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Modelling multi-use within selected OWF of the Dutch North Sea

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Summary

This study provides the first assessment of bottom-up cumulative effects of multi-use within offshore wind farms in the Dutch North Sea, focusing on seaweed aquaculture, mussel aquaculture, and offshore floating photovoltaic (OFPV) deployments. Three scenarios were developed: a current scenario deploying multi-use within three OWFs (Borssele, Hollandse Kust Zuid, and Hollandse Kust Noord) using available aerial passports as guidance, and two tendered scenarios deploying multi-use within six Offshore Wind Farms (OWFs) from the Routekaart Windenergie op zee 21GW plan without predefined spatial allocations. These scenarios allow comparison between discrete small-scale deployments and lumped large-scale deployments.

The modelling approach used the 3D Dutch Continental Shelf Model – Flexible Mesh (DCSM-FM) with Delft3D-FLOW and Delft3D-Water Quality modules. Multi-use deployments were implemented based on previous studies of individual applications and combined for this analysis. Results show that OWFs, mussel, and seaweed aquaculture have diffuse impacts extending beyond deployment areas, while OFPV causes strong but highly localized effects. All forms of multi-use influence chlorophyll-a concentrations through different mechanisms: seaweed via nutrient competition, mussels through grazing, and OFPV by decreasing light availability. Deployment location and size are critical for aquaculture yield and ecosystem effects.

The limitations of this study include: reliance on previous modelling work, lack of calibration for ecosystem processes, simplified representation of OFPV (light effects only), and absence of field data for validation. Despite these constraints, the findings suggest that spreading and mixing multi-use types within OWFs can minimize negative impacts and optimize co-benefits. The modelling tools are valuable for identifying broad patterns, supporting high-level strategic marine spatial planning. Future work should include experimental field data collection, development of MSFD indicators and thresholds to assess impact severity, and refinement of scenarios as spatial planning data becomes available.

Contents

1 Introduction

The Netherlands aim to enable multi-use of offshore wind farms (OWFs). Potential commercial multi-uses within OWFs include mariculture (seaweed, shellfish), renewable energy (e.g. solar energy, energy storage), passive fishing and nature restoration and development. Multi-use in OWFs influences marine ecology, just as OWFs themselves affect marine ecosystems. However, research on the cumulative effects of multi-use within OWFs is still in its infancy.

In 2023 and 2024, at the request of the Ministry of Infrastructure and Water Management, exploratory studies were carried out on the possible ecological effects of co-use standalone (T. Prins et al., 2024) and in cumulation with each other and OWFs (Prins & Schneider, 2024). Those reports focused on the three forms of multi-use of wind farms in the North Sea: seaweed farming, mussel farming and offshore floating photovoltaic (OFPV).

Using those previous reports as a basis, a model scenario study was conducted with the aim of researching potential bottom-up ecosystem effects of three forms commercial multi-use within OWFs (grey rows in Table 1-1), namely seaweed farming, mussel farming and OFPV. This modelling study did not take the effects of passive fishing and nature restoration areas within OWFs into account. The aim of this modelling study was to simulate semi-realistic deployments of multi-use according to current Dutch policy documents as well as large-scale, unrealistic deployments of multi-use to test ecosystem response.

The 3D Dutch Continental Shelf Model – Flexible Mesh was used to run multi-use scenario(s). This report summarizes the approach and analysis of this modelling study. The remaining subsection of Chapter 1 will focus on what kind of multi-use was simulated, at which locations, and in which type of cumulation. Chapter 2 then describes the technical modelling methods employed, while Chapter 3 presents the modelling results. Chapter 4 discusses the modelling results and Chapter 5 presents an outlook.

1.1 Definition of cumulative multi-use

While this report focuses on cumulative effects of multi-use, we will not carry out a cumulative impact assessment. A cumulative impact assessment (CIA) indicates (through qualitative or quantitative methods) which ecosystem components are most under threat and the main activities and pressures responsible for this threat (Piet et al., 2023). A CIA focuses on all marine activities.

For this study, we will focus only on the bottom-up ecosystem effects that results from one (or more) multi-used OWF area(s). We define cumulative effects as the overall effect a certain set of pre-defined anthropogenic pressures has on the base of the marine ecosystem. In this case those pre-defined anthropogenic pressures are OWFs and multi-use within OWFs. In line with previous reports, we will define multi-use here as seaweed aquaculture, mussel aquaculture and OFPV energy generation within an OWF farm. All three forms of anthropogenic multi-use will take place within one OWF area. This means that the reference is an area with only OWF energy generation to which we add the additional pressures of the other three forms of multi-use. Figure 1-1 illustrates how definitions for cumulative effects and multi-use can vary, while the red circle illustrates how we define them for this report.

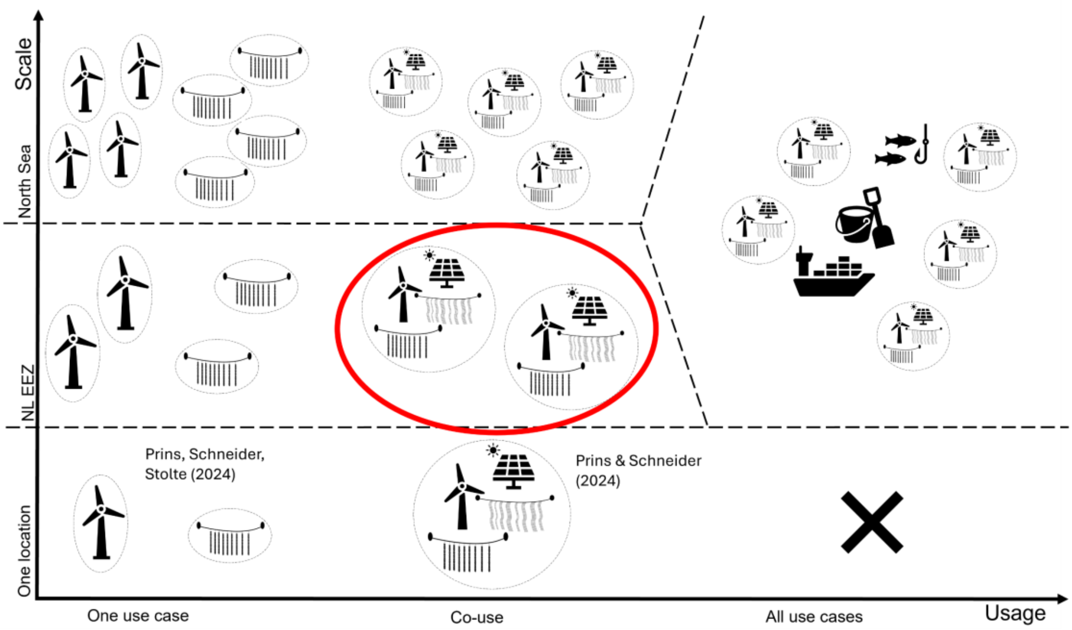


Figure 1-1 A schematic of different definitions for the cumulative effects of multi-use of OWF areas. The red circle highlights the combination of effects used in this report. The figure is a translation of figure 2-1 from (Prins & Schneider, 2024).

1.2 Potential ecosystem effects of cumulative multi-use

Table 1-1 provides a summary of the effects that each form of use within an OWF could have on the marine ecosystem. The ecosystem effects described in Table 1-1 can be assigned to five different categories. Firstly, the abiotic effects, which include effects on water temperature, mixing or stratification, nutrient concentrations and oxygen concentrations across the water column and near the seabed (highlighted as grey rows in Table 1-1). Secondly, the effects on primary producers (phytoplankton, also highlighted as grey rows) and, thirdly, the effects on primary consumers (zooplankton). The fourth category groups the effects on higher trophic levels such as marine mammals, fish, seabirds and seabed habitats. And lastly, the fifth category groups other effects such as non-indigenous species, marine litter and parasites/pathogens.

For this report we focus only on the abiotic effects as well as the effects on phytoplankton. The rationale behind this is that the North Sea is a bottom-up driven ecosystem, e.g. Lynam et al., (2017) and changes to bottom-up processes can potentially have a larger effect on the ecosystem compared to top-down effects. It is important to mention that ecosystem effects need to be analyzed in terms of their near-field, local effects as well as their far-field, downstream effects. Some of the impact of multi-use might occur locally at the site of deployment, while other impacts might occur downstream from the actual deployment site. This has been shown to be the case of seaweed aquaculture (Vilmin & van Duren, 2021).

Table 1-1 An overview of the abiotic and biotic effects associated with offshore wind farms (OWFs), offshore floating photovoltaic systems, shellfish farming, and seaweed farming. Each row highlights a specific ecological effect, while the columns indicate its impact across different multi-use scenarios. Abiotic and primary production effects are highlighted in grey. Effects that are explicitly modelled in this study are bold. Table translated into English from table 4-1 in (Prins & Schneider, 2024).

↘ *Effect leads to a decrease* ↗ *Effect leads to an increase* ↕ *Effect can lead to an in- or decrease depending on the surrounding* ? *Effect is unknown/unclear*

Effect on		**Offshore Floating Photovoltaic**		**Shellfish Farming**		**Seaweed Farming**		**Wind Farms**
Water temperature	↕	**Block sunlight**, heat emission					↘	**Increased mixing in the water column**
Mixing	↗	**Interrupt water flow**	↗	Interrupt water flow	↗	Interrupt water flow	↗	**Interrupt water flow**
Stratification	↘	**Decreased surface water warming, increasing mixing**					↘	**Increased mixing**
Nutrients	↗	**Less primary production**, remineralization, **change in stratification**	↗	**Remineralization of (pseudo)faeces**	↘	**Uptake by seaweed**	↗	Remineralization, **change in stratification**
Oxygen water column	↘	Respiration by increasing fauna and **blockage of atmosphere-water exchange**	↘	**Respiration by shellfish and fouling fauna**	↗	**Primary production**	↕	**Changes in primary production** and respiration of growing fauna
Sedimentation (organic) material	↗	Fouling	↗	Biodeposition and fouling	↗	Seaweed and fouling	↗	Fouling
Phytoplankton	↘	**Blockage of light** and increase in grazing	↘	**More grazing, partly compensated by remineralization of nutrients**	↘	**Competition for nutrients and light**	↕	More nutrients / **less light**
Zooplankton	↕	Less food (phytoplankton), more predation (fish)	↕	Less phytoplankton, more predation of small zooplankton and more fish predation	↕	Less food (phytoplankton), more predation (fish)	↕	Change in phytoplankton; predation by growing fauna
Marine Mammals	?	Resting place, foraging, risk of entanglement, electromagnetic fields	?	Resting place, foraging opportunities, risk entanglement	?	Resting place, foraging opportunities, risk entanglement	?	Foraging opportunities, risk entanglement, electromagnetic fields, noise

Effect on	Offshore Floating Photovoltaic	Shellfish Farming	Seaweed Farming	Wind Farms
Fish	? Shelter and foraging, absence of fishing	? Shelter and foraging opportunities, change in food supply, absence of fisheries	? Shelter and foraging opportunities, change in food supply, absence of fisheries	? Shelter and foraging opportunities, change in food supply, absence of fisheries
Birds	? Resting place, obstruction of water column	? Resting place, foraging opportunities	? Resting place, feeding possibilities	Higher probability of mortality
Bottom oxygen	Increased supply of organic material	**Increased supply of organic material**	**Production of oxygen**, increased supply of organic material	Increased supply of organic material
Benthic animal community	? Less oxygen, physical disturbance by anchoring, reef formation	? Less oxygen, physical disturbance by anchoring, reef formation	? Physical disturbance by anchoring, more oxygen	No bottom fishing
Non-native species	Stepping stone	Stepping stone	Stepping stone	Stepping stone
Litter/ microwaste/ contaminants	Material release	Material release	Material release	Material release, contamination (e.g. hydraulic oil)
Parasites, pathogens, etc.		Cultivation	Cultivation	

1.3 Multi-use scenarios

For this study, we decided to work with two multi-use scenarios using Figure 1-2 as a basis. The first multi-use scenario, called “current multi-use” scenario, focusses on the OWFs currently in use (OWFs 1-3 in Figure 1-2) and which have an aerial passport (“gebiedspaspoort”). The aerial passport provides spatial information about the allocation of multi-use within an OWF. Three OWFs that have an aerial passport are Borssele, Hollands Kust (Noord) (HKN) and Hollands Kust (Zuid) (HKZ).

The second multi-use scenario, called “tendered multi-use” scenario, would take the already tendered, but not yet constructed OWFs into account as well (i.e. OWFs 1-6 in Figure 1-2). These future OWFs do not have an aerial passport available yet. It was decided to not include the OWF “Ten noorden van de Waddeneilanden” and “Doordewind” as in the current planning they are primarily reserved for demonstration of hydrogen production and/or active fishery.

The technical implementation of seaweed and mussel farming as well as OFPV within the model is described in detail in chapter 2.3.

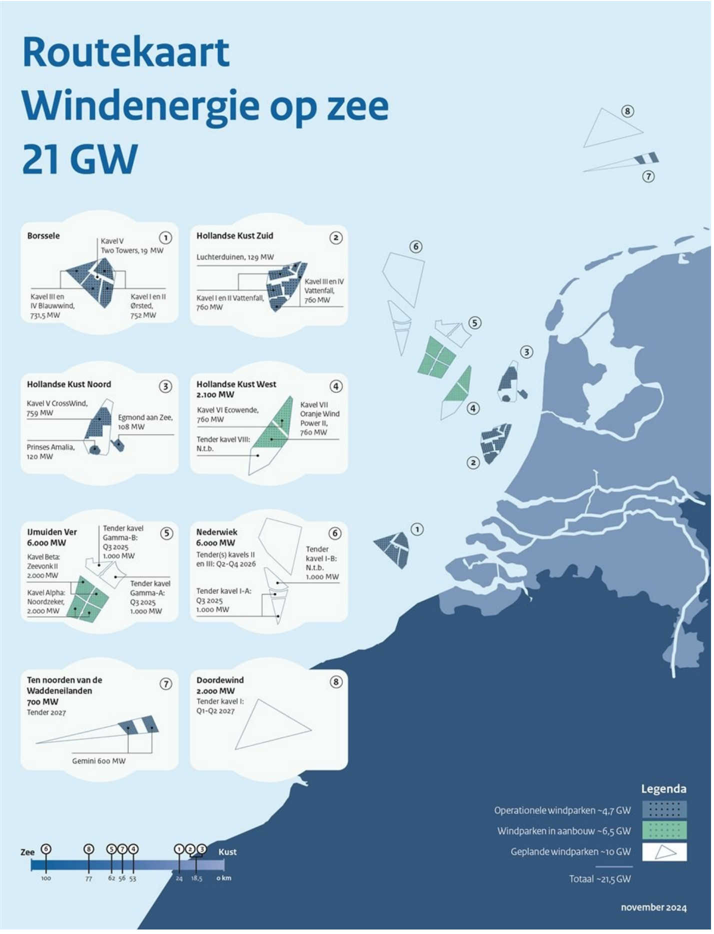


Figure 1-2 Routekaart Wind Op Zee 21 GW. A map of the spatial distribution plan for OWF areas in the North Sea, reproduced from Nordzeeloket (2025).

2 Technical modelling methods

This study focusses on the additional effects of multi-use on the marine environment. We built on and expanded work completed within other studies, namely OSPAR (Prins et al., 2023), Wozep (WOZEP, 2025), IMPAQT (IMPAQT, 2025), ProSeaweed (Vilmin & van Duren, 2021) and FutureMARES (Shin et al., 2023). The model we used is called the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) (Zijl et al., 2023). 3D DCSM-FM is developed with the Delft3D Flexible Mesh Suite and can be used to assess potential changes in hydrodynamics. The model can be coupled to Delft3D-Water Quality to model changes in sediment dynamics, light attenuation as well as primary and secondary production.

We used 3D DCSM-FM as developed in OSPAR as a starting point and implemented modules to simulate the effect of OWFs and multi-use using knowledge gained for the other projects mentioned above. As 3D DCSM-FM has already been compared to *in-situ* data within the OSPAR project, we did not simulate a base scenario without any form of anthropogenic use. Furthermore, this modelling study focussed on a hypothetical situation that all OWFs as well as all forms of multi-use are constructed and operational. We did not simulate conditions in which OWFs and the different forms of multi-use are under construction or being dismantled.

2.1 3D Dutch Continental Shelf Model – Flexible Mesh (DCSM-FM)

2.1.1 Model version, domain and resolution

The scenarios are run using a version of 3D DCSM-FM which has been developed and validated using data from the Dutch national monitoring programme (MWTL) and other available sources in the context of recent OSPAR-related work on river nutrient load scenarios (Prins et al., 2023). This version of the model was based on the latest Deltares/Rijkswaterstaat North Sea hydrodynamics release (name of the model version: *dflowfm3d-noordzee_0_5nm-j22_6-v1a - Informatiepunt Leefomgeving (2025)*). The model set-up is very similar to the water quality release (name of the model version: *dflowfm3d_dwaq_0_5nm-j17_6_v1 - Informatiepunt Leefomgeving (2025)*), but some improvements have been implemented.

3D DCSM-FM covers the Northwest European Continental Shelf, including the North Sea and adjacent shallow seas, such as the Wadden Sea (Figure 2-1). There is a coarse grid available with a horizontal resolution of about 4 by 4 nautical miles over the entire domain as well as a fine grid version. For the fine grid version, the grid size varies with the bathymetry with 4 by 4 nautical miles at the boundaries down to 0.5x0.5 nautical miles along the coasts and in the Dutch EEZ. The water column is divided into a fixed number of 20 layers up to depths of 100m (sigma-layers). In areas over 100m deep, the deeper part of the water column are further divided into a maximum of 30 additional layers at fixed depths (z-layers).

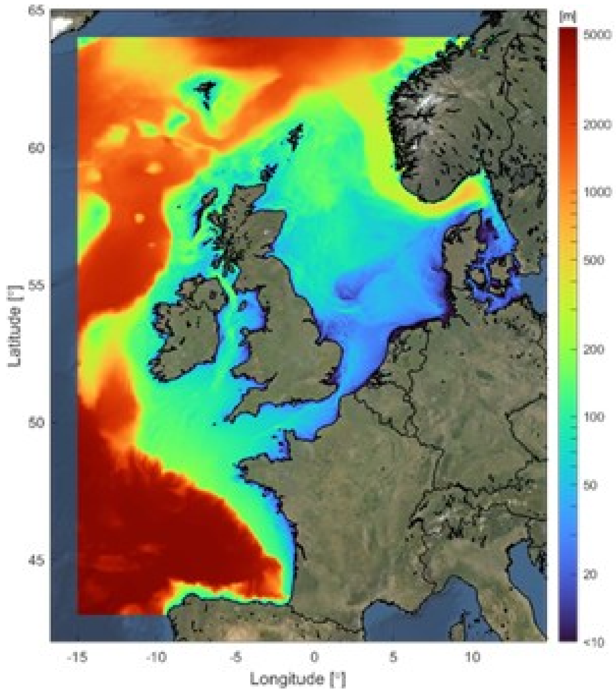


Figure 2-1 Domain and bathymetry (based on EMODnet data) of the 3D DCSM-FM model (Zijl et al., 2023).

2.1.2 Water quality processes

Water quality processes are simulated with the D-Water Quality module which is fully integrated within D-Flow FM. The base processes are taken from the model developed for OSPAR (T. C. Prins et al., 2023). The water quality module simulated the cycles of major nutrients (nitrogen, phosphorus and silica, herein noted N, P and Si), organic carbon (C) and dissolved oxygen (O2). Simulated state variables are listed in Table 1-1 and processes comprised are shown in Figure 2-2:

- Phytoplankton photosynthesis and associated uptake of nutrients and O2 production that depend on the light climate;
- Vertical attenuation of photosynthetically active solar radiation;
- Phytoplankton respiration and mortality resulting in the release of nutrients and the consumption of O2;
- Mineralization of organic matter in the water column and in the sediment and associated O2 consumption
- Dissolution of biogenic silica in the water column and in the sediment;
- Settling of organic matter and phytoplankton and burial of detrital organic matter;
- Nitrification;
- Denitrification in the water column and in the sediment;
- Atmospheric deposition of NH4 and NO3;
- Oxygen re-aeration at the water surface;
- Carbon uptake, nutrient recycling and growth dynamics of shellfish, using Dynamic Energy Budget modelling (blue mussel population in the Wadden Sea, Ensis population elsewhere along the coast)

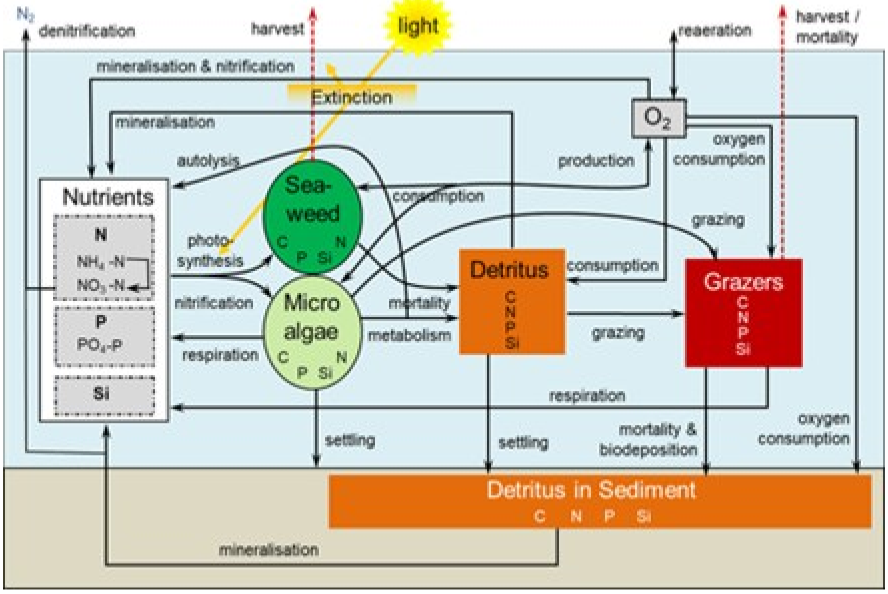


Figure 2-2 Scheme of simulated state variables and processes. The seaweed compartment is deactivated for the runs without multi-use.

Table 2-1 3D DCSM-FM state variables. Active substances are those transported by advection and dispersion processes.

D-Water Quality state variable [unit]	**Description**	**Active**
Water level [m]		
Salinity [‰]		x
Temperature [ºC]		x
Ux [m/s]	Eastward current velocity	
Uy [m/s]	Northward current velocity	
OXY [g/m3]	Dissolved oxygen	x
NH4 [gN/m3]	Ammonium	x
NO3 [gN/m3]	Nitrate	x
PO4 [gP/m3]	Phosphate	x
Si [gSi/m3]	Silica	x
POC1 [gC/m3]	Detrital Particulate Organic Carbon	x
PON1 [gN/m3]	Detrital Particulate Organic Nitrogen	x
POP1 [gP/m3]	Detrital Particulate Organic Phosphorus	x
Opal [gSi/m3]	Biogenic silica	x
DOC [gC/m3]	Dissolved Organic Carbon	x
DON [gN/m3]	Dissolved Organic Nitrogen	x
DOP [gP/m3]	Dissolved Organic Phosphorus	x
Alka	Alkalinity	x
DetCS1, DetNS1, DetPS1, DetSiS1	Sediment detritus carbon, nitrogen, phosphate and silica	
DIAT_X, DINO_X, FLAG_X, Phae_X (X [E, N, P]) [gC/m^3]	Diatoms, dinoflagellates, flagellates and *Phaeocystis* (energy-, nitrogen- and phosphorus-limited)	x

MALS [gDW/m2], MALC [gC/m2], MALN [gN/m2], MALP [gP/m2]	Macroalgae structural biomass and internal C, N and P reserves	
Mussel_V, Mussel_E, Mussel_R [gC/m^2]	Mussel structural biomass, energy reserves and gonadal biomass	
Ensis_V, Ensis_E, Ensis_R [gC/m^2]	*Ensis* structural biomass, energy reserves and gonadal biomass	

2.2 Reference run

The reference run is defined as the OSPAR model described in the previous chapter with the effects of OWF included. In terms of water quality, this reference run matches the previous OSPAR model and includes natural mussels and ensis at the seabed (none on the wind farm pillars) and the typical water quality processes described above. The OWF were implemented using the 'routekaart' 21GW offshore windfarm scenario (Nordzeeloket, 2025) as a base. As OWF were also placed within “Ten noorden van de Waddeneilanden” (7) and “Doordewind” (8), those two OWF were not included in the reference run (even though no multi-use was simulated in those two OWFs). OWFs were implemented according to Zijl et al. (2023) as briefly described in the following sections.

2.2.1 Effect of OWF pillars on flow

As the piles of the OWFs are too small to explicitly include in the model schematization, a sub-grid approach was used. In this approach, a quadratic sink term is included in the horizontal momentum equations. The energy extracted from the main flow (sink term) is at the same time reintroduced as a source term in the equation for turbulent kinetic energy (k). The OWFs are specified in the hydrodynamic model by defining a polygon the size of the OWF and placing it at the geographic location of the OWF. In each grid cell within an OWF polygon, the appropriate sink and source terms are computed considering the pile density (number of piles per unit of area), mean pile diameter and the drag coefficient. The drag coefficient combines the total friction experienced by the flow due to the presence of the OWF. This consists of both the shape of the structure and its surface roughness.

2.2.2 Effect of OWF on suspended sediment

The sediment module cannot be coupled to the current OSPAR model version and instead can only be forced at the surface, based on available satellite imagery. However, in an older Delft3D-FM model version, used e.g. in the Wozep project, the explicit modelling of the effect of OWF on sediment was possible (Zijl et al., 2023). These model runs were used to determine the potential impact of offshore wind farms on suspended sediment loads. To include these effects in the multi-use model (based on the newer OSPAR model set-up), we calculated the percentage difference in the surface suspended sediment from Wozep and applied it to the surface suspended sediment forcing from satellites, used by OSPAR. This difference is applied locally, within the OWF area for Borssele, HKZ, HKN, HKW, IJmuiden-Ver, Nederwiek, Doordewind and Ten noorden van de Wadden. It is important to note, that the Wozep (old 3D DCSM) runs were simulated for 2007 (Zijl et al., 2023). The difference in surface sediment forcing from 2007-Wozep is repeated on an annual cycle onto these simulation years for the multi-use scenarios run here. As a result, the effect of OWF was forced in this model and not simulated explicitly. This contrasts with all other effects of (multi-)use that were simulated explicitly.

2.3 Multi-use scenarios

2.3.1 Current multi-use scenario

For the current multi-use scenario, the aerial passports for Borssele, HKN and HKZ were used for the placement of multi-use within each OWF. The geographical location of the different multi-use areas per OWF was provided by IenW in the form of shapefiles. As OFPV is the only form of energy multi-use taken into account in this study, the whole area allocated to alternative energy generation within the aerial passports was attributed to OFPV. This is not the case for aquaculture as we wanted to take mussel and seaweed aquaculture into account. However, the aerial passports only provide spatial information for aquaculture in general and not specifically for mussel and seaweed farm. It was decided to allocate the same amount of space for seaweed and mussel farming over all three OWFs instead of allocating seaweed and mussel farming within each OWFs. Thus, all of Borssele was allocated to mussel farming and all of HKZ for seaweed farming. This was decided based on the proximity of Borssele to already established mussel aquaculture in the Oosterschelde. To ensure an equal area of mussel and seaweed farming within the current scenario the large square in HKN was allocated to mussel farming and the small square in HKN to seaweed farming.

It is important to bear in mind that the deployment of multi-use within a numerical model needs to be translated to the model grid. That means that the geographical location of the multi-use from the aerial passports was modified to fit the numerical model grid. This was done using Python preprocessing and the Deltares interactor software and resulted in .pol files that are readable by the modelling software. The area of multi-use taken from the aerial passports was compared to the area of the created .pol files to ensure that the area modelled remained in an acceptable range (see Table 2-2). Figure 2-3-A visualizes distribution of multi-use within the three OWFs of the current multi-use scenario.

Table 2-2 Area in km^2 for the current multi-use scenario, as calculated from the arial passports and the .pol files.

	Aquaculture		**Alternative energy generation**	
	Aerial passport (km^2)	**Grid (km^2)**	**Aerial passport (km^2)**	**Grid (km^2)**
Borssele	25	24.8	18	19
HKZ	22.8	22.7	12	11.9
HKN	8.9	9.2	1.5	1.6

2.3.2 Tendered multi-use scenario

For the tendered multi-use scenario, two additional model runs were set up. These include multi-use in the three OWFs of the current scenario (Borssele, HKZ and HKN) as well as three additional, tendered OWFs: Hollandse Kust West (HKW), IJmuiden Ver (IJM) and Nederwiek (NDW). Since the tendered OWFs do not yet have designated aerial passports, the potential area available for multi-use was estimated based on the average percentage of area designated for multi-use in the current wind farms. For Borssele, HKZ and HKN, the percentage of OWF area assigned to alternative energy generation (OFPV) and aquaculture is approximately 12%, 14% and 9% respectively, with an average of ~11.5%. This percentage was applied to HKW, IJM and NDW. Two versions of the tendered scenario were defined:

1. Coastal seaweed (following habitat suitability as defined in Steenbergen et al. (2023)
   - All of Borssele, HKZ, HKN and HKW is Seaweed
   - All of IJM is Mussel
   - All of NDW is OFPV
2. Coastal mussels (following preferences of the mussel sector):
   - All of Borssele, HKZ, HKN and HKW is Mussel
   - All of IJM is Seaweed
   - All of NDW is OFPV

As in the current scenario, the geographical location of the multi-use areas was adjusted to the model grid. The estimated percentage of area per OWF was first translated into km², and then further converted into the number of model grid cells. The total grid cell area was compared to the original geographical area to ensure that the representation in the model remained within an acceptable range (see Table 2-3). The resulting geographical distribution of the tendered multi-use scenarios are shown in Figure 2-3.

Table 2-3 Area in km^2 of the tendered multi-use scenarios.

	Mussel		Seaweed		OFPV	
	Reality (km^2)	Grid (km^2)	Reality (km^2)	Grid (km^2)	Reality (km^2)	Grid (km^2)
Coastal seaweed scenario						
Borssele + HKZ + HKN + HKW	125.3	117.8	0	0	0	0
IJM	0	0	72	66	0	0
NDW	0	0	0	0	47	43
Coastal mussel scenario						
Borssele + HKZ + HKN + HKW	0	0	125.3	117.8	0	0
IJM	72	66	0	0	0	0
NWD	0	0	0	0	47	43

2.3.3 Summary of the three multi-use scenarios

Table 2-4 A summary of the distribution of OFW (W), seaweed (S), mussels (M) and OFPV (PV) per OWF area and per model scenario.

Scenario	**Reference**				**Current**				**Coastal Seaweed**				**Coastal mussels**			
Marine Use	**W**	**S**	**M**	**PV**	**W**	**S**	**M**	**PV**	**W**	**S**	**M**	**PV**	**W**	**S**	**M**	**PV**
Borssele																
HKN																
HKZ																
HKW																
IJmuiden-Ver																
Nederwiek																
TNW																
Doordewind																

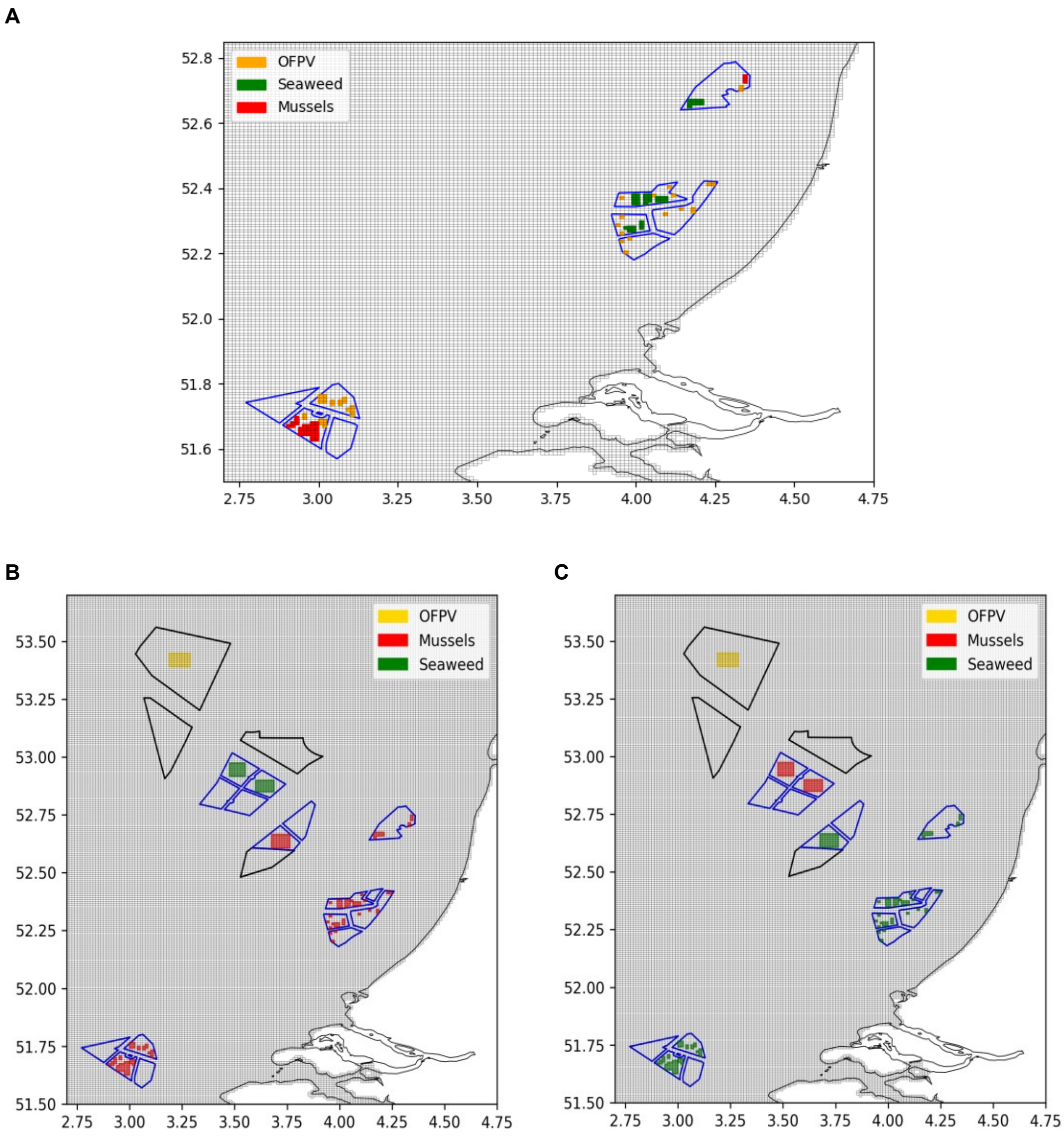


Figure 2-3 Maps showing the spatial distribution of aquaculture and offshore floating photovoltaic (OFPV) installations within OWF for three scenarios: the current scenario (A), the coastal seaweed scenario (B), and the coastal mussel scenario (C). Black outlines indicate the coarse outlines of OWF, while blue outlines, where available, represent higher-resolution data providing greater certainty regarding multi-use placement.

2.4 Implementing multi-use within 3D DCSM-FM

2.4.1 Seaweed aquaculture

Sugar kelp (*Saccharina latissima*) aquaculture for the North Sea has been simulated in (Vilmin & van Duren, 2021) and (Shin et al., 2023). The seaweed module (MALG) and its parameterization to simulate sugar kelp in the Dutch North Sea has been described in Vilmin & van Duren (2021) . For the Borssele I OWF in the 2010 historical state situation, Vilmin & van Duren (2021) calibrated the initial seaweed biomass to reach about 1 kgDW/m2 at the end of a cultivation cycle. We used their report and initialized seaweed aquaculture within the allocated OWFs areas

2.4.2 Blue mussel aquaculture

Blue mussel (*Mytilus edulis*) aquaculture in the North Sea has been simulated by Shin et al. (2023). Mussel aquaculture on longlines was simulated using the Dynamic Energy Budget modelling to simulate the carbon uptake, nutrient recycling and growth dynamics of shellfish. To initialize our model we will use results by Shin et al. (2023). In Vilmin & van Duren (2021), the initial mussel biomass was calibrated for Borselle I to reach a target yield of 179200 kg of fresh weight per hectare at the end of the cultivation cycle, i.e. ~1 kgDW/m2 using the model's conversion factor parameter of 0.056 gDW/gFW. We used their report and initialized mussel aquaculture within the allocated OWFs areas.

2.4.3 OFPV

OFPV was parameterized according to Hendriks et al. (2025) for the floating system concept. The processes affected by OFPV were split into two types of implementations. For simulating the effects on the heat flux through the air-water interface and adjusting the incoming shortwave radiation, polygons of each planned OFPV area are used. The incoming shortwave radiation is reduced by a factor of 0.2, which is an assumption since no *in-situ* data is available. It is based on the floating system concepts that is in direct contact with the water surface and so blocks any incoming forcing from the atmosphere.

For simulating the effects of OFPV on the water circulation and wind, the so-called 'forced ice cover' method is used, which is available in D-Flow FM. This method is applied at higher spatial resolution than the main model grid. On a separate curvilinear grid and within the OFPV polygon areas used for the heat and light reductions described above, the location of the OFPV platforms are defined. Within the areas that have OFPV actively blocking the flow and wind, we define a thickness (h_i), cover fraction per grid cell (A_i) and drag coefficient (C_d). The effect of OFPV on wind within the OFPV area is simulated by applying a linear wind drag option within the forced ice cover method. The following OFPV parameters will be chosen for this simulation:

- Thickness (h_i) = 0.31 m
- Cover fraction (A_i) = = 1.0 [-] (on specific grid cells)
- Drag coefficient (C_d) = 5×10^{-3}
- Decrease of incoming shortwave radiation (f_s) = 0.2

In this report, mussel growth under the OFPV structures is not modelled.

2.5 Simulating multi-use within 3D DCSM-FM

The simulations were carried out over a period from 2015 until 2017. This period was chosen to align with the OSPAR simulation period. It is standard to model 2 spin-up years and one analysis year. January 2015 until May 2015 will be used as a spin-up for OWF and OFPV structures on the model. In May 2015, the aquaculture mussels are added to the simulation and in September 2016, seaweed aquaculture is also added to the model runs, to match their cultivation cycles. The final period of the model runs which includes both types of aquaculture, OWFs and the OFPV structures is from September 2016 until September 2017. Therefore, the model forcing (e.g. boundary conditions for nutrients, climatology) are derived from data over this whole period. These years were chosen to be in line with simulations completed for OSPAR scenarios (Prins et al., 2023).

3 Results

This section shows on the results of the different modelling scenarios. The results are grouped into five sections. Section 3.1 and 3.2 focus on the analysis of the seaweed and mussel aquaculture yields, while section 3.3 focuses on the effect of OFPV deployments on the underwater light climate. Section 3.4 focuses on the near-field effects of multi-use by visualizing timeseries at two specific stations. Section 0 focuses on the far-field effects of multi-use by depicting growing season (March – September) averaged maps.

3.1 Yield of seaweed aquaculture

To illustrate the growth of seaweed, the OWF HKZ was chosen with the location Hollandse Kust Zuid Kavel I (station 4 in Figure 3-1) as it includes seaweed in both the current and nearshore seaweed scenarios (Figure 3-1 A and B). The nearshore mussel scenario features mussels in HKZ and serves as a control alongside the reference run. High-resolution timeseries for seaweed biomass were extracted for station 4 (Hollandse Kust Zuid Kavel I) and are visualized in Figure 3-2. Figure 3-3 plots maps of the seaweed dry weight distribution for each of scenario.

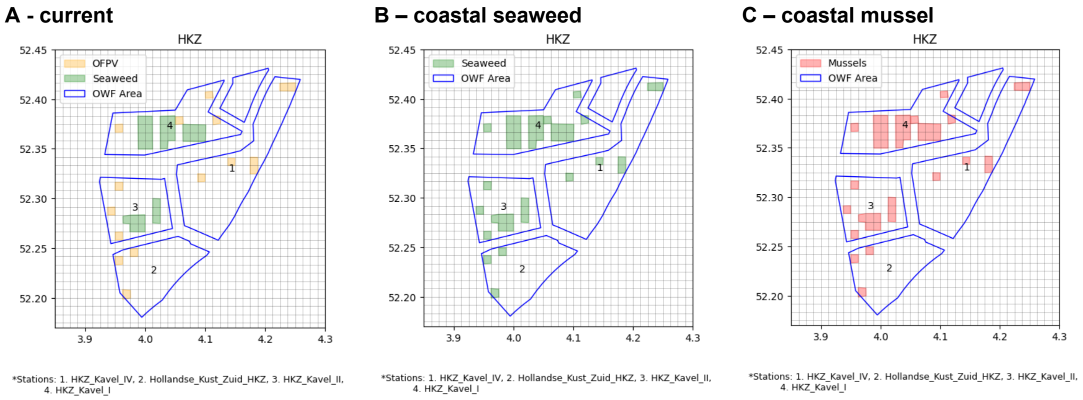


Figure 3-1 Maps of the three different multi-use scenarios at Hollandse Kust Zuid (HKZ). In A, the current scenario is displayed, matching the aerial passport, B shows the hypothetical future scenario with nearshore seaweed and C shows the hypothetical future scenario with nearshore mussels. The numbers in the maps represent observation stations. This shows that station 4 (Kavel I) either represents seaweed (A and B) or mussels (C) and used for further analysis.

Analysis of the seaweed growth curve at HKZ Kavel I (Figure 3-2) shows little growth during the initial months. Growth begins around January–February, accelerates through spring, and reaches its peak between June and July 2017, followed by a decline toward the end of summer. The order of magnitude compares well to the growth curves simulated by Vilmin & van Duren (2021) and Shin & van Duren (2023). When comparing the growing-season (March–September) averaged dry weight of seaweed at the surface across the three scenarios - current, coastal seaweed, and coastal mussels (Figure 3-3) - the highest concentrations occur in Borssele (Panel B), the most upstream offshore wind farm. HKZ and HKN show comparatively lower seaweed weights. Further offshore, HKW (Panel B) and IJmuiden Ver (Panel C) exhibit intermediate values, falling between the lower concentrations of the other Hollandse Kust farms and the peak observed in Borssele. Within individual OWFs, a pattern of competition can be observed, with upstream areas displaying higher concentrations than downstream areas. This is particularly evident in the larger patches of seaweed, such as HKW and IJmuiden Ver.

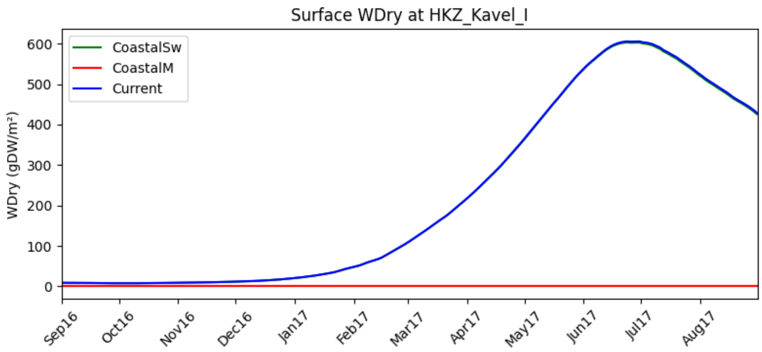


Figure 3-2 Dry weight timeseries of seaweed showing their growth curve at Hollandse kust Zuid (HKZ) Kavel I over a cultivation cycle from September 2016 until September 2017.

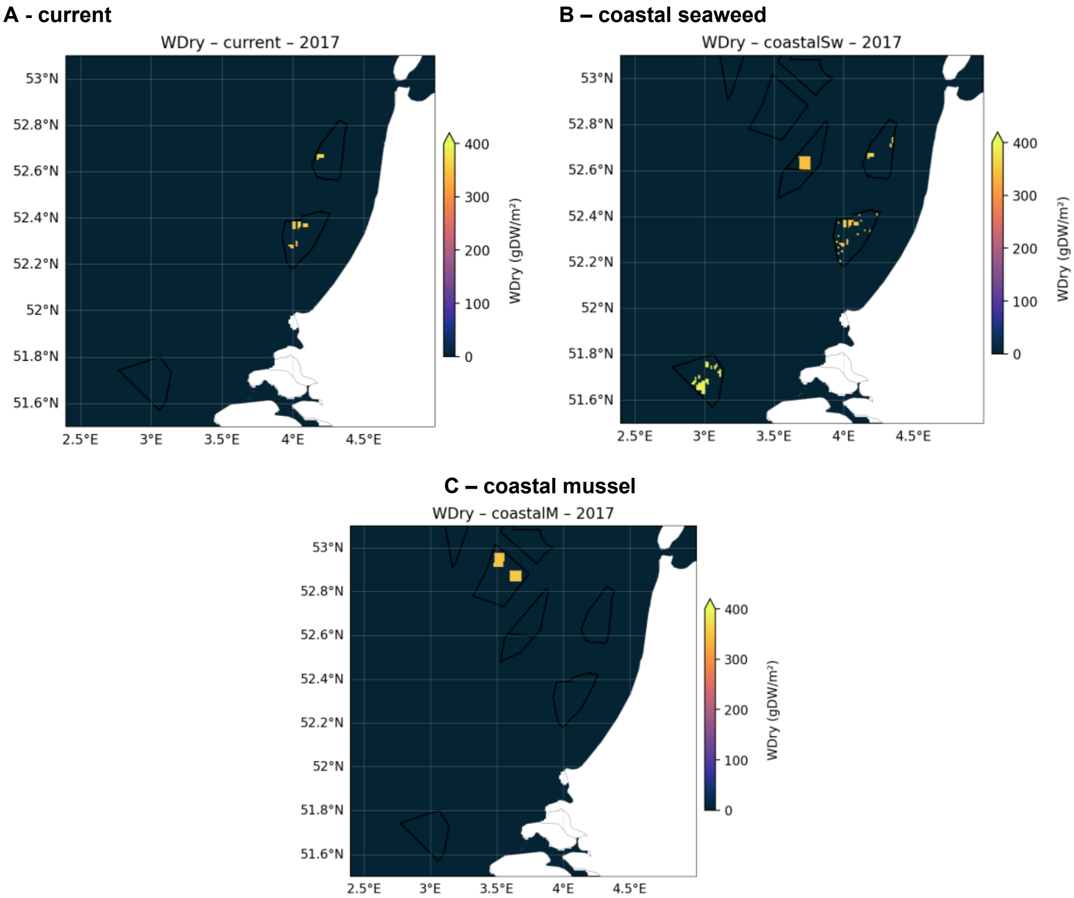


Figure 3-3 Maps of the growing season averaged weight of seaweed in the surface water of the three scenarios. A is the current scenario, B is the coastal seaweed scenario and C is the coastal mussel scenario.

3.2 Yield of mussel aquaculture

To illustrate the growth of mussels, the observation station 3 (namely Borssele) was chosen, which is located in the Borssele OWF (Figure 3-4), as it includes mussels in both the current and nearshore mussel scenarios (Figure 3-4A and C). The nearshore seaweed scenario implemented seaweed in Borssele and serves as a control alongside the reference run. High-resolution timeseries for seaweed biomass were extracted at this station and are visualized in Figure 3-5. Figure 3-6 plots maps of the mussel ash-free dry weight distribution for each of scenario.

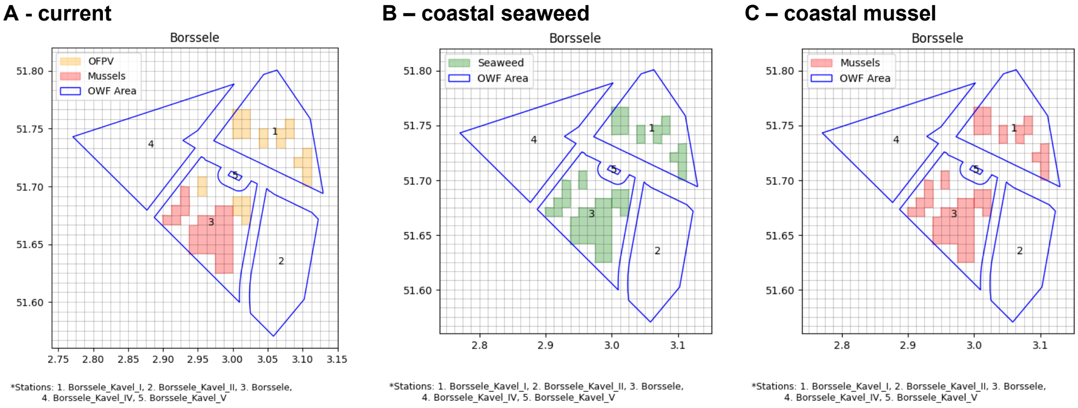


Figure 3-4 Maps of the three different multi-use scenarios at Borssele. In A, the current scenario is displayed, matching the aerial passport. B shows the hypothetical future scenario with nearshore seaweed and C shows the hypothetical future scenario with nearshore mussels. The numbers in the maps represent observation stations. This shows that station 3 either represents mussels (A and C) or seaweed (B) and used for further analysis.

Analysis of the mussel growth curve at Borssele (Figure 3-5) indicates a period of low growth from late summer (around September) until March 2017. From March onward, the ash-free dry weight increases sharply, stabilizing by mid-April and reaching its maximum between July and August. This peak is followed by a decline toward the end of summer. In the current scenario, which has a lower spatial distribution of mussels, their weight is the largest. This is particularly evident in summer at the peak of the growth cycle. When comparing the annual averaged ash-free dry weight of mussels near the surface across the three scenarios - current, coastal seaweed, and coastal mussels (Figure 3-6) - the highest concentrations occur closest to the coast, particularly in Borssele, HKZ, and HKN. These differences in ash-free dry weight can be as much as twofold, as suggested between HKN and HKW. Within a OWF, upstream grid cells again show higher weights than downstream cells, reflecting a similar spatial pattern as observed for seaweed aquaculture.

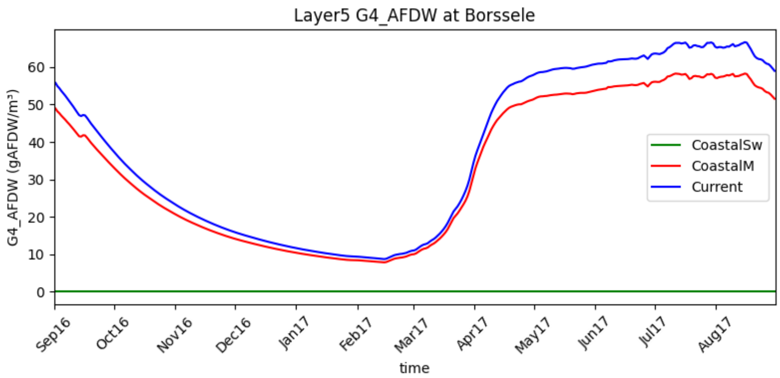


Figure 3-5 Ash-free dry weight timeseries of mussels showing their growth curve in Borssele over a year from September 2016 until September 2017 at near-surface depth.

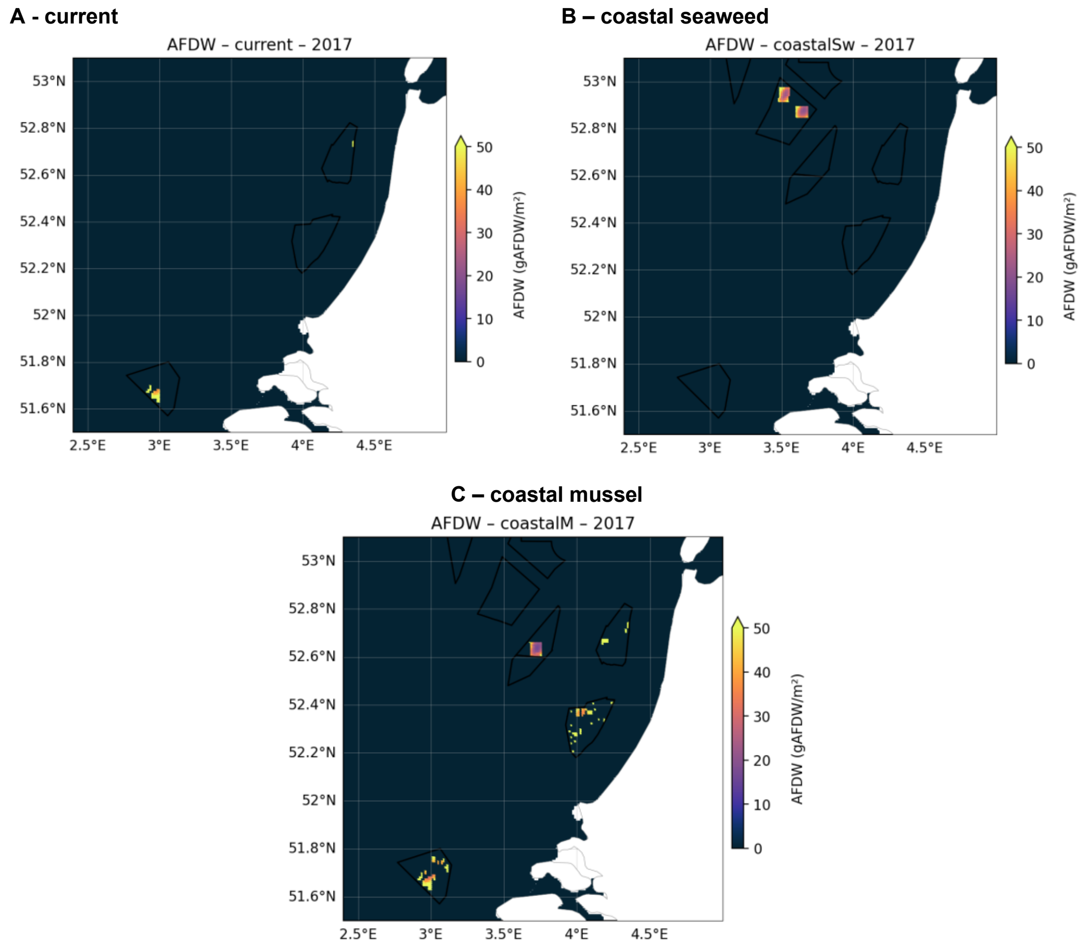


Figure 3-6 Maps of the near-surface annual average of the ash-free dry weight of mussels within the three scenarios. A shows the current scenario, B shows the coastal seaweed scenario and C shows the coastal mussel scenario.

3.3 OFPV effect on light

Figure 3-7 plots maps of the OFPV effect on the light availability at the water surface. As mentioned in the previous chapter, there are only two different OFPV deployment scenarios. In the current scenario, simulates discrete, small-scale deployments, while the coastal seaweed and coastal mussel scenarios simulate large scale, lumped deployment of OFPV. It shows that light only decreases underneath the platforms and that it is not affected outside of the deployment area, regardless of the type of deployment.

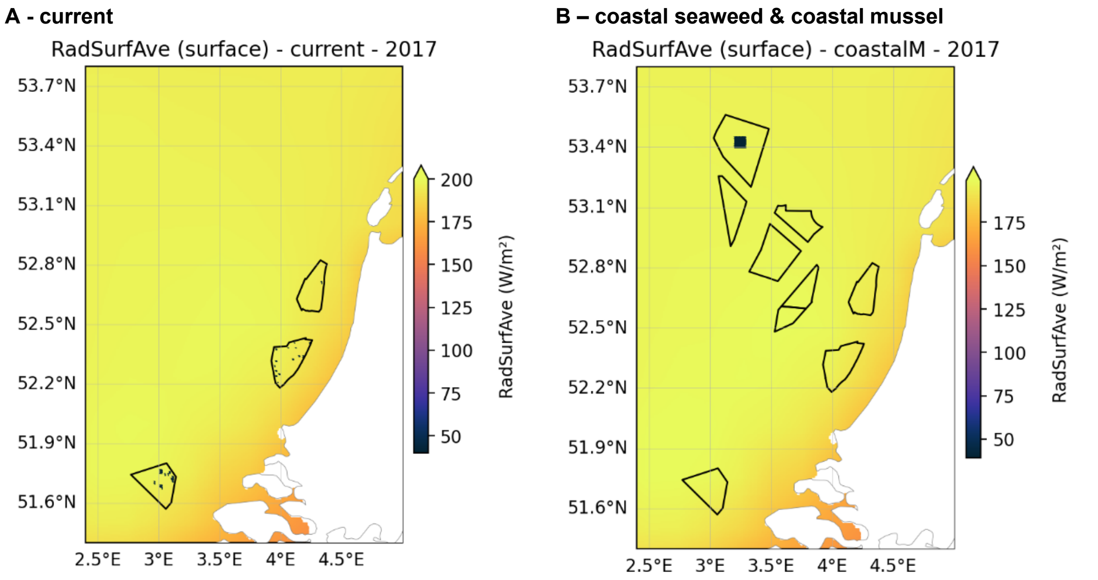


Figure 3-7 Maps of light available at the water surface. A shows the current scenario, while B represents both the coastal seaweed and coastal mussel scenarios.

3.4 Near-field cumulative effects of multi-use

While analysing the cumulative effect of multi-use it is important to distinguish between the near-field local effects and the far-field, downstream effects. In this section we will look at the local, near field effects for two OWF i.e. Borssele and Nederwiek. The OWF Borssele offers the possibility to examine the impact of the different multi-use scenarios at one single location. Nederwiek represents an extreme-case, large-scale, lumped deployment of OFPV.

3.4.1 Borssele

Figure 3-8 shows that observation point Borssele (number 1) is located within different forms of multi-use deployment for each scenario. The current scenario includes OFPV at this location, while the coastal seaweed scenario and coastal mussel scenario deploy seaweed and mussels, respectively at that location.

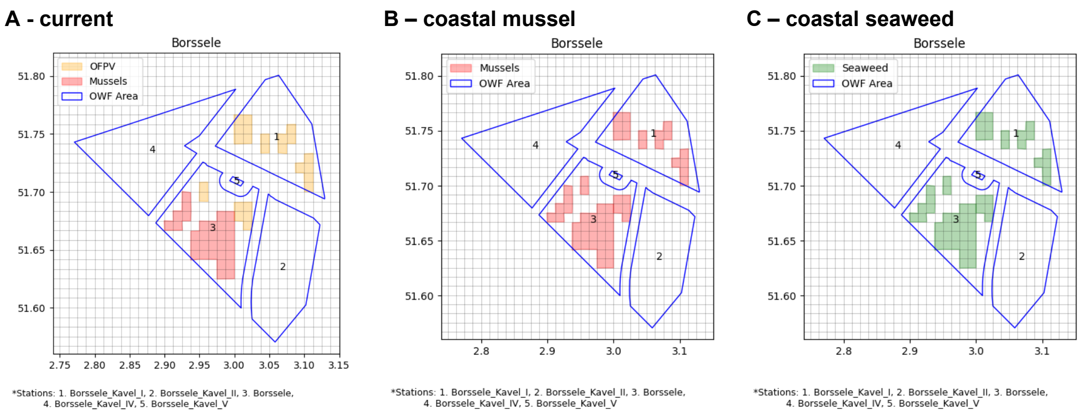


Figure 3-8 Maps of the offshore wind farm Borssele and its multi-use design for the three different scenarios. The figure clearly shows that observation point Borssele (number 1) is located within different forms of multi-use deployment for each scenario. In the current scenario, observation point Borssele falls within OFPV deployment. For coastal mussel and coastal seaweed, observation point Borssele lies within mussel and seaweed deployment, respectively.

Figure 3-9 and Figure 3-10 show high-resolution model outputs for each scenario, for a range of nutrients and primary production parameters. The Borssele station clearly shows that each form of multi-use has distinct, but different impacts on ecosystem parameters.

Locally at the observation point Borssele, abiotic variables such as temperature and stratification are less affected by multi-use scenarios than biotic variables, with chlorophyll-a showing the strongest response. Seaweed aquaculture (the green lines in the coastal seaweed scenario of Figure 3-9 and Figure 3-10) has the smallest impact on chlorophyll-a, causing only a slight decrease compared to the reference scenario (represented by the black line). This is driven by the light and nutrient competition of seaweed and phytoplankton. However, seaweed has the largest influence on nutrients and bottom oxygen: DIN decreases due to uptake by seaweed biomass, while bottom oxygen increases during summer months as a result of photosynthetic oxygen release of seaweed. Changes in temperature-related variables remain negligible.

OFPV installations (represented as the blue lines in the current scenario of Figure 3-9 and Figure 3-10) reduce surface chlorophyll-a more than seaweed aquaculture, primarily because shading under the floating structures limits light availability for phytoplankton growth. A slight decrease in primary production is also observed during summer, consistent with reduced light penetration. For other variables (nutrients, temperature, and oxygen) the near-field impact at Station Borssele is negligible, as OFPV does not directly alter nutrient cycling or oxygen dynamics beyond its footprint.

Mussel aquaculture (the red lines in the coastal mussel scenario of Figure 3-9 and Figure 3-10) produces the strongest reduction in chlorophyll-a across all scenarios because mussels actively filter phytoplankton from the water column. Nutrient concentrations show a small increase during winter months, likely driven by remineralization of organic matter from mussels. Primary production shifts similarly to the current scenario, reflecting changes in phytoplankton biomass and nutrient recycling. Temperature and oxygen variables remain largely unaffected, as mussel activity does not significantly alter thermal structure or oxygen beyond localized biodeposition effects.

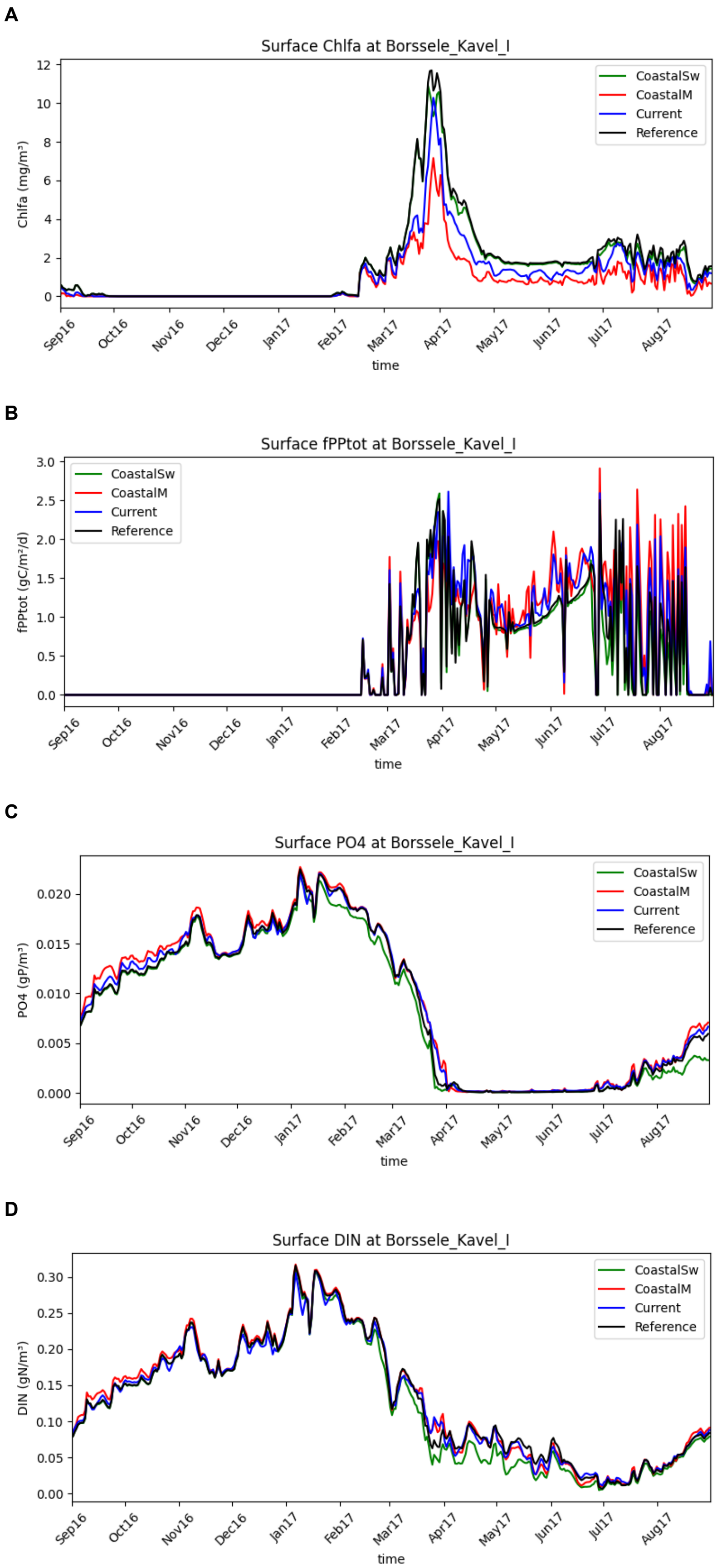


Figure 3-9 Timeseries of surface (A) chlorophyll-a, (B), primary production, (C) phosphate and (D) DIN. from September 2016 until September 2017 for the reference run and the three scenarios.

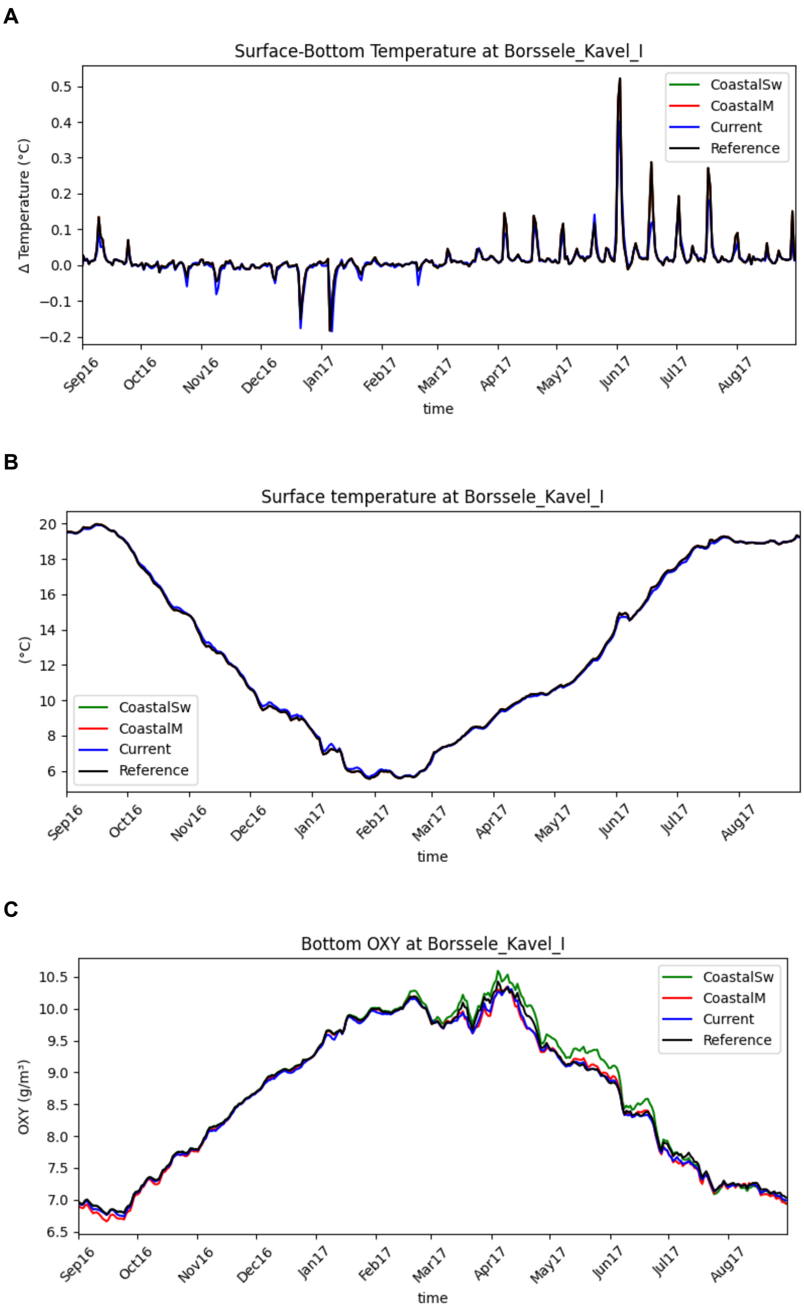


Figure 3-10 Timeseries of the (A) difference between the surface and bottom water temperature, (B) the surface temperature and (C) the bottom oxygen concentration in Borssele Kavel I from September 2016 until September 2017 for the reference run and the three scenarios.

3.4.2 Nederwiek

Nederwiek represents an extreme-case example of an OFPV installation in offshore coastal seaweed and mussel model scenarios. The extreme-case deployment is quite unrealistic. In the area highlighted in yellow in Figure 3-11, incoming solar radiation is decreased by 80%. The resulting impact on the water column at Station 1 (Nederwiek North) is examined in detail using high-temporal-resolution timeseries plots shown in Figure 3-12 and Figure 3-13.

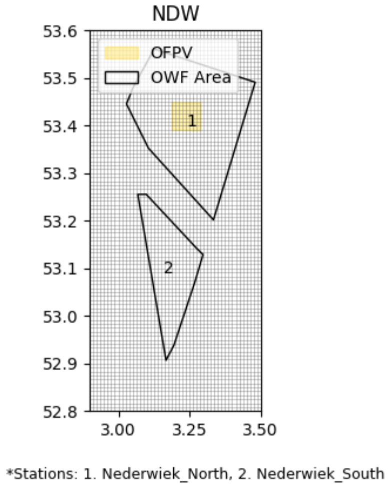


Figure 3-11 Map of the distribution of OFPV in the Nederwiek offshore wind farm, as implemented in the coastal seaweed and coastal mussel scenarios.

Primary production and temperature difference show the largest impact through the implementation of OFPV within Nederwiek. For both variables, the values drop to zero under the OFPV implementation in the model. This large impact was not visible in the Borssele timeseries, in which the OFPV deployment was much smaller. Chlorophyll values decrease as well in the order of magnitude as could be seen in the Borssele timeseries for chlorophyll. Bottom oxygen shows a very slight decrease in summer (but never close to oxygen depletion) caused by the decrease of primary production. This was not visible in the Borssele OFPV deployment which was much smaller in comparison. Throughout the year nutrients show a slight increase compared to the reference run.

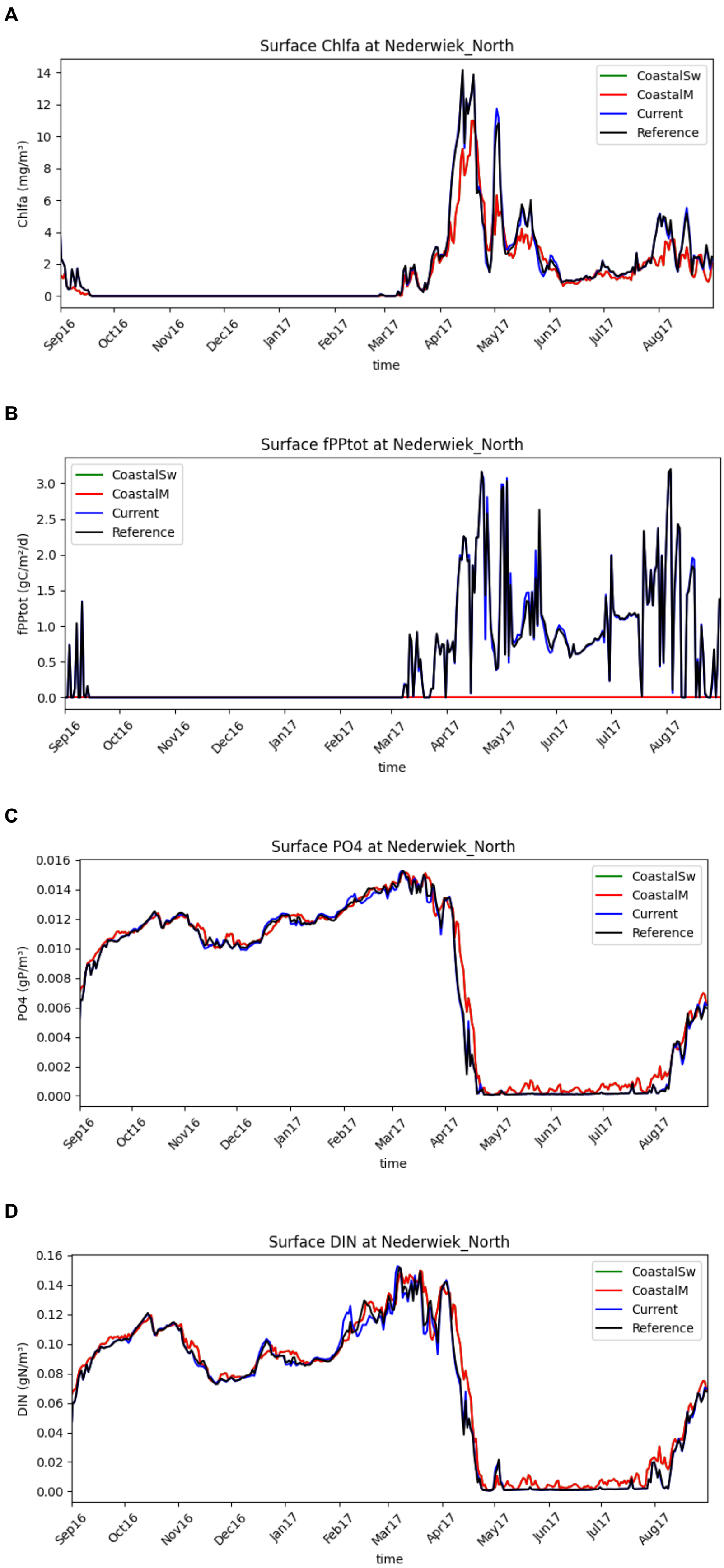
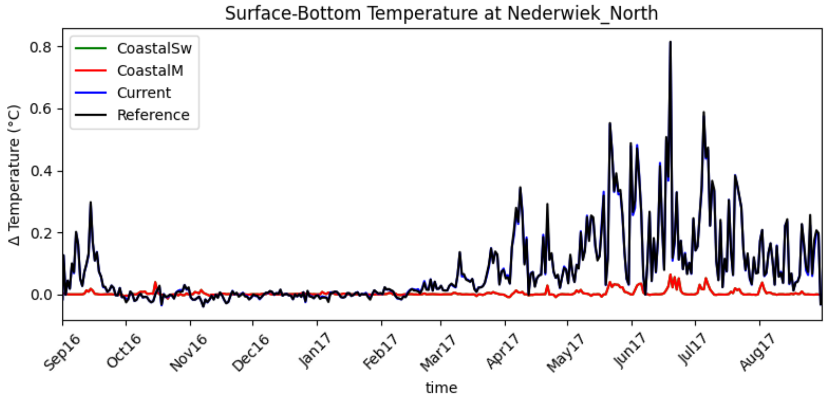
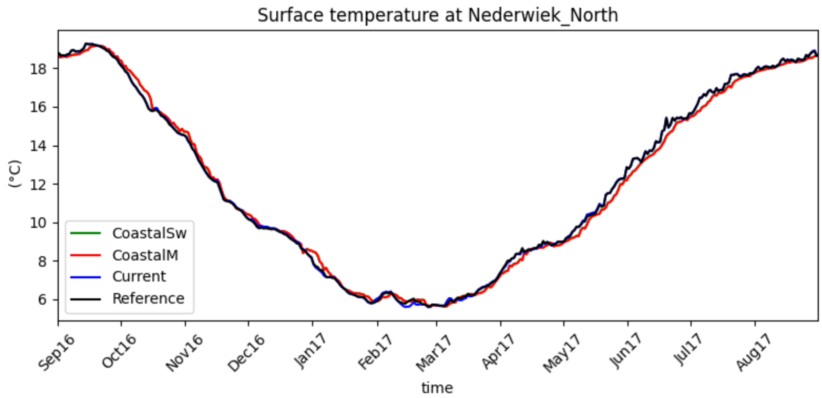


Figure 3-12 Timeseries of surface (A) chlorophyll-a, (B), primary production, (C) phosphate and (D) DIN.

A



B



C

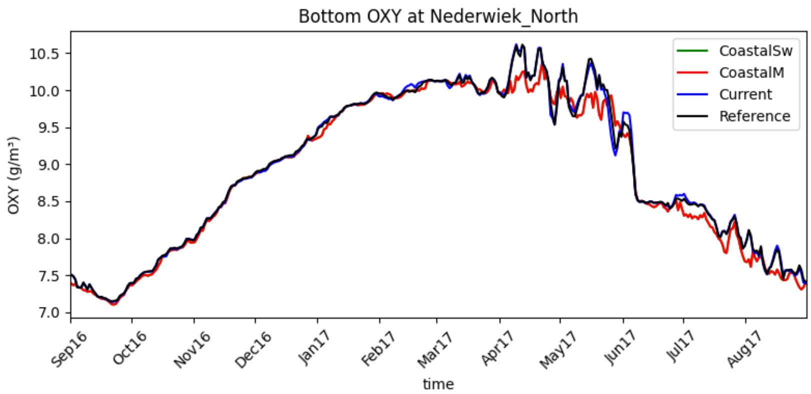


Figure 3-13 Timeseries of the (A) difference between the surface and bottom water temperature, (B) the surface temperature and (C) the bottom oxygen concentration.

3.5 Far-field, downstream effects of multi-use

To assess regional-scale effects and their spatial distribution, maps were generated for key variables: surface chlorophyll-a concentration (Figure 3-14), depth-integrated primary production (Figure 3-15), surface nutrients (PO_4 and DIN; Figure 3-16 and Figure 3-17), surface temperature (Figure 3-18), bottom oxygen (Figure 3-19), and the temperature difference between surface and bottom waters (Figure 3-20).

3.5.1 Chlorophyll-a

The reference run for surface chlorophyll-a (Figure 3-14 A) reflects the expected patterns in the Dutch North Sea, with high concentrations (>8 mg/m³) nearshore and lower values offshore. In the current scenario (Figure 3-14 B), OFPV is implemented in all three OWFs, while mussel aquaculture is implemented in Borssele, seaweed in Hollandse Kust Zuid, and a mixed aquaculture setup in Hollandse Kust Noord. In this scenario as well as in the mussel aquaculture areas of the coastal seaweed (Figure 3-14 C) and coastal mussels (Figure 3-14 D) runs, the mussel cultivation drives the strongest local decrease in chlorophyll-a, exceeding 1 mg/m³, with effects extending slightly beyond the OWF boundaries. Seaweed aquaculture also decrease chlorophyll-a, but the magnitude is smaller (~0.25 mg/m³ even within the farm area). OFPV installations at Nederwiek (Figure 3-14 C and D) cause a localized decrease of approximately 0.5 mg/m³, confined mainly to the platform footprint and not propagating across the full OWF area. Where decreases occur outside the OWF domain, they generally follow hydrodynamic transport patterns, moving north-eastward (along the coastline). Some patchy, weak anomalies appear downstream of OWF areas, which most likely fall into the natural variability of the system. However, we could not test that as we only simulated one analysis year.

3.5.2 Rate of primary production

The reference map for depth-integrated primary production shows relatively uniform values across the Dutch North Sea, without a pronounced coastal gradient (Figure 3-15 A). Differences between scenarios show very localized effects, even more confined than those observed for surface chlorophyll-a concentrations. OFPV installations at Nederwiek (Figure 3-15 C and D) cause the strongest impact, with decreases of approximately 1 gC/m²/day directly beneath the platform footprint, reflecting strong light limitation. Mussel aquaculture areas exhibit a slight increase in primary production (up to ~0.25 gC/m²/day), likely driven by nutrient remineralization from mussel growth. In contrast, seaweed aquaculture leads to a minor decrease in primary production, barely detectable in most areas, due to shading and nutrient uptake by seaweed. Overall, while OFPV implementation eliminates primary production, the effect remains local. In contrast, the strength of mussel-driven increases and seaweed-driven decreases are lower, but the effect is spatially more diffuse compared to the local effect of OFPV.

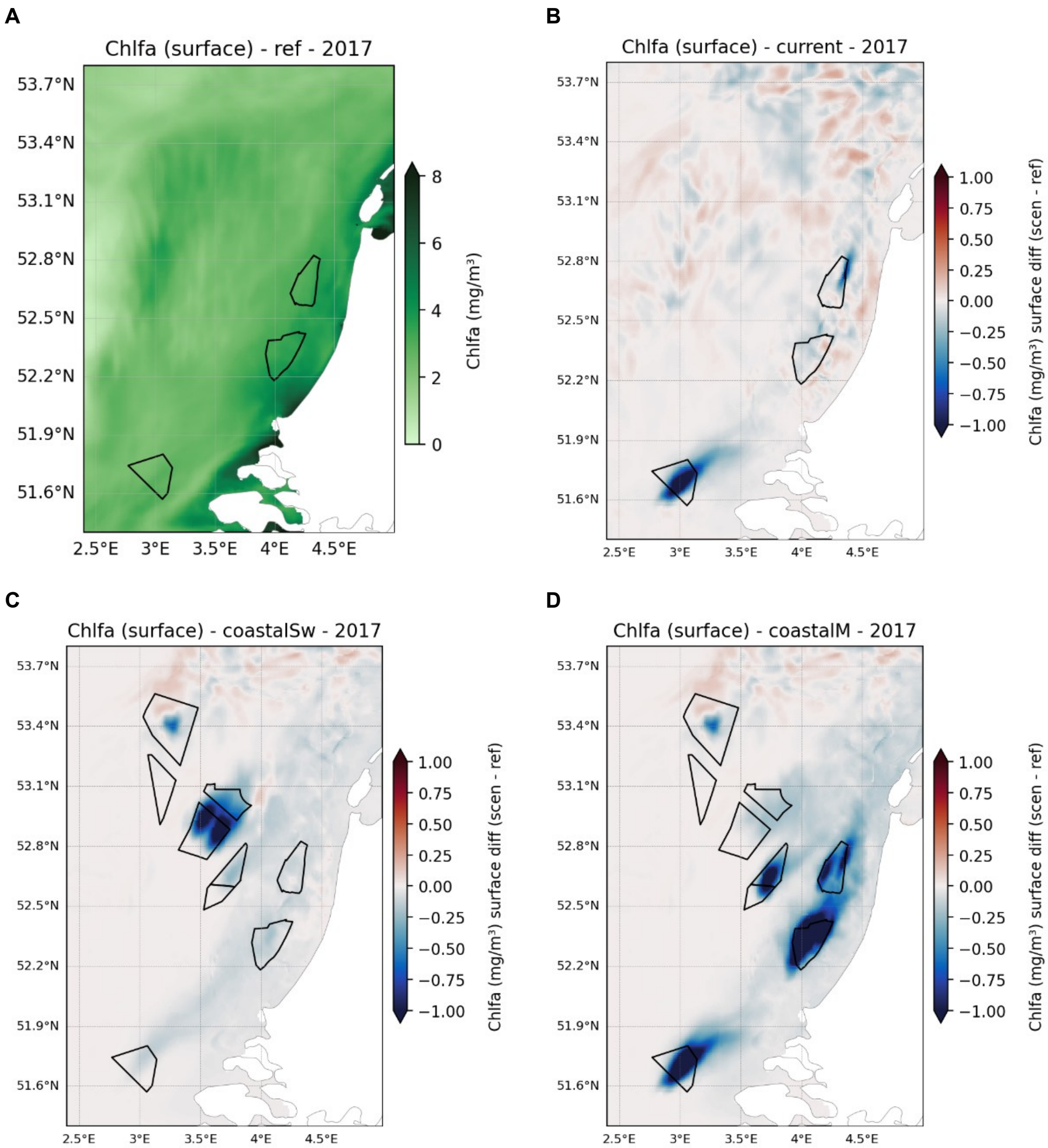


Figure 3-14 The spatial distribution of surface growing-season averaged chlorophyll-a concentration in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

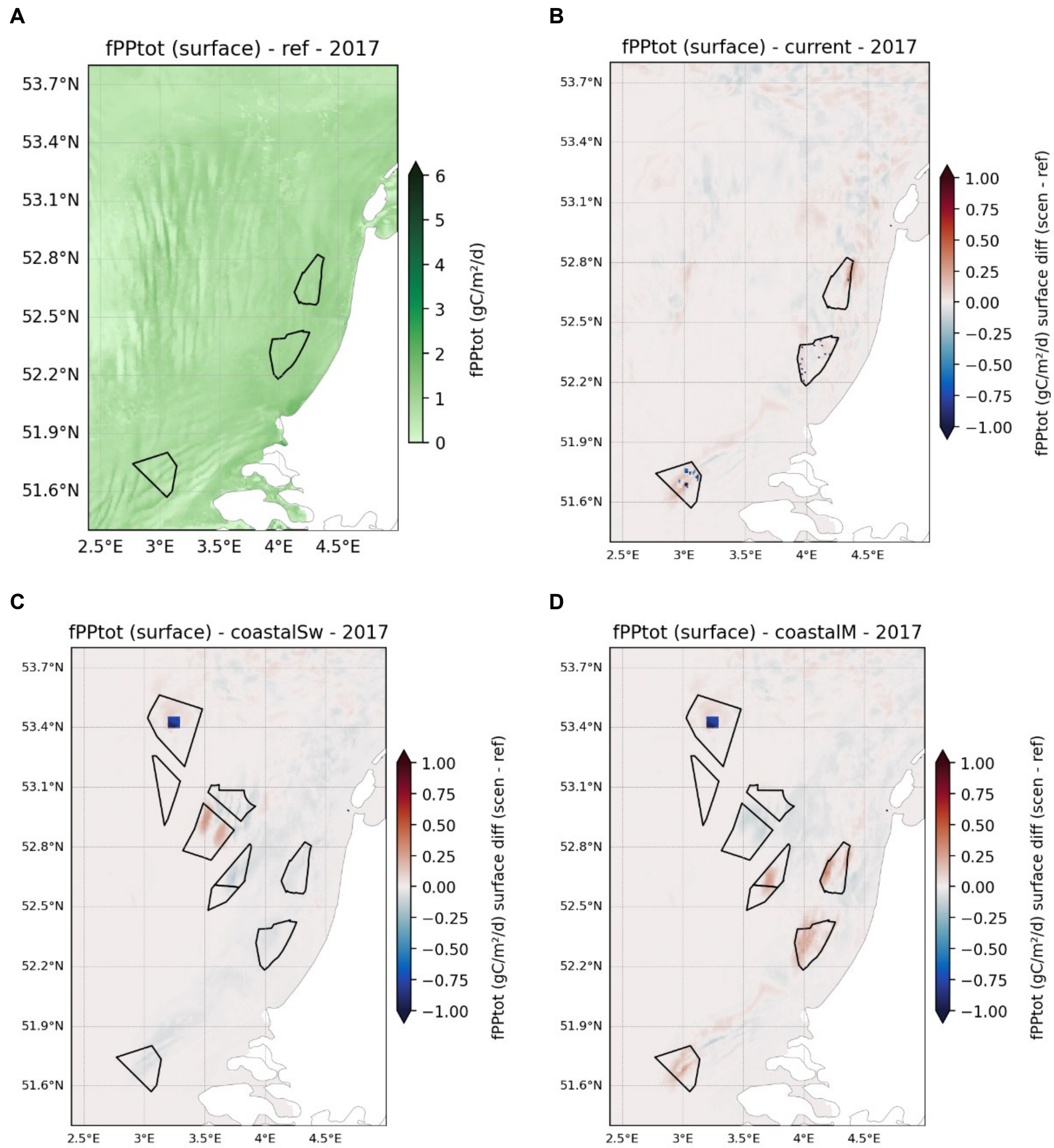


Figure 3-15 The spatial distribution of surface growing-season averaged primary production in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

3.5.3 Nutrient concentrations

The reference map for winter surface phosphate concentrations (Figure 3-16 A) shows a similar pattern to chlorophyll-a concentrations, with elevated values near the coast and specifically around river mouths. In the current scenario (Figure 3-16 B), the spatial pattern is diffuse, and the changes cannot be easily linked to the placement of the different forms of multi-use. For the tendered scenarios, clearer trends emerge: seaweed aquaculture consistently decreases PO_4 concentrations within- and extending farm footprints (Figure 3-16 C and D), reflecting nutrient uptake by seaweed biomass. In contrast, mussel aquaculture areas show increases in PO_4, likely driven by remineralization of organic matter from mussels. These changes are on the order of ±0.001 gP/m³ but do not remain as localised as for the previous variables and instead spread along most of the Dutch coastal region, following hydrodynamic paths.

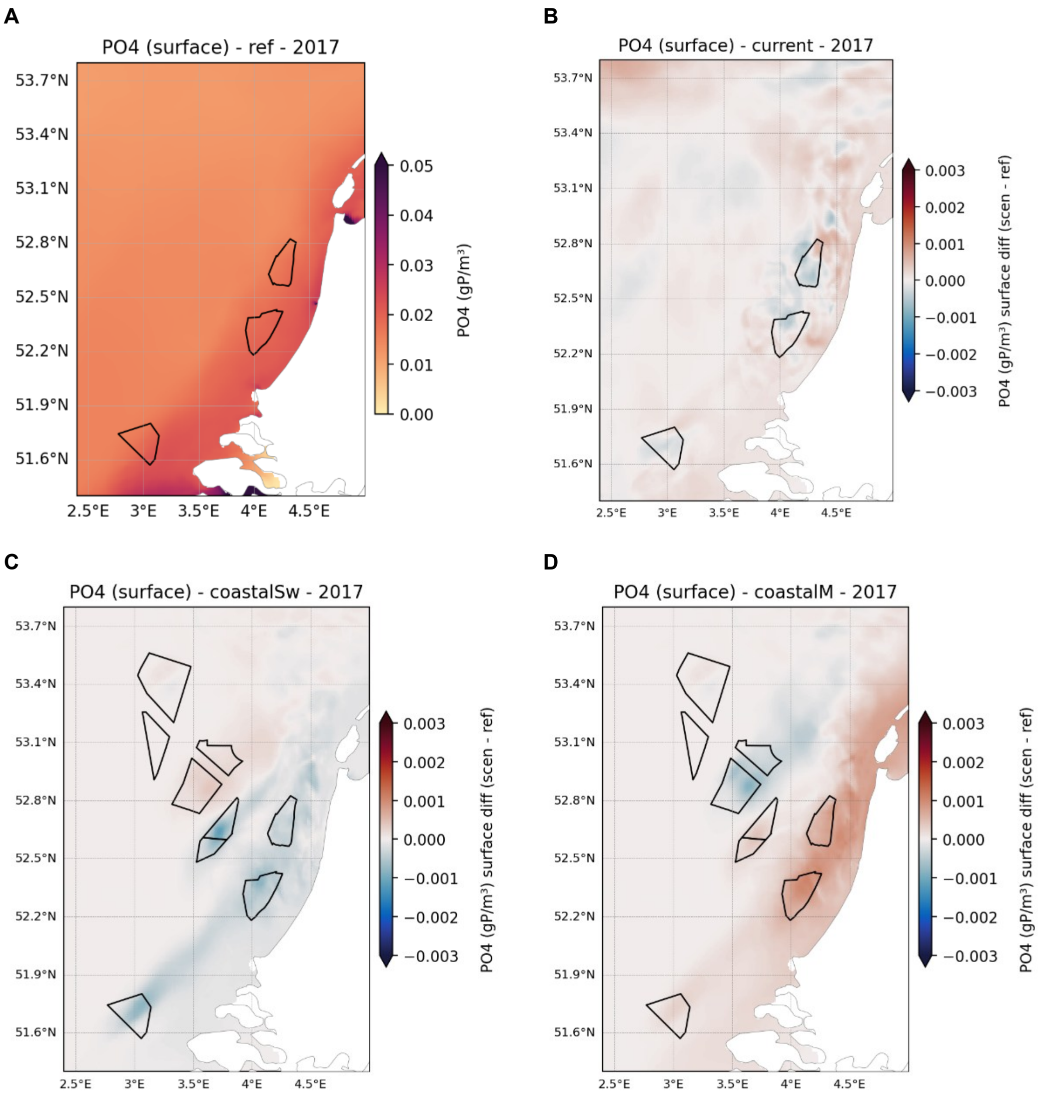


Figure 3-16 The spatial distribution of surface growing-season averaged phosphate concentration in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

The reference map for winter surface DIN (Figure 3-17 A) again shows a clear nearshore gradient, with higher concentrations along the coast and lower values offshore. In the current scenario (Panel B), the pattern of change is diffuse, and the changes cannot be easily linked to the placement of the different forms of multi-use. For the tendered scenarios, clearer trends emerge: seaweed aquaculture consistently decreases DIN within and beyond farm footprints (Figure 3-17 C), reflecting nitrogen uptake by seaweed biomass. In contrast, mussel aquaculture areas show increases in DIN (Figure 3-17 D), likely driven by remineralization of organic matter from mussels. These changes are on the order of magnitude of ±0.01 gN/m³. Overall, DIN responses mirror those observed for phosphate, with seaweed-driven decreases and mussel-driven increases largest within the aquaculture zones but spreading downstream following hydrodynamic pathways.

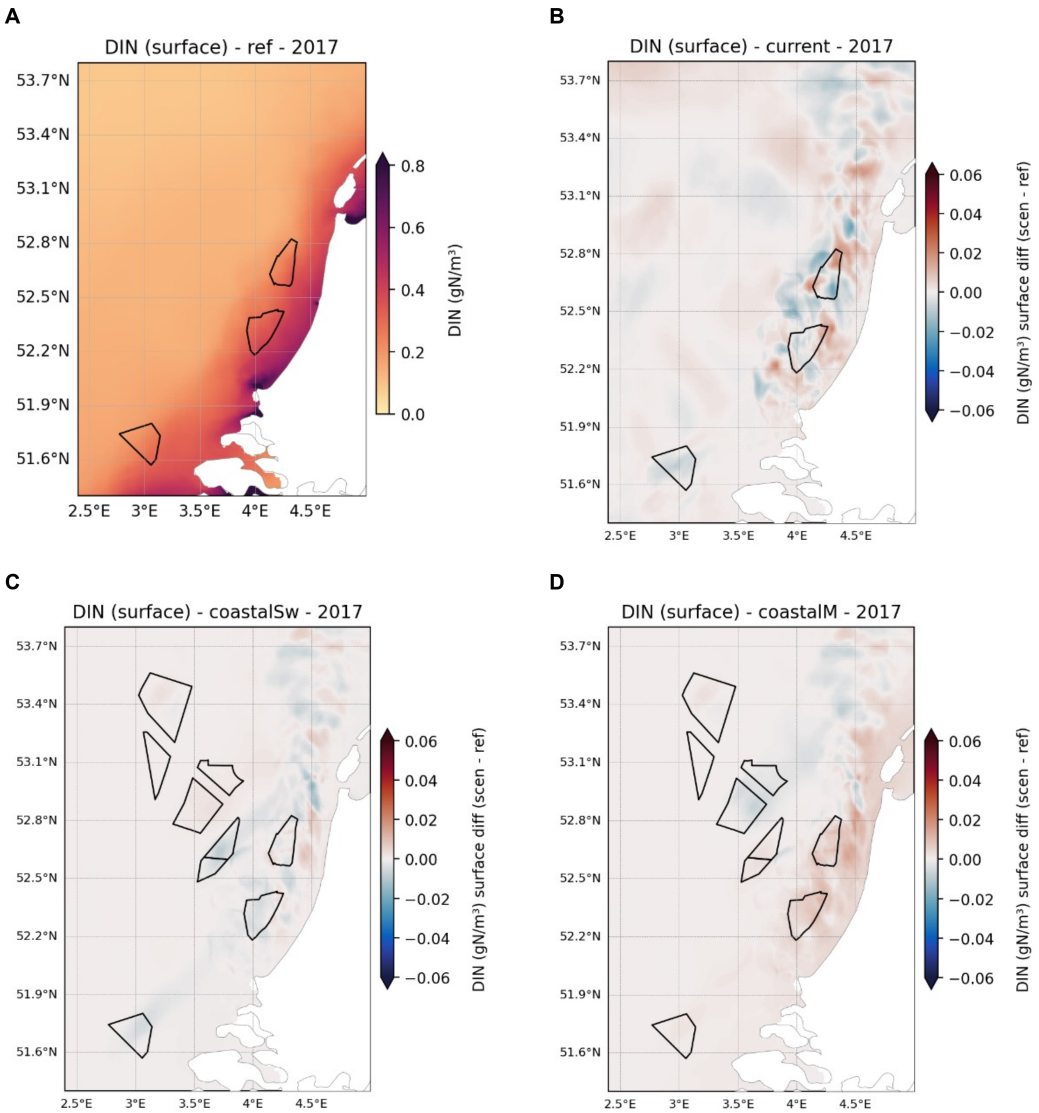


Figure 3-17 The spatial distribution of surface growing-season averaged dissolved organic nitrogen (DIN) concentration in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

3.5.4 Temperature

The reference map for growing season surface temperature (Figure 3-18 A) shows the expected seasonal gradient, with warmer waters nearshore in shallower regions and cooler waters offshore. Scenario differences indicate that temperature is most strongly influenced by OFPV installations while aquaculture hardly has an effect. OFPV structures cause surface water cooling, with reductions exceeding ~0.2 °C in the centre of the tendered scenarios that have the highest OFPV density. The shading effect also generates a distinct plume extending downstream from the platforms, following prevailing hydrodynamic patterns.

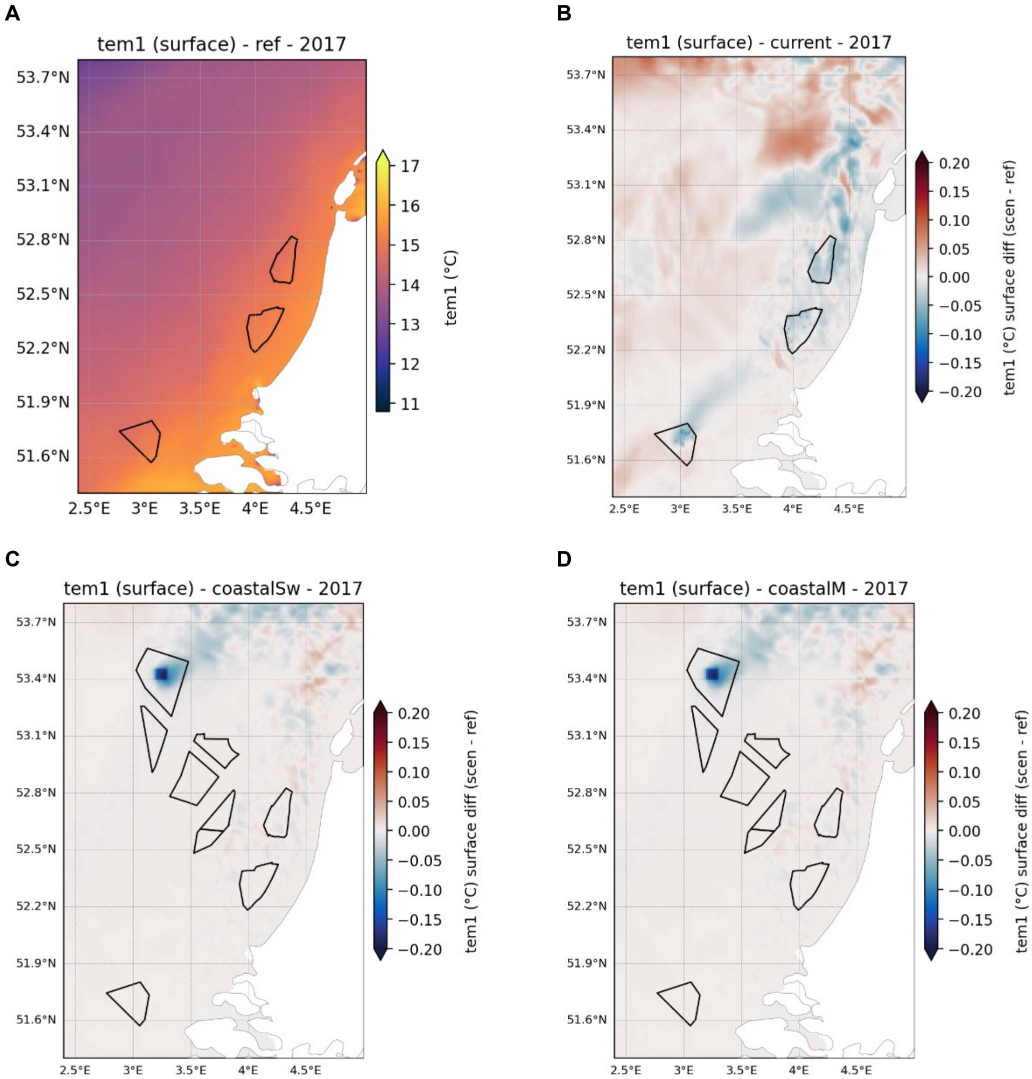


Figure 3-18 The spatial distribution of surface growing-season averaged water temperature in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

3.5.5 Bottom oxygen

The reference map for growing-season averaged bottom oxygen (Figure 3-19 A) shows uniformly concentrations between 8 and 9 g/m3 across the Dutch North Sea, typical for well-mixed oxygenated waters. Scenario differences reveal localized impacts associated with aquaculture and OFPV installations. Seaweed aquaculture areas exhibit slight increases in bottom oxygen (Figure 3-19 C and D), likely due to enhanced photosynthetic activity and oxygen release from seaweed biomass. In contrast, mussel aquaculture zones show small decreases in bottom oxygen, reflecting increased organic matter deposition and subsequent microbial respiration. OFPV installations also contribute to localized oxygen reductions beneath the platform footprint, driven by shading and reduced primary production. These changes are in the order of magnitude of ±0.2 g/m³ and are strongest locally, with a small wake effect observed outside the OWF areas.

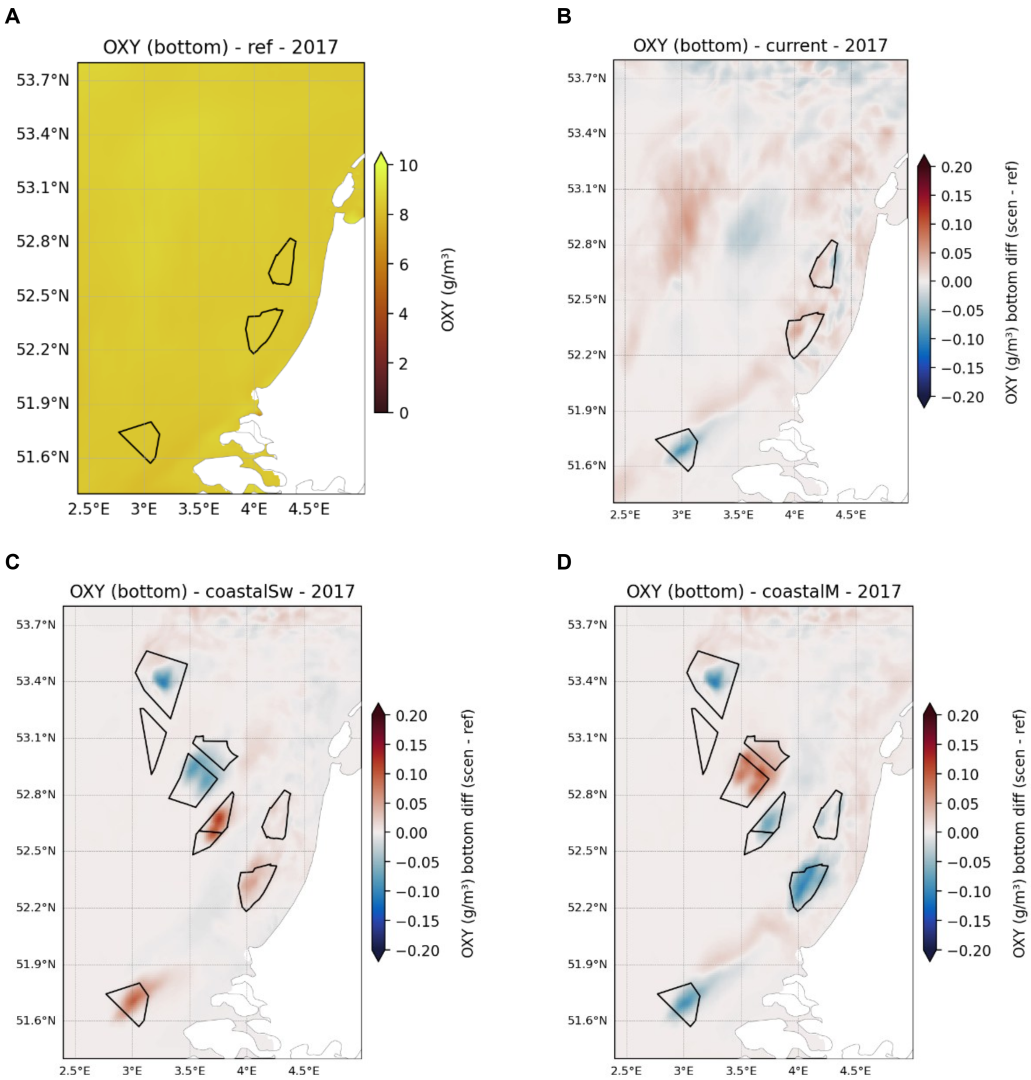


Figure 3-19 The spatial distribution of surface growing-season averaged oxygen concentration in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

3.5.6 Temperature difference surface-bottom

The reference map (Figure 3-20 A) shows the modelled growing season stratification pattern, with surface waters generally warmer than bottom waters. However, this temperature difference is small (rarely exceeding 1 °C) and is not strong enough to signal stratification. Scenario differences indicate that changes in vertical temperature gradients are mainly associated with OFPV installations. These structures create localized reductions in the surface–bottom temperature difference, with changes up to ~0.2 °C in the centre of the densest OFPV installations in Panel C and D, reflecting shading and slight cooling of surface waters. Some downstream model artefact instabilities are again observed in the difference maps. Some patchy, weak anomalies appear downstream of OWF areas, which most likely fall into the natural variability of the system. However, we could not test that as we only simulated one analysis year.

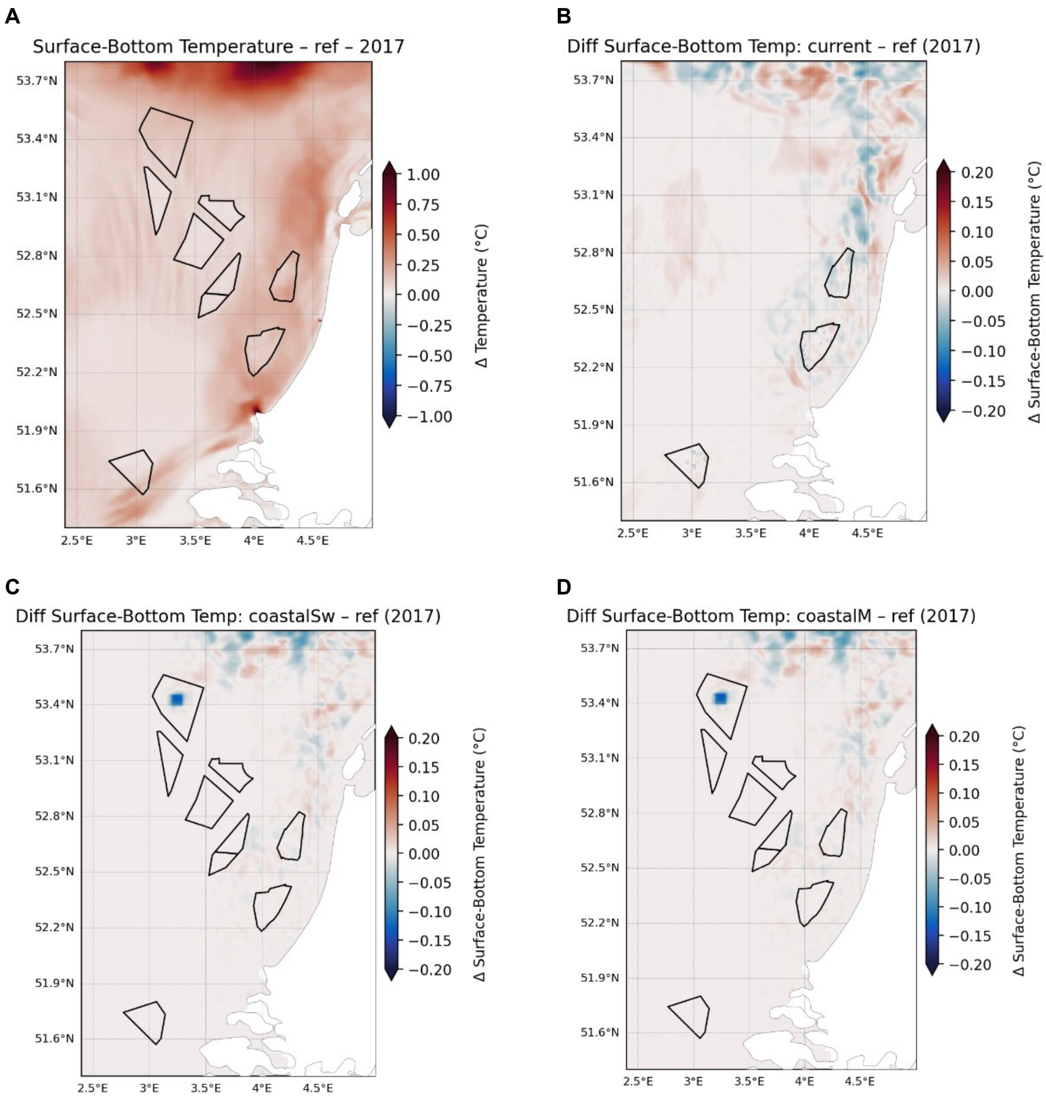


Figure 3-20 The spatial distribution of surface growing-season averaged bottom water temperature in different scenarios. A presents the reference run, while B-D illustrate the difference from the reference run for B - current scenario, C- coastal seaweed and D- coastal mussel scenarios.

4 Discussion, summary and outlook

The aim of this study was to model the impact of multi-use within OWF, specifically mussel aquaculture, seaweed aquaculture, and OFPV. Currently, only three OWF have aerial passports and even those do not designate the location for each type of multi-use specifically. Thus, scenarios were designed that explore the effects of both discrete, small-scale deployments and more extensive, large-scale, unrealistic deployments of multi-use. Each scenario produced distinct outcomes, enabling us to highlight various aspects of multi-use potential and impact. Overall, the impacts of mussel and seaweed aquaculture as well as OFW are diffuse and extend beyond the immediate deployment zones, whereas OFPV effects remain localized despite having a stronger local impact intensity.

4.1 Ecological impact of different forms of multi-use

Generally, the different forms of multi-use exhibit distinct ecological impacts. Within this modelling study, seaweed and mussel aquaculture show predominately far-field effects (especially on nutrients and chlorophyll-a), while OFPV shows predominately near-field local effects (especially on primary production and temperature).

Seaweed aquaculture primarily decreases nutrient concentrations (Xiao et al., 2017), especially during winter, and increases oxygen levels during summer, while having little impact on chlorophyll-a (Shin et al., 2023; Vilmin & van Duren, 2021). As a primary producer added to the ambient food web, this is in line with expectations. Seaweed uptake nutrients primarily in winter and thus their impact on chlorophyll (proxy for ambient phytoplankton) is indirect. During their growth phase, they produce oxygen as a by-product of photosynthesis.

Mussel aquaculture, on the other hand, impacts the ambient phytoplankton community through grazing (visible in the decrease of chlorophyll-a concentration) and organic matter decomposition leads to decreases in oxygen concentrations. Mussel aquaculture does, however, increase nutrient availability through remineralization which leads to a local increase in the rate of primary production during the growing season (Shin et al., 2023). Thus, while the overall ambient phytoplankton community decreases, the rate at which the rest of the phytoplankton photosynthesizes increases slightly through the faster local remineralization of nutrients.

OFPV systems strongly affect the rate of primary production and oxygen concentrations locally, i.e. these impacts remain confined to the deployment area without downstream effects. Offshore wind farms themselves influence primary production through hydrodynamic changes that alter suspended sediment and light availability, creating downstream effects (Christiansen et al., 2023; Van Duren et al., 2021; Zijl et al., 2021, 2023).

4.2 Impact of location and scale

However, the deployment location plays a critical role in determining the effectiveness of multi-use, particularly for aquaculture yield. For OFPV deployments this is of no importance. Aquaculture sites closer to the coast generally achieve higher yields due to more favourable environmental conditions (higher nutrient and chlorophyll-a concentrations). Areas with fewer deployments in the vicinity experience less competition for resources, further enhancing yield. Importantly, downstream effects are not limited to competition within a single offshore wind OWF; they can also occur between multiple OWFs, influencing broader spatial dynamics.

These spatial dynamics are also influenced by the size of the deployments. The coastal mussel and coastal seaweed scenarios show that larger deployments generally produce stronger ecological changes. This is regardless of whether the deployments are concentrated in large blocks—as in OWFs such as Hollandse Kust West, IJmuiden, and Nederwiek—or distributed across numerous smaller sites, as in OWF Borssele, Hollandse Kust Zuid en Noord. For aquaculture, the larger the deployment, the more pronounced the downstream effects. This is not directly the case of OFPV: small deployments have no downstream effect, while large deployments exhibit a localized effect on temperature without affecting primary production. This could however as be a result of the modelling choices that were made for OFPV which are discussed in more detail in the next section. In general, these impacts highlight the importance of deployment size, spatial arrangement and location of multi-use within in marine spatial planning.

4.3 Caveats and limitations

Several caveats should be considered when interpreting the results of this modelling exercise.

Aquaculture was implemented in this study based solely on work completed within other projects. The implementation was validated within those projects and so that step was not repeated here. For seaweed cultivation, frond growth could lead to nutrient limitation when fronds become too long. Although this effect is likely small—since most nutrient uptake occurs during winter when fronds are short—it may result in an overall overestimation of seaweed's impact on nutrient removal. For mussel aquaculture, mortality rates may be underestimated, which could lead to inflated estimates of mussel yield and growth, and consequently an overestimation of their influence on ambient environmental conditions. Lastly, seaweed and mussel harvest was not simulated. This is not a huge limitation on the model results as the harvest occurs in the late summer (~September) where our model simulation ends. For a multi-year analysis, harvesting would have to be explicitly included.

In the case of offshore floating photovoltaic (OFPV) systems, only the effects on incoming solar radiation and platform roughness were considered. Other processes, such as biofouling beneath the platform (Mavraki et al., 2023, 2025) and changes in ocean-atmosphere exchange, were excluded, likely causing an underestimation of OFPV's overall impact. Evidence from OWF (Maar et al., 2009) and a modelling study on biofouling on OFPV (Nalmpanti et al., 2025) suggests that bivalves can affect phytoplankton communities also in the far-field, which was not accounted for in OFPV modelling.

Additional limitations of study include the visualization of only the growing season (March – September), despite seasonal variability in effects: seaweed exerts its strongest influence in winter, mussels during the growing season, and OFPV throughout the year. Furthermore, the model covers only a single year, restricting insights into long-term dynamics. Also, the composition of phytoplankton was not analysed, leaving potential shifts in community structure unexplored. Lastly, the scenarios were designed to explicitly also deal with worst-case assumptions for large-scale, lumped deployments which is most likely not a real-life deployment strategy, especially not for OFPV. These constraints highlight the need for caution when interpreting the results and underscore areas for future research.

Furthermore, two additional modelling decisions must be stated as caveats. Firstly, the impact of OWF on suspended sediment was not explicitly modelled but forced. This contrasts with the other forms of multi-use which were all explicitly modelled. This means that in the model simulations the hydrodynamic impact of OFPV deployments does not affect the suspended sediment concentrations. However, it is expected that OFPV deployments will also affect suspended sediment distribution and so this is a large caveat in this modelling study. Secondly, we did not test model significance. We know that models are sensitive to changes in initial conditions and additional processes. This is good because this enables us to be able to test the effect of anthropogenic pressures on the marine ecosystem through modelling. At the same time, it is important to have a good grasp on model sensitivity. However, within the capacity of this project we could only run two spin-up years and one analysis year. That is not enough to do an analysis on the sensitivity of the models towards changes. That is something that needs to be considered and ideally picked up in upcoming projects.

It must be noted that assessing the impact of multi-use remains challenging due to the absence of clear thresholds within the Marine Strategy Framework Directive (MSFD). The MSFD descriptor D4 Food webs describes the conditions of the pelagic lower trophic food web (phyto- and zooplankton) but the D4 indicators lack quantitative thresholds. The MSFD Descriptor D5 Eutrophication has threshold for indicators relating to nutrient (D5C1) and chlorophyll-a concentrations (D5C2), but only upper thresholds are available, while for the impacts of multi-use lower threshold would be necessary. This lack of quantitative thresholds makes it difficult to judge whether observed model changes are significant or negligible. For most variables, changes are smaller than one order of magnitude; however, chlorophyll and primary production (PP) show larger variations, and without thresholds, their ecological relevance cannot be determined.

In this report we concentrated on chlorophyll-a as a proxy for phytoplankton biomass; analogous to the descriptors in the MSFD. Note that some of the impacts on chlorophyll are due to shading effects. Earlier work in Wozep has indicated that decreased light availability can in the model lead to a shift in phytoplankton to species adapted to lower light conditions (Zijl et al. 2024). Microalgae adapted to low light levels, tend to have more chlorophyll per unit biomass (Jakobsen & Markager, 2016). Hence, chlorophyll is not always a perfect proxy for algal biomass. While the models are based on scientific literature regarding higher chlorophyll contents in low light-adapted algae, how well this is quantified in the model still needs validation.

Lastly, there is no in-situ validation data for pilots available that allow us to validate these model simulations. Within the near future pilot deployments also seem unlikely, so mesocosm experiments offer a method to collect data on the ecosystem impact of mussel and seaweed aquaculture as well as OFPV deployments.

4.4 Summary and outlook

A first tentative conclusion from this modelling study could be that marine spatial planning strategies should prioritize spreading and mixing the different modelled forms of multi-use, i.e. seaweed aquaculture, mussel aquaculture and OFPV, rather than assigning a single type of multi-use to each OWF. Larger deployments amplify both local and downstream effects, making scale an important consideration. The varying impacts of different forms of multi-use do not necessarily cancel each other out as they occur at different times of the year—seaweed exerts its strongest influence in winter, mussels during summer, and OFPV throughout the year. By mixing and matching multi-use types across OWFs, it may be possible to minimize negative impacts while optimizing overall benefits.

In summary this study demonstrates that DCSM-FM and the software Delft-3D-Water Quality can simulate the cumulative effects of multi-use for different scenarios. This study highlights the strength of the model in capturing general tendencies and interactions between different multi-use forms. The model’s usefulness would increase with more realistic scenarios and available MSFD thresholds, allowing to judge the more realistic scenarios.

At present, the model serves primarily as a tool to identify broad patterns rather than precise predictions, emphasizing its role in high-level strategic marine spatial planning.

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A Current multi-use scenarios

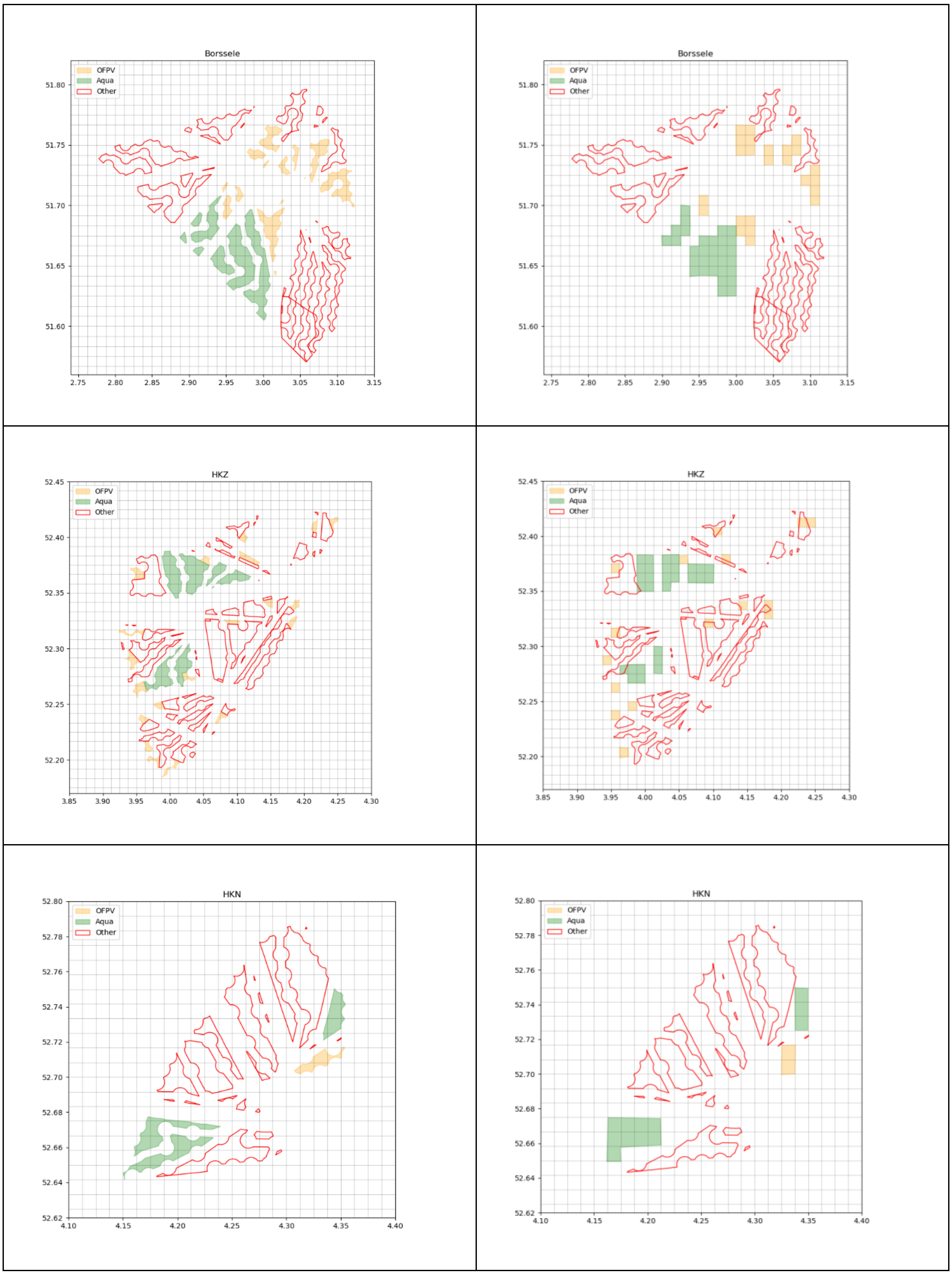

Figure A 1 Multi-use areas as designated within the aerial passport (left column) and as designed to fit the model grid (right column). The rows depict the three current offshore wind farms (top: Borssele, middle: HKZ, bottom: HKN) and the colors illustrate the two categories aquaculture and alternative energy generation.

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