species to the scenarios is different in different areas of the North Sea. Where in the northern North Sea, less prey biomass is observed (~15 %) in the *#4* and *#4+10% scenarios*, an increase (~5 %) is observed. This increasing trend is also found for other effect areas such as the German Bight central and Elbe plume, where phytoplankton biomass is about similar or considerably smaller (see Appendix II.3 for additional figures). This corroborates the earlier finding that local peaks in phytoplankton translate into near-North Sea wide responses in fish biomass.

Biomass of apex predators remains similar or decreases slightly (up to 5 %) from the base scenario *No OWF* to the two *Partial Revision* scenarios (e.g. a decrease in Intermittently Stratified and Norwegian Trench). There is a near-North Sea wide increase in mid-range predators. Changes between the three scenarios are largest for the prey fish. This makes sense, as this is the lowest trophic level of the fish and therefore the most influenced by changes in primary production. However, there is no clear correlation between primary production and biomass of prey fish on the scale of effect areas in EwE. The northern effect areas typically show a decrease in prey fish biomass in the *Partial Revision* scenarios (up to 10 %), whilst the more southern effect areas near river plumes typically show an increase in prey fish biomass (up to 5 %).

As illustrated in Figure 3.6 local differences in primary production do not propagate to local differences in the three trophic levels. The increase in phytoplankton biomass in the German Bight seems to propagate to more biomass of prey fish. However, a similar reasoning cannot be drawn for the increase in phytoplankton biomass around the Scottish Isles.

Overall, there is a net increase in phytoplankton biomass in the *scenario 4* of the *Partial Revision +10 %,* which results in a very small increase in biomass of all trophic levels especially in the northern half of the North Sea. Biomass density of prey increases by up to about 0.3 tonnes/km^2, mid-range predators up to about 0.15 tonnes/km^2 and apex predators by less than 0.05 tonnes/km^2. These increases amount to less than 2 % for apex and mid-range predators and less than 4 % for prey fish.

Figure 3.6 Temporal development of biomass of phytoplankton (blue; left vertical axis as model input) and of the three trophic levels of fish (brown, amber and green lines; right vertical axis as model output) for three different effect areas in the North Sea for the scenario *No OWF* (continuous line), *Partial Revision #4* (dashed line) and *Partial Revision #4 +10 %* (dotted line). Model: EwE-NS



3.3.2 Fish groups

First, the spatial and temporal development of biomass in the base scenario *No OWF* is explained. This is followed by a comparison with the scenarios *Partial Revision #4* and *Partial Revision #4 +10 %*.

Scenario *No OWF*

The simulated biomass fields of the six fish types in the scenario *No OWF* (Figure 3.7) show a spatially smooth distribution, with no pronounced local maxima and sharp transitions. For all fish types, the north to northwestern parts of the North Sea generally harbour the most biomass. However, the spatial variation between the northern and southern parts of the North Sea differ for the fish types. For example, especially gadoids and other demersal fish, and to some extent also pelagic fish, are mostly found in the northern North Sea and have relatively little stocks in the southern North Sea. This trend is weak for elasmobranchs. Flatfish and marine mammals are generally homogeneously distributed across the North Sea. As mentioned before, note that water depth is typically not included in EwE simulations. Thus, an apparent correlation with water depth (more biomass for deeper regions on the North Sea) cannot be drawn based on these simulations.

Temporal variation in biomass can mainly be ascribed to pelagic fish and other demersal fish (Figure 3.7). All other fish types remain about constant in their biomass. These show a weak decrease in late spring and summer time. This seems to coincide with the North Sea wide increase in phytoplankton; there is yet no clear relation between the phytoplankton biomass and fish stocks on the level of the effect areas. The biomass of the other four fish types (gadoids, flatfish, elasmobranchs and marine mammals) remains largely constant throughout the year.

Figure 3.7 Temporal development of biomass of phytoplankton (line; left vertical axis as model input) and of the six fish types (stacked bars; right vertical axis as model output) for the different effect areas in the North Sea for the scenario *No OWF*. Model: EwE-NS



Comparison with *Partial Revision* scenarios

Similar to the base scenario *No OWF*, both *Partial Revision* scenarios also exhibit smooth spatial and temporal gradients in biomass. There are a few key findings and differences between the three scenarios that can be distilled from Figure 3.8. Firstly, there is a North Sea wide increase in biomass of flatfish of around 10 % from the scenario *No OWF* to the *Partial Revision* scenarios; of the three scenarios, the scenario *Partial Revision #4 +10 %* has the largest biomass of flatfish. The elasmobranchs and marine mammals remain about equal in biomass across the three scenarios and therefore seem not significantly impacted by the tested changes in primary production.

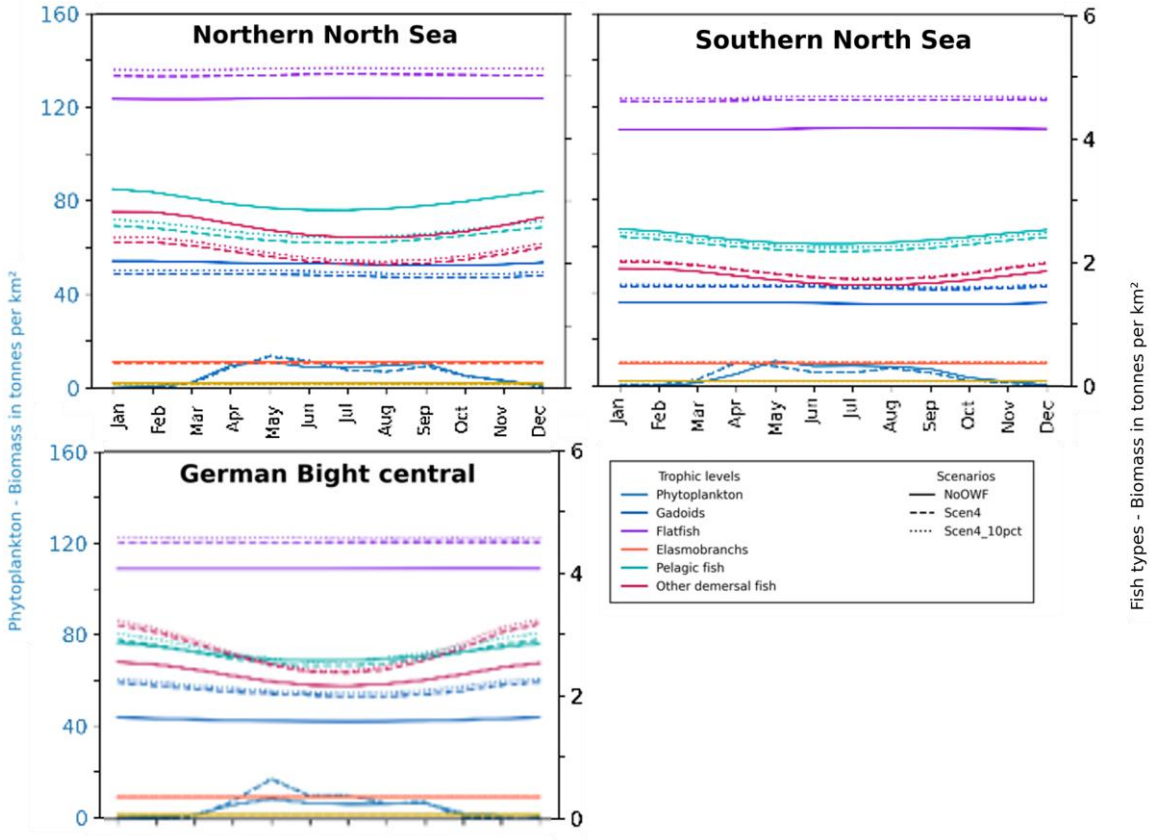
Interestingly, the seasonal oscillation in biomass increases for the gadoids and especially the other demersal fish along the Dutch and German coasts (e.g. effect areas Elbe plume, Ems plume, German Bight central, Outer Coastal Wadden and Rhine plume, see Figure 1.2 for the location of effect areas). In most of these 'coastal' effect areas, the yearly averaged biomass of gadoids and other demersal fish increases as well (up to 30 %), with the exception of the Outer Coastal Wadden, where the yearly averaged biomass of other demersal fish remains largely similar to the scenario *No OWF*. In contrast, the yearly averaged biomass of gadoids and other demersal fish decreases in the north-to-northwestern effect areas on the North Sea (e.g. Norwegian Trench, Intermittently Stratified, Scottish Sea) by up to 20 %. Prey fish generally show a decline in biomass across the North Sea, which is smallest for the effect areas in the southern parts of the North Sea (a few percent) and up to 30 % in the northwestern-most effect areas (e.g. Scottish Sea).

Also, the decrease in prey fish biomass is larger in the scenario *Partial Revision #4* than in *Partial Revision #4 +10 %,* with respect to the base scenario *No OWF*. This difference is in the order of only a few percent points.

There seems to be a slight temporal delay in the dip in biomass of prey fish (approximately May-July) to other demersal fish (approximately June - August) to gadoids (approximately August - October). This is most evident in the effect areas Elbe plume, Outer Coastal Wadden and German Bight central.

All fish groups exhibit in all effect areas a slightly higher biomass in the *scenario 4* of the *Partial Revision +10 %* than in the *scenario 4* of the *Partial Revision*. This increase is in the order of only a few percent. Relatively largest increases are found in the Northern North Sea, Norwegian Trench and Scottish Sea and most plume effect areas.

Figure 3.8 Temporal development of biomass of phytoplankton (blue; left vertical axis as model input) and of the six fish types (colours correspond to Figure 3.7; right vertical axis as model output) for three different effect areas in the North Sea for the scenario *No OWF* (continuous line), *Partial Revision #4* (dashed line) and *Partial Revision #4 +10 %* (dotted line). Model: EwE-NS



4

Discussion

4.1 Introduction

Following the plain description of the model outcomes of OSMOSE-NS and EwE-NS, this discussion will reflect on the underlying model functioning and ecological meaning of these outcomes. Firstly, the two ecological models are discussed separately in Section 4.2, focusing on how different scenarios differ in biomass and species composition. From there, the results of both models are compared in Section 4.3, including a comparison of the functionality of the two ecological models in light of the main aim of this study. Finally, key disclaimers and recommendations for follow-up studies are provided (Section 4.4).

It should be noted that the model outcomes and the ecological assessment down below are strongly bound by the schematization and functionality of the numerical models, and the primary production fields by Deltares, which are not always in line with field data (pers. comm., not tested in this study). This discussion is therefore in part a reflection on how the model functionality affects the outcomes, and to what extent this raises questions and/or produces functionally realistic results. The findings do not provide quantitatively correct and validated information e.g. to base policy or legislation on.

4.2 Ecological assessment

4.2.1 OSMOSE-NS

On the large-scale of the food web of the North Sea, the model OSMOSE-NS appears to allocate an ecologically sound distribution of prey fish, mid-range predators and apex predators. In particular, the biomass of apex predators may be up to a hundred times smaller than prey fish biomass. As only part of the production is transferred in biomass per trophic level, a smaller apex predator biomass is in the line of expectation. However, given that the trophic level from prey fish to apex predators only increases by about 1-1.5 points on average, a slightly larger apex predator biomass was expected (Yang, 1982).

OSMOSE-NS also shows that the relatively erratic change in primary production, both in absolute terms, as well as in spatial differences, results in smaller changes higher in the food web. This can be expected, given ecological process such as the aforementioned energy loss per trophic level and mobility of species.

Responses to the *Partial Revision* scenarios (*#4* and *#4+10 %*) compared to *No OWF-scenario* greatly differs in time and space. The general observation is that changes in primary production is more erratic than the response in fish biomass. Moreover, a decline in total fish biomass can be observed, while an increase in primary production is provided. Especially for prey species, such biomass decreases can be up to 60 %[1] in a single effect area. To a large extent, this can be accredited to how primary production is redistributed in the *Partial Revision* scenarios: peaks in summertime are on average larger, but the main hotspots in wintertime diminish (see e.g. Outer Coastal Wadden and Eastern North Sea in Figure 3.1 and appendix II.2). Less prey

[1] The example of a 50 % change is an extreme. In many effect areas, the effect size is in the order of magnitude of 10-20 %. See Appendix Figure II.5 for more examples.

fish is able to make it through winter as food becomes scarce in the model. There may be additional processes that play a part in the observed trend of fewer prey fish biomass. Below, five main discussion points are elaborated:

- *Timing of growth and recruitment*: In its current setup, OSMOSE-NS allows for year-round recruitment. It is unclear how this non-seasonal representation of creating offspring affects how lower trophic biomass propagates to higher trophic levels;
- *Predator-prey interactions*: In the north, higher predator biomass (mid-range +20 %, apex +5-10 %) can limit net gains of prey fish, as already seen in the base scenario, where juvenile prey is probably eaten. In the southern half of the North Sea, however, this does not apply. Mid-range predators decrease there too (up to 30 %). If predation were the main driver, prey fish should have increased. By analysing the turnover rates within the simulation, it could be determined if this is the case.;
- *Spatial distribution of food*: Whilst the total amount of zooplankton and feeders/benthos (as proxy of phytoplankton) may increase, it may become concentrated in hotspots with less productive waters in between. This is especially the case for the *Partial Revision +10 %* simulation. Increasing distance between hotspots may therefore lead to fewer predator and prey (or prey and lower trophic levels) encounters. However, this cannot be the main cause for the strong decline in particularly prey fish by up to 60 % in some effect areas;
- *Cascading effects*: If food is insufficient, starvation reduces growth and survival. Fewer spawners also means weaker recruitment. A moderate change in food supply can therefore produce a large change in biomass. However, on the scale of the whole North Sea, with a net increase in lower trophic level biomass availability in the *Partial Revision* scenarios, this cannot explain the full picture;
- *Habitat initialisation and movement*: In OSMOSE-NS, the areas where fish migrate to are governed by the habitation initialisation maps and the random walk movements. Upon the limited investigation executed in this study, initialisation appears to be a dominant force within the model. As such, in different areas, different responses to primary production changes can be expected. This could also indicate spatial and temporal mismatches between primary production and higher trophic species. To determine why this effect is more pronounced in prey fish, additional understanding of the functioning of the modelling is required.

Likely, a combination of these factors may explain the simulated trend of fewer prey fish biomass. Further research is required which of these processes are dominant and to what extend these processes are a model artifact or a realistic ecological process. The results suggest that OSMOSE-NS responds to the spatial distribution and timing of food available to fish, not to the total amount of primary production. Whether this is true requires more rigorous testing and analysis of scenarios that is beyond the scope of this study. Predation may amplify the response but cannot explain the strong decline in the south-east.

4.2.2 EwE-NS

On the large-scale of the food web on the North Sea, the model EwE-NS produces a logical biomass allocation between prey fish, mid-range predators and apex predators. Prey biomass is largest and an order of magnitude larger than apex predators, which constitute the trophic level with the lowest biomass. However, there are some key elements in the outcomes that require further elaboration, including the spatial homogeneity of the results and the dip in prey fish biomass in summertime.

EwE-NS transmits changes in primary production only weakly and very globally. Phytoplankton peaks, which are more than twice as high in the Ems and Rhine plumes during summertime, were not matched by proportionally larger biomass in prey fish (increase up to 15 %) in the model. At the same time, a decrease in prey fish biomass up to 20 % was observed in the northern effect areas of the simulations, whilst phytoplankton peaks also occurred there. The observed change there seems not fully attributed to local changes in primary production. Rather, the functionality of EwE, as a mass balance model, may dilute changes over a large spatial scale. Energy is redistributed through the whole food web, where fish biomass is spread over space based on habitat suitability, which by default is homogeneous. The very gentle gradients are therefore a property of EwE-NS and not ecological evidence per se.

This may also explain why the local increases in phytoplankton during summertime near the Scottish Isles and in the German Bight in the *Partial Revision* scenarios do not lead to a similar relative local increase in prey fish biomass.

Similarly, the *Partial Revision +10 %* simulation, which amplified changes in primary production by 10 %, produced only minor biomass responses: less than 4 % for prey fish and less than 2 % for predators. Relative to the base *Partial Revision* scenario, these simulations showed greater local clustering of biomass. This result suggests that the model is primarily sensitive to large changes in primary production. Under smaller perturbations, biomass patterns appear to be governed more strongly by other processes, such as top-down control.

The summer dip in prey fish is hard to reconcile with bottom-up control. If primary production limited prey fish, the late spring and summer phytoplankton blooms should be followed by an increase in prey fish biomass, like in OSMOSE-NS. Instead, prey fish biomass declined in EwE-NS. The delayed dips in other demersal fish (June to August) and gadoids (August to October) followed the prey fish dip, which is consistent with how a perturbation propagates up the food web. Yet, this leaves the dip in prey fish biomass during summer unexplained. Whilst the limited set of simulations in this study do not identify the cause, there are a few topics that may require further investigation:

- *Age-structure dynamics*: Herring showed the largest seasonal oscillation in biomass and were modelled with juvenile and adult stanzas. So, internal stanza dynamics could in theory create these oscillations, but this is unlikely to be the main cause. Stanza cycles in EwE normally follow the age of cohorts and last several years. They are not tied to the calendar year. There may be some forcing in phase of the phytoplankton biomass, which could lead to amplification of the response. This may be tested by running a year-round flat primary production. If herring still oscillates, the cause is internal. If not, it is forced;
- *Turnover and top-down control*: Prey fish predation may be elevated during summer. Rather than the increased primary production resulting in more prey fish biomass, this increase in production could be captured by mid-range and apex predators. This may explain the relatively large proportion of apex predators in EwE-NS compared to OSMOSE-NS. However, there are two trends that argue against this: (*i*) the weak propagation pattern of other demersal fish (and to a lesser extent: gadoids), and; (*ii*) the aggregations of mid-range and apex predators remain nearly constant year-round. Given the constant mid-range and apex predator biomass, predation on prey fish can only rise if predators start eating more prey or switch their diet. Neither is expected given the diet matrix in EwE-NS. Constant predator biomass does not prove constant predation, so monthly predation mortality on prey fish should be investigated. However, this is not a standard output of EwE-NS and requires additional postprocessing steps to derive.

4.3 Comparison OSMOSE-NS and EwE-NS

4.3.1 Comparison of *Partial Revision* scenario results

At a high level, the two models give a broadly similar picture of the North Sea. In both, prey species are concentrated in the southern half and appear to respond most strongly to primary production, as expected. Mid-range predators are fairly homogeneously distributed across the North Sea, whilst apex predators predominantly occur in the northern half of the North Sea. This distribution of fish is probably also partly evolved due to the impacting force of the habitat initialisation maps in the case of OSMOSE-NS and a minimum food threshold per time step, which seems to prevent particularly prey fish and apex predators from spreading across the whole North Sea.

Absolute biomass comparison between OSMOSE and EwE is not possible as in EwE the mass balance is rescaled to match the value it was validated on. Comparing both model results in relative terms shows a contradictory response to the *Partial Revision* scenarios. The Deltares input from the *Partial Revision* scenarios provides local changes in primary production, with a net increase over the North Sea. Counterintuitively, in the OSMOSE-NS, this results in a net decrease in biomass. Locally, such decreases can amount up to 60 %, with no apparent connection to local changes in primary production.

On the other hand, EwE-NS does show a net increase in biomass, yet the spatial connection between primary production and fish biomass is weak. Locally, changes in biomass amount up to a 10 % increase in the northern parts of the North Sea, and 5 % decrease in the southern parts of the North Sea.

In both models, amplifying the changes in primary production by 10 % had limited effect on the results. This is consistent with the general attenuation of production changes at higher trophic levels (<10 %). The response of OSMOSE-NS to the amplified primary production changes was relatively linear, whereas EwE-NS showed increased spatial aggregation (which could also be linear-like). In EwE-NS, the large local increases in phytoplankton biomass near the Ems and Rhine river plumes appear to influence the food web composition across the entire North Sea, owing to the model's mass balance constraint.

4.3.2 Comparison of model behaviour

Group composition

In EwE-NS, flatfish have a much higher biomass relative to the other fish groups compared to OSMOSE-NS. This is partly structural: EwE-NS simply contains more flatfish species, spread across mid-range and apex predators. In OSMOSE-NS, fewer and only mid-range predator flatfish are included. Part of the difference in simulated biomass (relative to the other fish groups) between the models therefore reflects not only the underlying ecology (food web) but also how species were aggregated and represented. Additionally, OSMOSE-NS does not use primary production (PP) directly as an input. To overcome this, the diet matrix of EwE was applied to translate PP into the model (see Appendix I.4). Due to this approach, the models handle the lowest trophic levels (PP to zooplankton and benthos) in a similar fashion.

Spatial patterns

Because of the mass balance constraint and the way EwE works, EwE-NS produces very gentle spatial gradients. These spatial patterns are highly unrealistic. A different setup (e.g. altering fish mobility, which is now the same for all species, and revising the habitat suitability maps) might improve this, but in the current configuration OSMOSE-NS gives a more realistic spatial distribution in comparison with EwE-NS, yet remain unvalidated with in-situ measurements. It is also interesting that depth is not explicitly included in the models, yet its influence seems partly visible in the distribution of the fish groups across the North Sea. This could be a result of the apparent dominant force of habitat initialisation. There are additional processes at play that may affect the spatial distribution of species in case of OSMOSE-NS. Firstly, fish have a minimal food threshold that must be met every time step to prevent mortality. And since every mid-range and apex predator has their own diet preferences, this may create soft boundaries in the model for species to stay in certain areas on the North Sea. Secondly, fishing pressure may remove species from certain areas of the North Sea to such a degree that a large sustainable population cannot form.

These hypotheses, however, cannot really explain the similar trend in EwE-NS, which has very gentle spatial gradients and fishing pressure in the whole the North Sea in the mass balance (instead of spatial and temporal co-occurrence of fish and fishing vessels like in OSMOSE-NS).

Overview of modelling capabilities

Given their differences in structure and functionality, the two models offer different strengths and limitations for addressing specific research objectives within the field of ecosystem modelling. Therefore summarizes possible components of interest and evaluates the suitability of each model for analysing them. Per aspect, the suitability is categorised into 'suitable', 'not suitable' or 'suitable with limitation'. In case of the latter, the limitation is provided.

Table 4.1 Suitability of EWE-NS and OSMOSE-NS for different objectives related to ecosystem modelling

Objective	EWE-NS suitability	EWE-NS limitation	OSMOSE-NS suitability	OSMOSE-NS limitation
explore temporal food-web responses	suitable with limitations	only intertemporal changes within mass balance (fixed diet matrix)	suitable with limitations	effect dependent on dominance of driving force, allowing for (more realistic) dynamic food web relationships
translate local changes in primary production into fish responses	suitable with limitations	dependent on driving force of PP and other influential model settings	suitable with limitations	dependent on driving force of pp and other influential model settings
incorporate response of species to abiotic changes (including hydrodynamic changes or climate conditions)	suitable		suitable	
incorporate spatial exclusion of fisheries	suitable with limitation	the spatial module of EwE (Ecospace) as applied in this study resulted in relativity homogenous (unrealistic) output. Additional model development may be required to improve reliability of results	suitable	
explore role of or changes in lowest trophic level interaction (e.g. zooplankton en benthos)	suitable with limitation	defined through diet matrix	suitable with limitation	allows for more custom parametrization
produce absolute biomass changes based on different input data	suitable with limitation	may require recalibration of model configuration	suitable	
run large simulations for multiple scenarios within a day	suitable		suitable with limitations	running simulation including movement tracking per species group requires large amount of memory and computational power (cluster access necessary)
incorporation of birds in the ecosystem model	suitable with limitations	depending on the availability of models containing birds in the Ecopath database	not suitable	model is not configurated for airborne species
incorporation of marine mammals in the ecosystem model	suitable	already included	suitable with limitations	mammals of interest must be included in the species list (including role in food web)

4.4 Conclusion and recommendation

We assessed how OWF-induced changes in primary production may propagate to higher trophic levels using OSMOSE-NS and EwE-NS. Given the limited number of simulations conducted, the results should be interpreted as indicative rather than conclusive. Nevertheless, both models consistently showed that changes in fish biomass were less pronounced than the forced changes in primary production, both in magnitude and spatial extent. Across the simulations, the estimated OWF effects ranged from net biomass gains to net biomass losses, indicating crucial uncertainty in the response.

Based on the conceptual structure and model results, EwE-NS appears less suitable than OSMOSE-NS for addressing for spatial responses to OWFs, which may be insightful to asses cumulative impacts.

EwE-NS is strong in ensuring a consistent, balanced food web. However, the added value of a 2D spatial domain is limited. It proves a much more useful and fast tool by considering the whole of the North Sea as a single basin (1D), as was done in e.g. Hill et al. (2021). In contrast, OSMOSE-NS provides a more explicit representation of the spatial structure of the food web and is therefore better suited to assess spatially heterogeneous responses to changes in primary production. Therefore, we believe that OSMOSE-NS can, in principle, be used to investigate the effects of OWFs, as these individual farms affect primary production patterns (amongst others) on a scale much smaller than the whole of the North Sea. Still, the findings of OSMOSE-NS seem in part counterintuitive, which asks for further study.

It should be noted that EwE-NS has many functions which were not explored within this study. This includes input parameters such as temperature, current and wave dynamics and species tolerance thresholds. Including such functionalities into the study may provide additional insight and lead to spatial results that are more in line with our current understanding of how the food web on the North Sea functions. Then again, this does not overcome the mass balance constraint, which makes it less applicable to our context.

We therefore recommend to explore the OSMOSE-NS model further and investigate how OWF-induced changes affect higher trophic species.

Based on our first exploration, we have included some disclaimers, which could provide a starting point for additional research:

- *additional input data*: In the current study, a limited set of primary production data were extrapolated and used as input data. This had introduced a number of limitation to this study. One example of this, is that for the EwE modelling, the North Sea configurations were maintained as much as possible, as this configuration was validated and reliable (pers. com. EwE-support). Including more or different (changes in hydrodynamics) output from the Deltares studies, may allow for different analysis providing a better insight into possible response of the ecosystem to OWFs;
- *timing of ecological processes*: A key hypothesis, also indicated by Zijl et al. (2024), is that changes in primary production may also cause misalignment of ecological processes. Our OSMOSE result indicate that such changes may occur, through the habitat initiation of species. Based on our limited explorative study, we cannot assess if this is function is an accurate representation of the underlying ecological process. at this time if the part. A deeper understanding of possible misalignment of primary production and the presence of species may especially relevant in combination with climate change (e.g. earlier spring blooms may even affect breeding success of birds (Benninghaus et al., 2026). As discussed, timing of growth and recruitment was not included in the current modelling, but may be value in addressing cumulative impacts of OWFs.
- *research into zooplankton interaction*: In this study, the role of zooplankton is oversimplified, while we know that this group plays a crucial role in the energy transfer from primary production to the food web. At the same time, this group is so diverse that it is challenging to develop a representative model. Within MONS research program, dedicated research into zooplankton of the North Sea is included. This research could improve their representation in existing and new ecological models, if research results can be linked to the presence of OWFs;
- *exploration of sensitively to top-down or bottom-up*: In this study, we forced changes at the bottom of the food web and investigated how this affected higher trophic levels. Some of our results seem to show that top-down forces on the ecosystem may be more dominant. Rather than improving the ecological models, we can also investigate which species groups are sensitive to bottom-up changes using the existing models. This could result in a smaller group of sensitive species, which provides a smaller research scope for future studies;
- *additional scenarios and analyses:* In this study, we explored three scenarios to model the effects of OWFs and study the sensitivity of the model outputs to primary production input. As the base model infrastructure is now developed, investigation of additional scenarios can be run with relatively limited effort. This includes e.g. further amplification of primary production changes, different OWF scenarios and changes in diet matrices. Moreover, the current setup allows for ecological analysis of other aspects aside from biomass that may be analysed. This includes species composition and timing of ecological processes, which can provide more insight into possible ecological changes. Finally, additional analysis of the current modelling may be possible, such as determining turnover rates within the simulation. As we

see a drop in prey biomass, it may be possible that a large part of this biomass is overturned into higher trophic species;
- *additional model(s)*: The ensemble approach taken in this study is valuable, as it increases confidence in the results in a highly complex system. However, to address spatially explicit questions, EwE has fundamental constraints. Rather, we see opportunities making use of models being developed within the Ecowind research program (e.g. Trifonova et al., 2025) or other similar ecological models.

Ultimately, this study has explored the feasibility of two existing ecological models to assess the impact of OWFs on the ecosystem. Given the above mentioned disclaimers and the bandwidth of the model results (up to 50 % decrease for OSMOSE and 5 % decrease in EwE[1]), a clear conclusion of the impact of OWFs cannot be drawn. At the same time, these models provide ample opportunity to improve understanding of consequences of changes in the lowest part of the food web induced by offshore wind farms for higher trophic species.

[1] Both examples are extreme outcomes of the models. See appendix II for a comprehensive overview of results.

5

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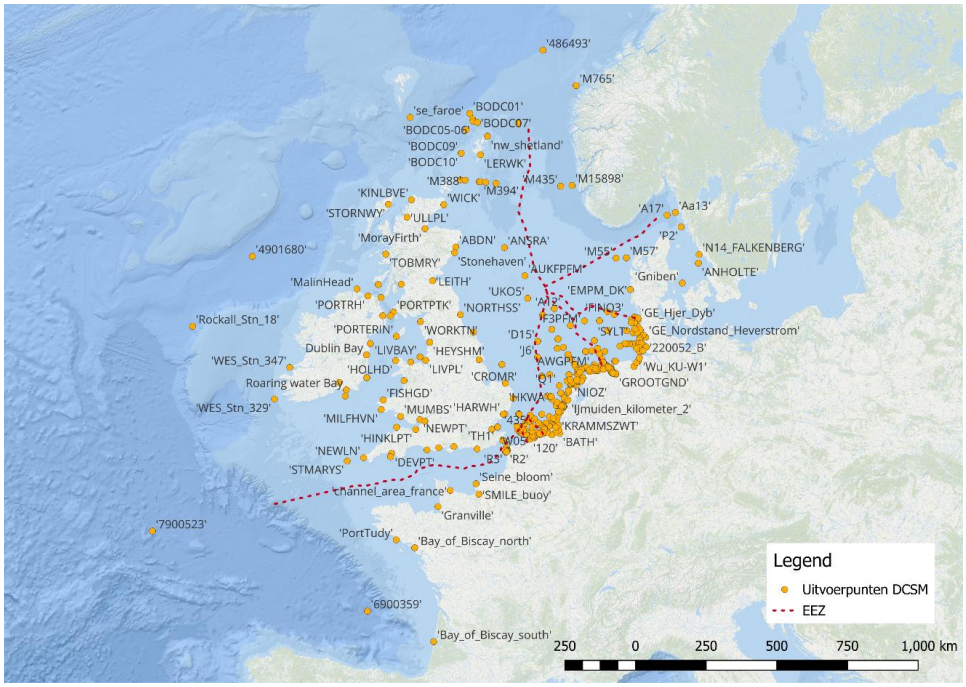
Appendices

Appendix: Preprocessing the Deltares output

Deltares modelled the potential hydrodynamic and ecological impact of large-scale OWF development on the North Sea through multiple OWF scenarios using a flexible mesh hydrodynamic model (van Duren et al., 2021; Zijl et al., 2023, 2024). Grid size varied from about 1 km near the coast up to 10 km further offshore. The grid size disallowed for an explicit representation of the individual piles of wind turbines in the model schematisation; instead, their impact on water movement was incorporated through a parameterised drag formulation. Per grid cell within an OWF polygon, the combined effect of the monopiles was determined based on their average diameter and spatial density. Hydrodynamic output included variables such as water temperature, salinity, water depth, currents and heat fluxes per timestep over a one-year simulation period. For a full explanation of the Deltares model setup, scenarios and output, the reader is referred to Zijl et al. (2024) and other Deltares reports in the reference list (chapter 5).

In this study, the Deltares output of two scenarios was used: a scenario without offshore wind farms (*No OWFs*) and scenario 4 of the *Partial Revision* (see section 2.3.2 of Zijl et al. (2024)). For both scenarios, daily output on chlorophyll-a, primary production and phytoplankton carbon (unit: gC/m^2/day) were available at **predefined output locations** (Figure I.1). In addition, **maps** of the spring-averaged (only scenario *No OWF*) and annual-averaged primary production (both scenarios) were available for the entire numerical grid. However, maps of primary production per time step were lacking. Therefore, the daily output data at predefined output locations and the maps of spring-averaged and annual-averaged primary production were used to reconstruct maps of primary production per timestep.

Figure I.1 Daily output locations of the Deltares model (Source: Deltares). Note that output locations are concentrated near the coast of Belgium, the Netherlands, Germany and Denmark, with little representation offshore



This model study adhered to the biweekly time step of OSMOSE-NS and the monthly time step of EwE-NS. As full spatial coverage data were not available (only for output locations in the following preprocessing steps had to be undertaken:

1 *Outlier handling:* disregarding unrealistically high values near coastlines and model grid boundaries;
2 *Simulation of time-series*: extrapolating the daily output to timeseries for each grid cell;
3 *Validation*: recalculating annual-averaged maps and comparing with the Deltares output;
4 *Input files preparation:* EwE-NS takes as input phytoplankton biomass (no conversion necessary), but OMOSE-NS requires biomass of the next lowest lower-trophic-level groups as input, which requires an additional conversion.

I.1 Outlier handling

The distribution of the raw Deltares output data clearly shows for both scenarios and their corresponding daily datasets a large number of extreme values. Whilst the Deltares model is known to have difficulty predicting primary production near the model grid boundaries, there was also a considerable number of outliers present within the smaller target grid used in this study. Therefore, a sanity boundary condition was applied (i.e. capping off negative and extreme values) such that all primary production falls between 0 and 20 gC/m^2/day.

I.2 Simulation of time-series

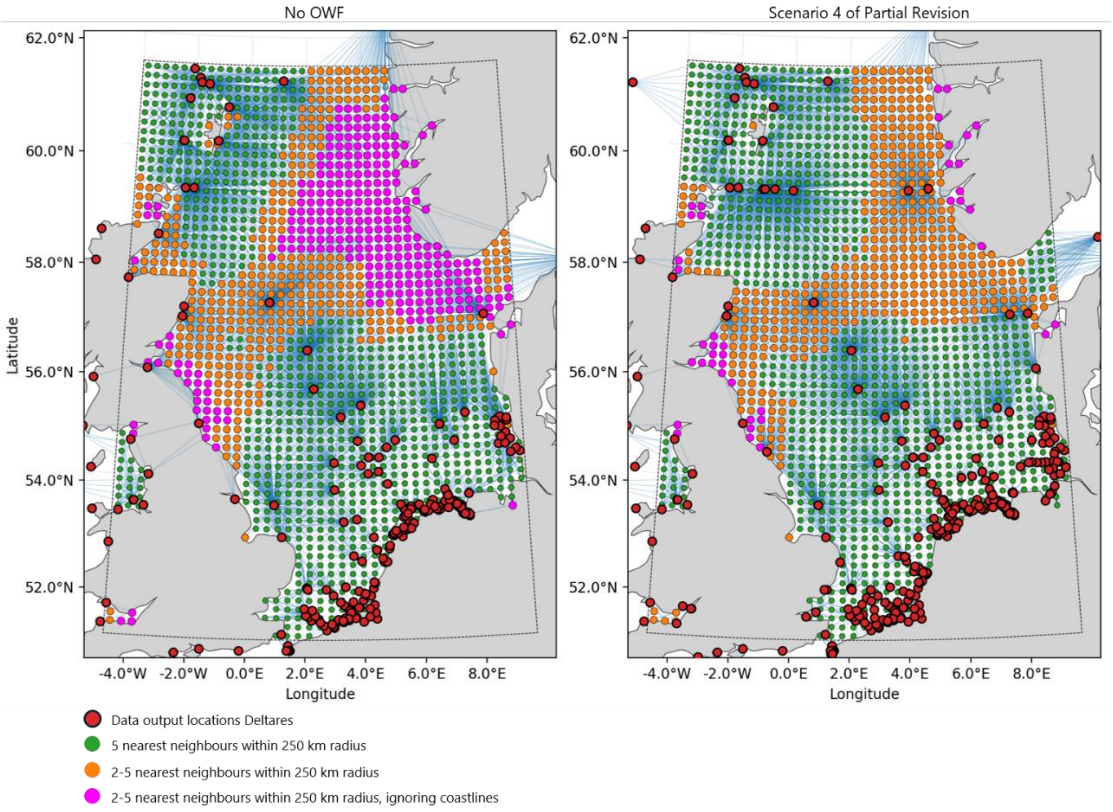
The next step was to simulate an annual time-series of primary production for each grid cell for which only a yearly averaged value was available. The aim was is to develop realistic daily time-series that preserve the spatial and temporal variability in the available Deltares data as much as possible.

Time-series with a known seasonal structure can be reconstructed using several approaches. This study used a weighted k-nearest-neighbour ((k)NN) reconstruction with an additional rescaling factor to preserve the annual mean This was done as follows. For each grid point, the $k = 5$ nearest reference points within the daily output dataset were identified and a distance-weighted average of their daily time series was calculated, assigning greater weight to closer neighbours. This provides a reconstructed daily temporal pattern for the target grid point. A maximum distance of 250 km was applied and connectivity was in principle only possible if the line-of-sight to the daily output datapoints was unobstructed by coastlines. This was done to make sure no interpolations would happen across e.g. the isle of the United Kingdom towards completely different seas. If less than 2 daily output datapoints were in line-of-sight within 250 km, the coastline was ignored. This mainly happened for grid cells in tidal bays and fjords. Only in a handful of locations did this method lead to unrealistic interpolations (e.g. across the isles of the United Kingdom). Given their location at the boundary of the grid, this was deemed acceptable for the aim of this study.

The southern part of the study area generally satisfied the $k = 5$ criterion, with several nearby daily-data locations, whereas points in the central and northeastern parts of the North Sea were less well connected to fewer locations (Figure I.2). The degree of connectivity provides an indication of the spatial support available for reconstructing the daily time series. Grid points with more nearby reference locations are expected to have a more representative and robust reconstruction, while those with fewer connections may be associated with greater uncertainty. As there are more daily output locations in the scenario 4 of the *Partial Revision*, general connectivity and representation is better than the scenario *No OWF*.

Next, the reconstructed daily time-series of each grid cell was rescaled linearly (all values multiplied by a single factor) so that the reconstructed annual mean matched the simulated annual mean by Deltares. Thus, the method preserves the spatial variation represented by the annual dataset while introducing a plausible seasonal pattern based on nearby locations with daily observations. Finally, the sanity boundary condition was applied again, capping off values to the range 0 to 20 gC/m^2/day.

Figure I.2 Nearest neighbours used to derive a temporal signal for each grid cell using the daily output data (red dots) by Deltares. Confidence declines as the number of nearest neighbours decreases from 5 (green), to 2-5 (orange) to 2 (magenta). Note that the number of data output locations by Deltares is larger for the scenario 4 of the *Partial Revision*



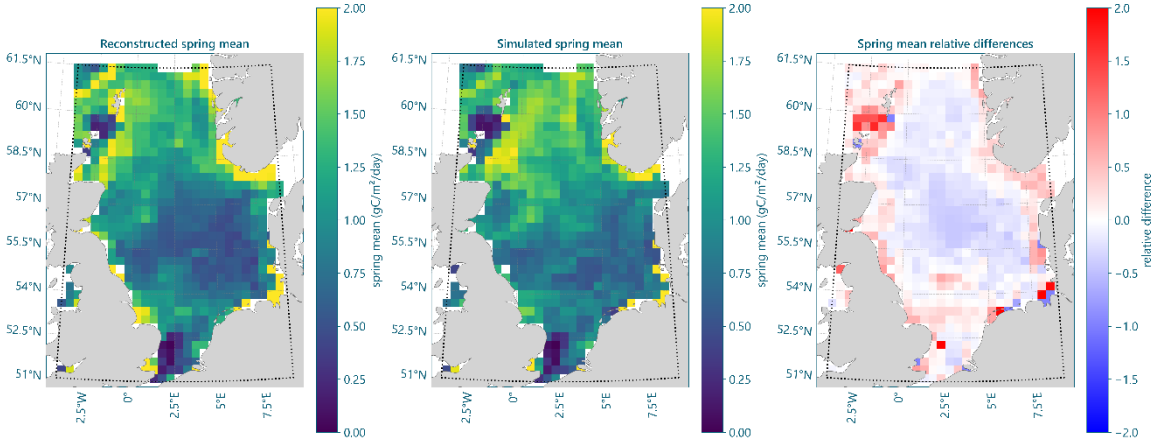
I.3 Validation

The third step was the validation of the simulated time-series by comparing the reconstructed spring mean maps with the calculated spring mean maps by Deltares. This provided insight in whether the reconstructed signals reproduced similar characteristics as the Deltares data. For the scenario *No OWF*, this was done using the simulated spring mean maps by Deltares. For the scenario 4 of the *Partial Revision*, no such map was available; instead, the spring means were calculated using the daily output locations only.

Scenario *No OWF*

In Figure I.3 this comparison is presented with a capped colour range to improve legibility (such that outliers up to 20 gC/m^2/day do not dominate). Generally, the reconstructed spring means are comparable to the simulated spring means by Deltares. Along coastlines, the reconstructed signal shows an overestimation of primary production, whereas in the central parts of the North Sea, the reconstructed signal shows an underestimation of the spring mean. The greatest outliers are at the edges (e.g. German Bight and Thames Estuary), which corresponds with locations of outliers in the original dataset by Deltares.

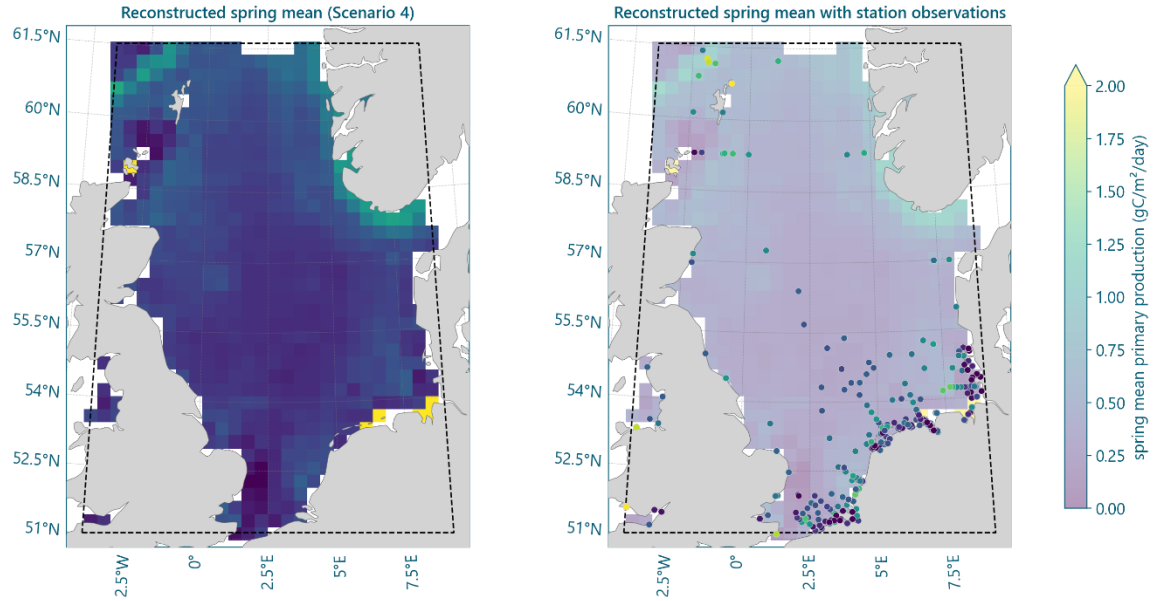
Figure I.3 Validation of reconstructed spring means against simulated spring means by Deltares in the scenario No OWF. (left) reconstructed spring means; (center) simulated spring means by Deltares; (right) relative difference between the two, calculated as the reconstructed minus the simulated spring means divided by the simulated spring means. Colour range is capped at 2 gC/m^2/day for improved legibility



Scenario 4 of *Partial Revision*

Comparison of the reconstructed spring mean with the spring means of the daily output locations shows generally similar trends (Figure I.4 Exceptions include some cells in the German Bight and at the northern tip of Scotland where a single daily data point seems to dominate in the reconstructed signal, producing a much larger value than is apparent from the other nearby daily data points. As the number of affected cells is low and their very locally position at the edges, the effect of such cells on the large-scale patterns on the North Sea was deemed to be limited.

Figure I.4 Comparison of the reconstructed (this study) and simulated spring mean primary production data points (dots in right panel) of the scenario 4 of the Partial Revision. The colour scale is capped at 2 gC/m^2/day to focus on the lower end of the spectrum. The colour range is the same in both panels



I.4 Input files preparation

Because OSMOSE-NS does not use primary production (PP) directly as an input, the available PP first had to be translated into the lowest-trophic-level groups that are represented in the model. In the OSMOSE-NS configuration, these groups are microzooplankton (microz), mesozooplankton (mesoz), deposit feeders (depfed), suspension feeders (susfed) and meiobenthos (meiob). Although five separate lowest-trophic-level groups are included in the model, their functioning in the diet matrices of OSMOSE-NS overlaps. Applying the standard OSMOSE-NS schematisation thus results in two different groups: zooplankton (microzooplankton and mesozooplankton) and benthos/feeders (deposit feeders, suspension feeders and meiobenthos).

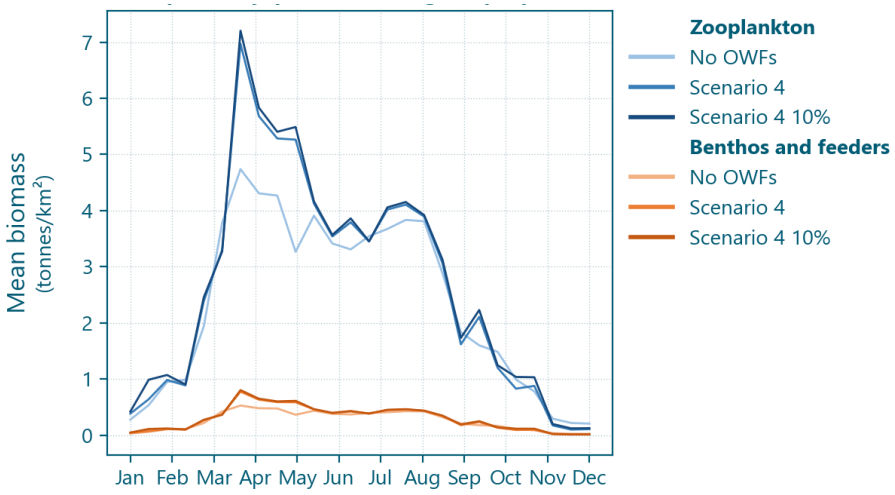
As opposed to OSMOSE-NS, EwE-NS includes a diet matrix that does describe how PP is divided between the lowest-trophic-level groups. Therefore, the diet matrix of EwE-NS was used to determine how the PP in OSMOSE-NS was translated into the two main groups (zooplankton; benthos/feeders), whilst also accounting for energy loss from PP to the next trophic level.

More specifically, a hypothetical 100 g wet weight of PP (~11 gC PP) (Link et al., 2006) was divided over the five groups in this study as follows, assuming an oversimplified 90 % energy loss:

- Microzooplankton: 4.285 g wet weight;
- Mesozooplankton: 4.285 g wet weight;
- Deposit feeders: 0.477 g wet weight;
- Suspension feeders: 0.477 g wet weight;
- Meiobenthos: 0.477 g wet weight.

In figure I.5 the resultant mean biomass of the whole North Sea is shown that was used as input to the OSMOSE-NS simulations. The biomass of zooplankton is about an order of magnitude larger than that of the benthos and feeders. An explanation of the scenarios is presented in the section 2.4 in the main report.

Figure I.5 The mean biomass allocation to the two main groups of the lowest trophic level based on the primary production by Deltares, used as input in the OSMOSE-NS simulations



II

Appendix: Additional model output

This appendix includes model output that are relevant for building and improving understanding of how changes in primary production may propagate to higher trophic levels but was not included in the main report.

II.1 Deltares

Figure II.1 bar plot of data output of Deltares scenario #4

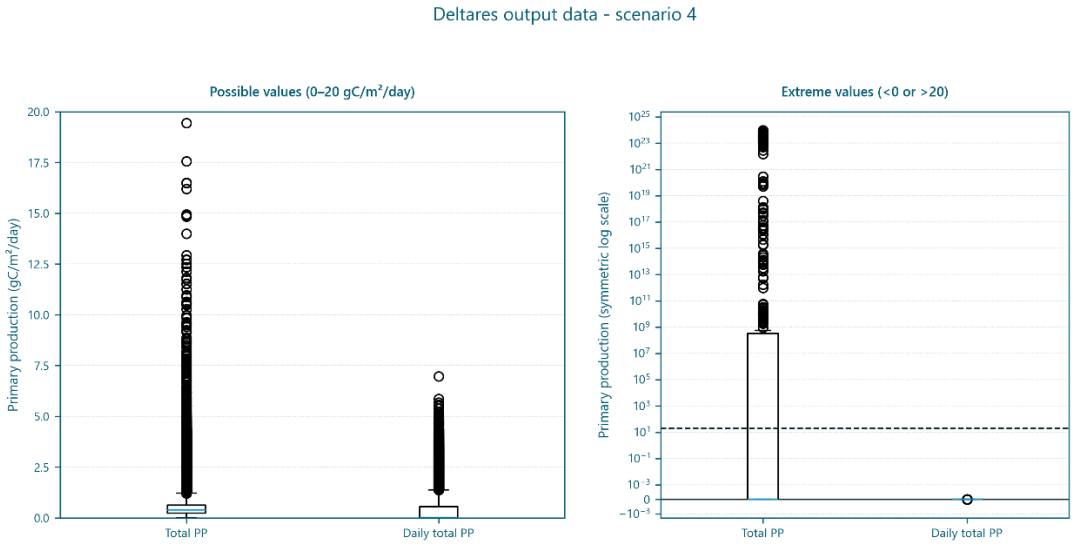
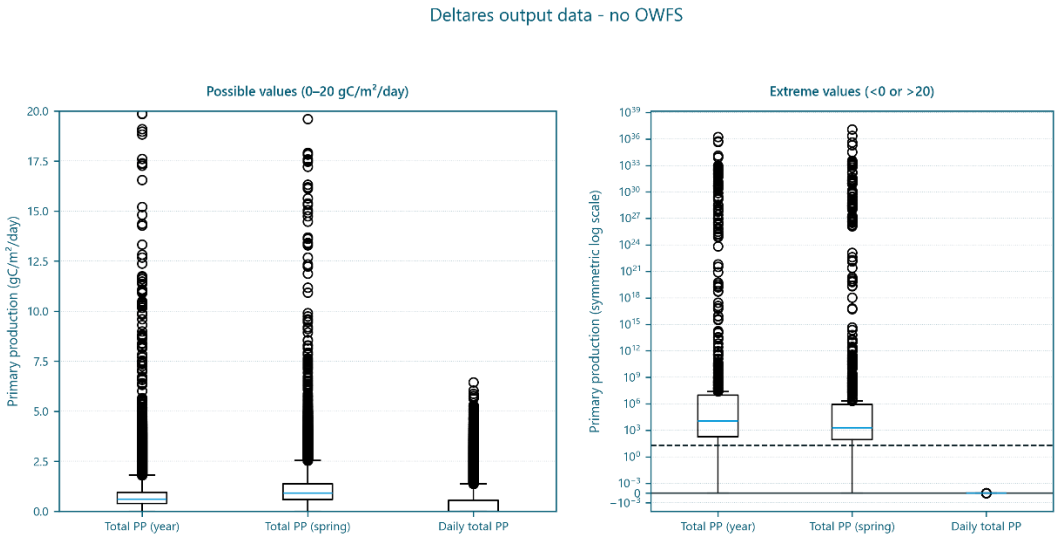


Figure II.2 bar plot of data output of Deltares scenario with no OWFs



II.2 OSMOSE-NS

Figure II.3 Temporal development of biomass per species, normalised against their yearly averaged biomass. Data includes the whole of the North Sea and the colour family signifies the trophic level of the species: apex predators (brown), mid-range predators (amber), prey fish (green). Model: OSMOSE-NS

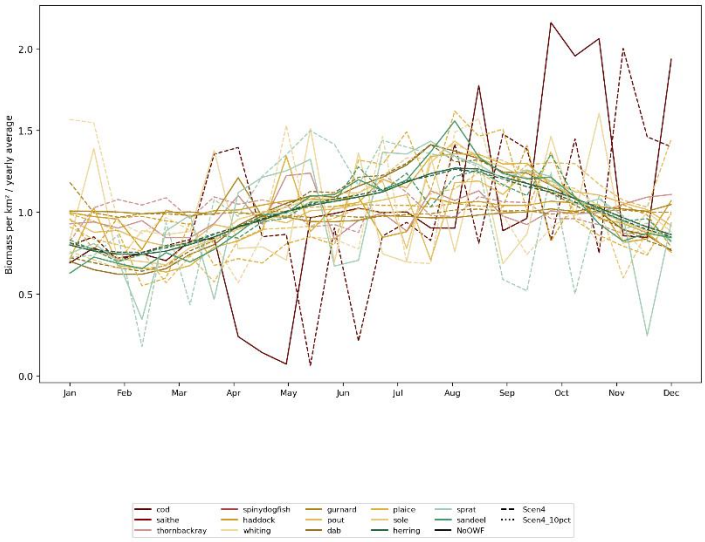


Figure II.4 Temporal development of biomass of phytoplankton (blue; left vertical axis) and of the three trophic levels of fish (brown, amber and green lines; right vertical axis) for the different effect areas in the North Sea for the scenario No OWF (continuous line), Partial Revision #4 (dashed line) and Partial Revision #4 +10% (dotted line). Model: OSMOSE-NS

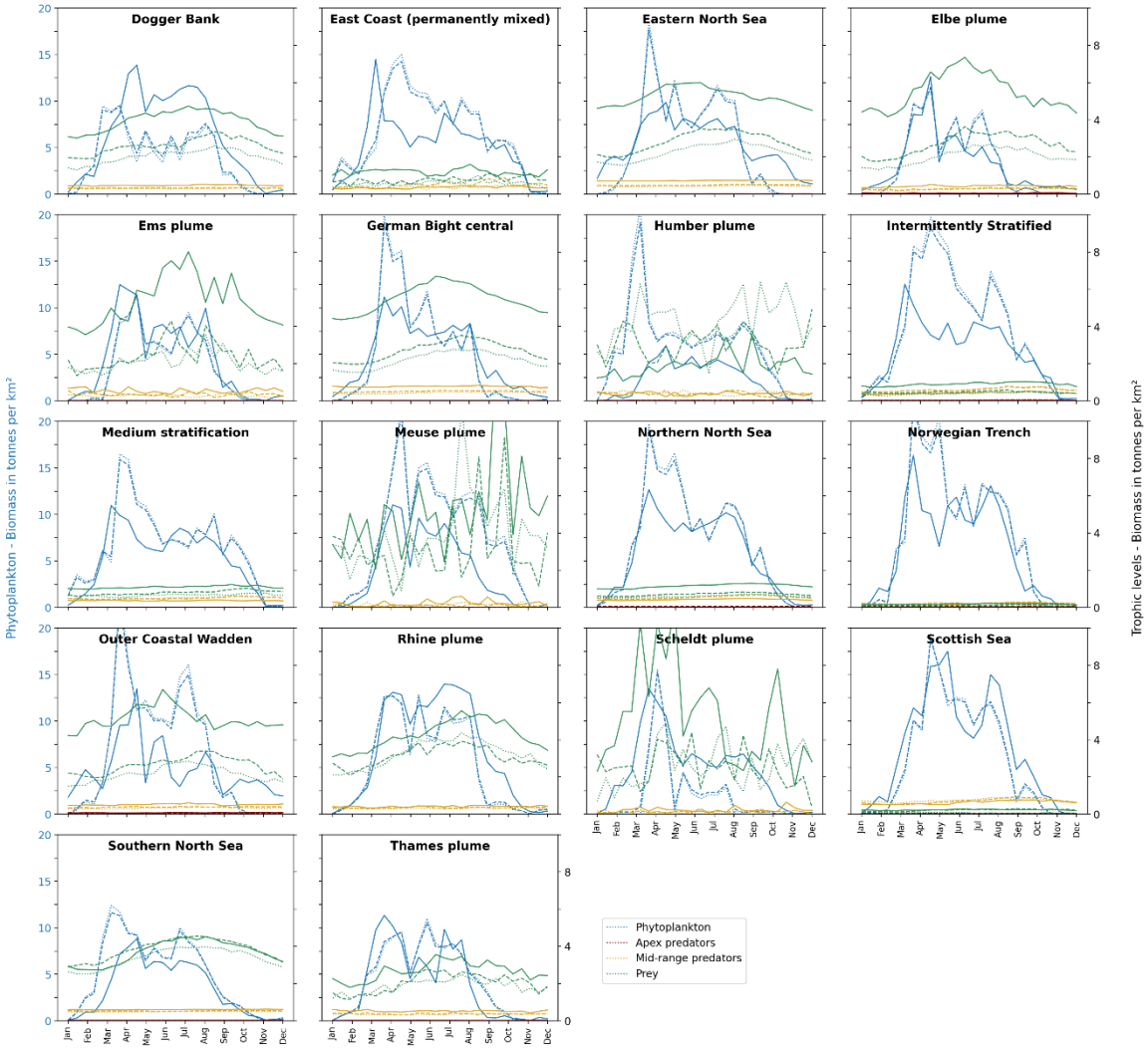
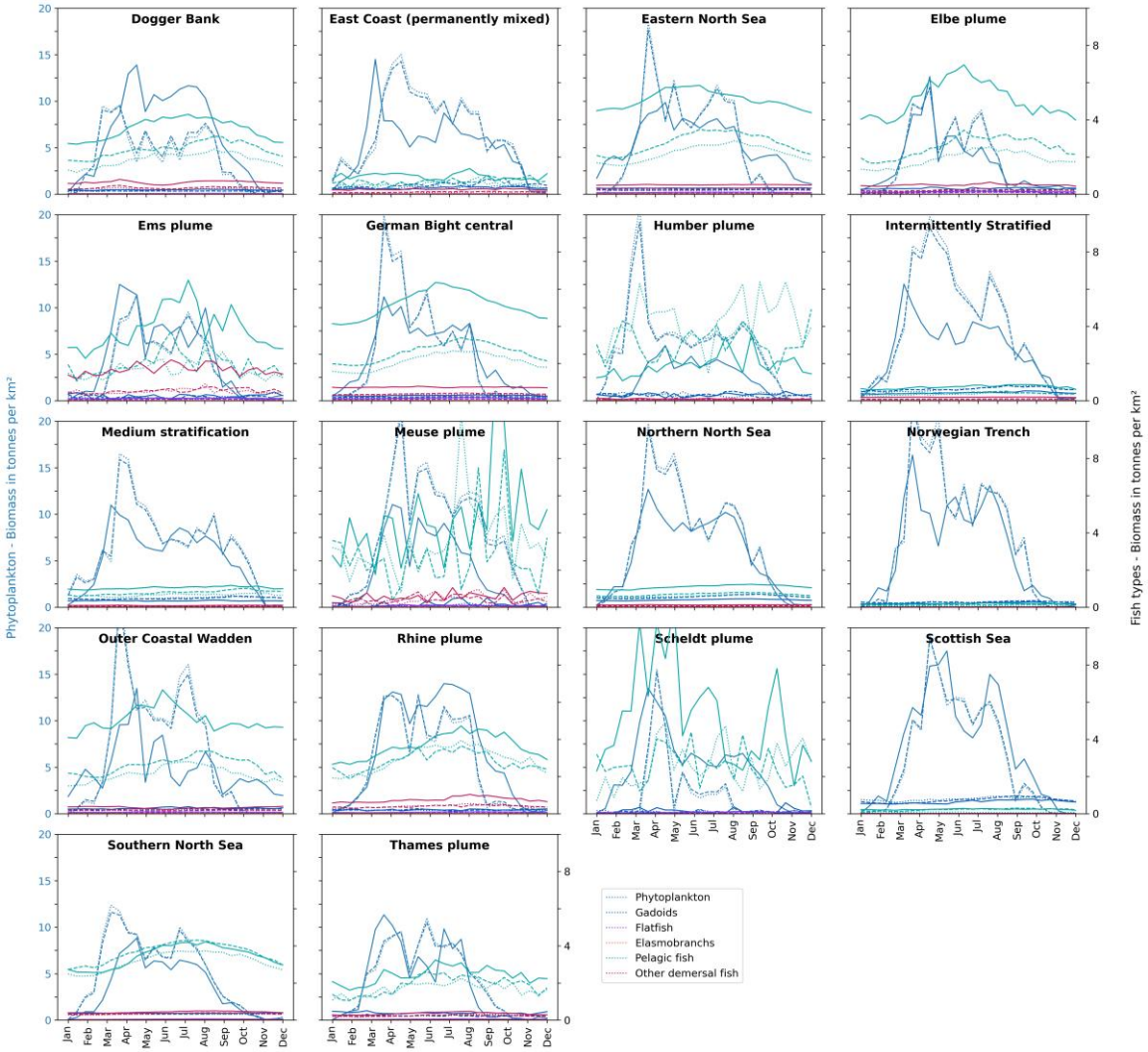


Figure II.5 Temporal development of biomass of phytoplankton (blue; left vertical axis) and of the five fish types (colours correspond to Figure 3.3; right vertical axis) for three different effect areas in the North Sea for the scenario No OWF (continuous line), Partial Revision #4 (dashed line) and Partial Revision #4 +10 % (dotted line). Model: OSMOSE-NS



II.3 EwE-NS

Figure II.6 Temporal development of biomass per species, normalised against their yearly averaged biomass. Data includes the whole of the North Sea and the colour family signifies the trophic level of the species: apex predators (brown), mid-range predators (amber), prey fish (green). Model: EwE-NS

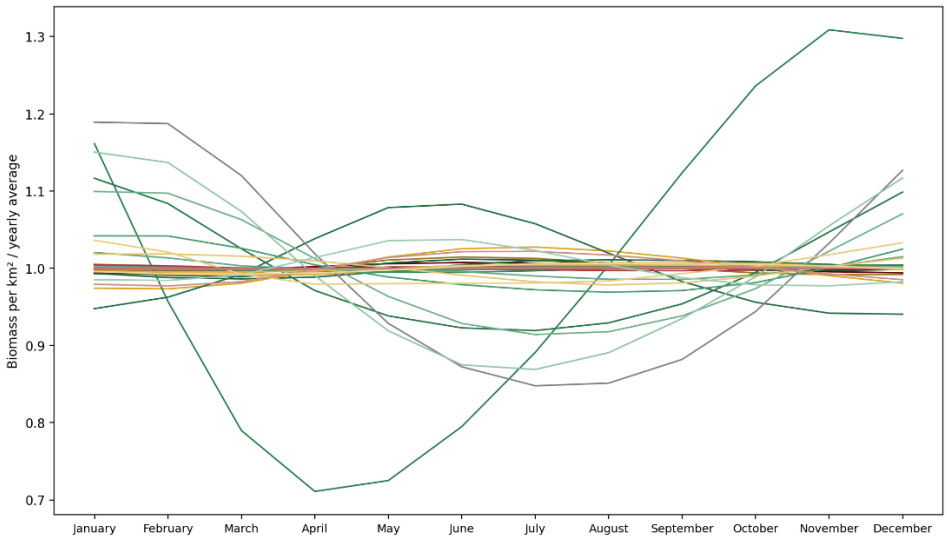


Figure II.7 Temporal development of biomass of phytoplankton (blue; left vertical axis) and of the three trophic levels of fish (brown, amber and green lines; right vertical axis) for three different effect areas in the North Sea for the scenario No OWF (continuous line), Partial Revision #4 (dashed line) and Partial Revision #4 +10 % (dotted line). Model: EwE-NS

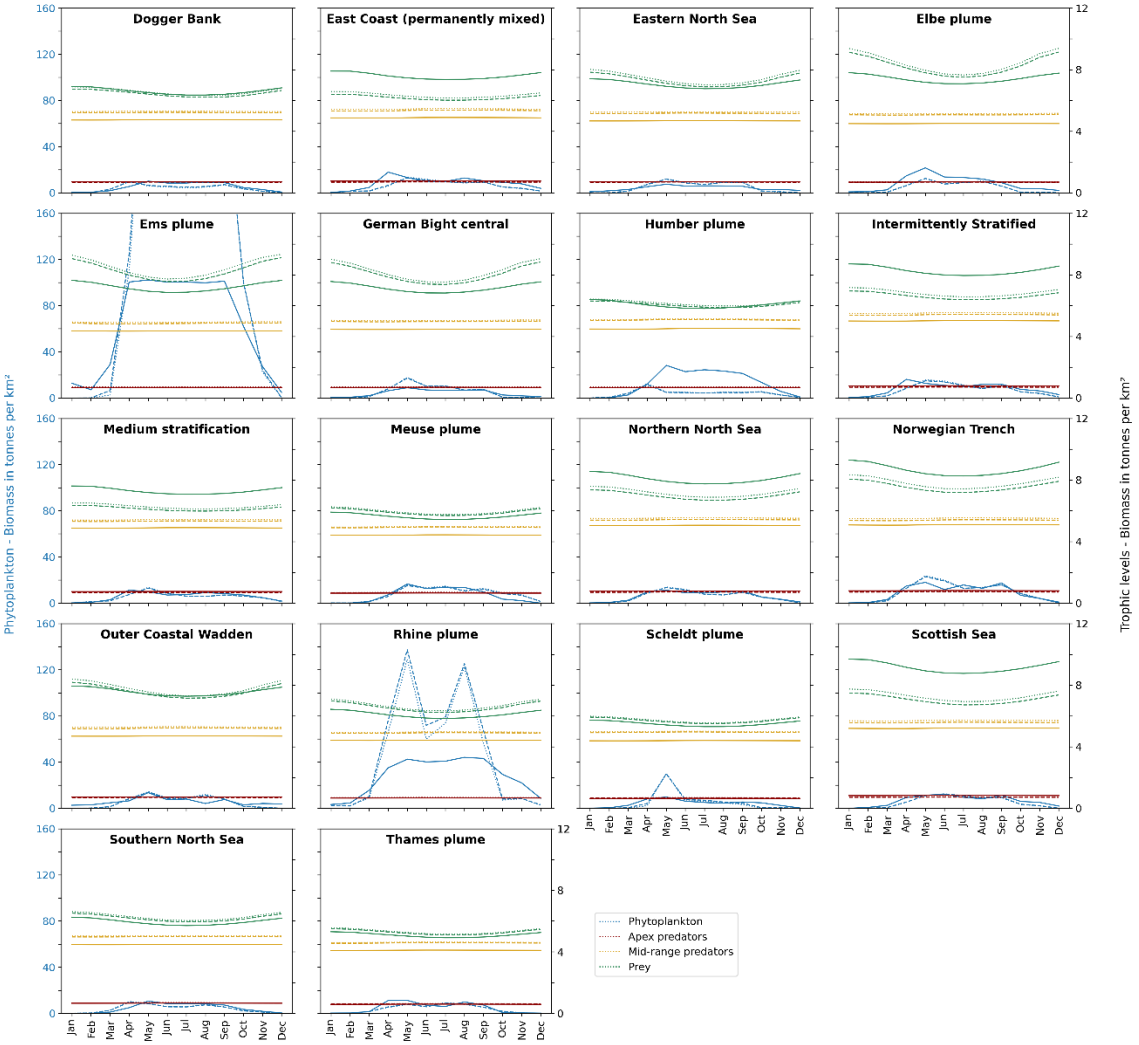

Dogger Bank
East Coast (permanently mixed)
Eastern North Sea
Elbe plume
Ems plume
German Bight central
Humber plume
Intermittently Stratified
Medium stratification
Meuse plume
Northern North Sea
Norwegian Trench
Outer Coastal Wadden
Rhine plume
Scheldt plume
Scottish Sea
Southern North Sea
Thames plume
Phytoplankton - Biomass in tonnes per km²
Trophic levels - Biomass in tonnes per km²
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Phytoplankton
Apex predators
Mid-range predators
Prey

Figure II.8 Temporal development of biomass of phytoplankton (line; left vertical axis) and of the six fish types (stacked bars; right vertical axis) for the different effect areas in the North Sea for the scenario No OWF. Model: EwE-NS

