Deltares

Impact of offshore wind development on the North Sea ecosystem

Scenario study for the Partial Revision

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Client	Rijkswaterstaat Water, Verkeer en Leefomgeving
Contact	Persoonsgegevens
Reference	
Keywords	Offshore wind farms; ecosystem effects; stratification; SPM; primary production

Document control	
Version	1.0
Date	06-05-2025
Project nr.	11210920-002
Document ID	11210920-002-ZKS-0001
Pages	53
Classification	
Status	final

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Summary

Offshore wind can have a non-negligible impact on the marine ecosystem, through bottom-up processes. These have previously been researched in Wozep and a modelling suite has been developed to investigate future offshore wind scenarios with respect to changes in hydrodynamics, suspended particulate matter (SPM) dynamics and ecological processes such as primary production.

Scenarios
This modelling suite has now been applied to a highly likely wind energy scenario for 2033, which will be used in the following evaluation round for assessing cumulative impacts of offshore wind in 2033 also known as “Kader Ecologie en Cumulatie, versie 5.0” (KEC 5.0). Since this scenario has a high probability of realisation, this is called the *reference scenario*.

Furthermore, the modelling suite has been applied to five (theoretical) scenarios for the Partial Revision of the North Sea Programme 2022 – 2027. This programme aims to ensure the continuity of offshore wind energy, by designating offshore wind farm zones to be developed after 2033. The areas under consideration are search area 6/7, part of the Doordewind and Doordewind (west) areas, and Lagelander. Search Area 6/7 is so large that zoning arrangements (which sub-areas will be suitable for offshore wind farms and which sub-areas will remain open) are being investigated. The five investigated scenarios look at the impact of all mentioned areas combined, with different options for the lay-out of area 6/7. Note: these scenarios are hypothetical and the model results are intended to investigate the extreme options. Four scenarios were run with the whole area being filled with a uniform distribution of different sizes and densities of turbines and one scenario was run with a broad, open space in the central part of the area. These scenarios were primarily assessed against the reference (used for KEC 5.0). Some comparisons were also made with a situation without wind farms in order to get an impression of the cumulative impacts.

All scenarios (i.e. reference scenario, and the five scenarios for the Partial Revision) contained a lay-out for offshore wind farms in North Sea countries other than the Netherlands, based on the best available information to date.

Results
The general pattern of impacts was in line with the difference found between sub regions in previous studies. In the reference scenario (KEC 5.0) most wind farms see a decrease in primary production due to elevated SPM concentrations in the top layer. The most pronounced effects are found in the German Bight, where local decreases are strongest and also most interaction occurs between wind farms. Particularly the areas “TNW” and the Gemini farms in the base scenario indicated clear negative effects on primary production. In these areas primary productivity was reduced by about 60%. In the larger “Doordewind” area primary production was reduced with about 25%, from around 0.4 g C/m^2/day to around 0.3 g/m^2/day. In the directly adjacent German farms the reduction will be larger due to interference and accumulation of effects.

For Doordewind primary production was reduced for a further 26-29% in the Partial Revision scenarios where the size of the area as well as the density of turbines was higher. The Lagelander wind farm area is located in an area with very limited stratification and showed slight (3-8%) reductions on primary production due to elevated fine sediment in the top of the water column (causing light limitation), but this was much less than impacts in the German Bight.

The Search Area 6/7 in all Partial Revision scenarios sees a boost in primary production and phytoplankton biomass, due to the fact that the summer temperature stratification, which limits productivity in that area, is reduced, more nutrients are available in the top layer for primary production. Stratification does not disappear completely, which confines any extra resuspended SPM to the layers below the pycnocline in the summer season, which means that it does not reduce light availability in the growing season of phytoplankton, as is the case for most other wind farm areas. The increase in primary production also increases the amount of phytoplankton biomass. Due to the increased mixing, particularly the bottom layers receive in some cases more than twice the amount of chlorophyll.
The magnitude of the effects is influenced by the energy density of the wind farm. However, increasing or decreasing turbine size has much less effect than changing the number of turbines per km^2. The density of turbines has more effect than their size.
One of the five scenarios (scenario 4) involved a large open space in the centre of the wind farm, and this scenario seemed to have the lowest impact on stratification and on annual average increases of SPM in the top water layer. However, in terms of primary production the differences between this scenario and scenario 5 (with similar turbine density and a higher total capacity of the wind farm and scenario 1 (with similar sized turbines and a similar total capacity of 24 GW) were relatively minor. Effects on primary production compared to scenario 1 and 5 were patchy, and at most 10% in the open space (about 0.05 g C/m^2/day). Averaged out over the whole of the farm differences were less than 4% compared to scenario 1 and just over 7% with scenario 5.

Contents

1 Introduction

1.1 Aim of this report

In 2023 / 2024 Deltares carried out scenario studies to assess the impact of different North Sea offshore wind scenarios on the base of the marine foodweb (Zijl et al. 2024). This report is an extensive summary of the original report, without the technical detail of the underlying model. It focusses specifically on the ecological impact and only shows those underlying results from impacts on hydrodynamics, waves and fine sediment that are essential to understand the impacts on primary production and the basis of the marine foodweb. For those interested in the details of the methodology, the detailed model assumptions and the additional results, we refer to the original report (Zijl et al. 2024). In this report we only highlight the most important impacts. The report is intended as background material for stakeholders and policy makers with some background knowledge on the topic.

With respect to impacts on the marine food web, the changes in primary production and in phytoplankton biomass are the most important. With respect to measurements, by far the most readily available proxy for biomass is chlorophyll. While there are some issues with using chlorophyll as a proxy for biomass, impacts on chlorophyll are discussed here as well. These will be discussed in more detail. With respect to other impacts, only those that are relevant to explain the impacts on primary production or the changes in distribution of phytoplankton (vertical and horizontal) will be highlighted, such as impacts on stratification for the hydrodynamics and impact on fine sediments in the top layer. For a full description of the details we refer to the original scenario report (Zijl et al. 2024).

1.2 Offshore wind and the marine environment

Wozep (the *Wind Op Zee Ecologisch Programma*) is an integrated research programme to reduce the knowledge gaps regarding the possible environmental effects of offshore wind farms (OWFs) on the North Sea.

Previous studies have indicated that ecosystem effects of large-scale offshore wind can locally be profound. These effects are due to interactions of the wind turbines with the ambient flow, resulting in changes in currents spatio-temporal patterns, stratification, changes in fine sediment dynamics and consequently changes in primary production. In a first study (Van Duren et al. 2021) we demonstrated the applicability of the new Dutch Continental Shelf model-flexible mesh (DCSM-FM) model to quantify such processes. In this first modelling study (Van Duren et al. 2021) a more or less hypothetical scenario layout was used to assess potential effects, as at that time the available plans for future offshore wind were limited to a few wind farms. A subsequent study (Zijl et al. 2023), already used a different, more likely set of scenarios, and an improved version of the model, in order to test large scale roll-out of offshore wind. These scenarios were on the one side based on realistic options for future offshore wind developments and hypothetical potential scale up locations on the other side. These scenarios were therefore still fundamentally aimed at research into potential effects.

Developments and further validation of the model is still ongoing, but the current version is now deemed fit for use in more applied project to assess potential effects of different configurations of wind farm lay-out, and to assess pros and cons of different options in marine spatial planning.

1.3 Designated areas (to be developed before 2032)

With the offshore wind target being increased from 11 GW to 21 GW by 2033, more areas for offshore wind farm development are needed. On the 18th of March 2022 the Dutch government approved the North Sea Programme 2022-2027, which among other things designates offshore wind farm zones that provide space for the development of wind farms up to and including 2030/31. The new designated areas included Nederwiek, Lagelander and Doordewind, while IJmuiden Ver (Noord) was reconfirmed, as was the southern part of Hollandse Kust West (Figure 1.1; Appendix D). At the same time, it was agreed that no more than 10,7 GW will be realised in these wind farm zones until 2033, and that the remaining parts are to be reconsidered in a Partial Revision (section1.4).

1.4 Beyond 2033: Partial Revision (PR)

The North Sea Programme 2022-2027 also announces an interim change, the Partial Revision (PR), with the aim of creating wind energy areas for the period after 2033 and thereby determine the spatial location of surrounding shipping routes. A Partial Revision is necessary to ensure the continuity of the realization of offshore wind farms. Designating wind energy areas is a necessary first step for this. Further background information regarding the Partial Revision and the links with other North Sea related policies can be found in the Concept Note Scope and Level of Detail[1]. In the PR search areas are investigated as well as (parts of) already designated areas that remain unused when implementing the Supplementary Roadmap 2030. In the North Sea Programme 2022-2027 it was agreed that the (parts of) the wind energy areas designated therein remain unused after the realization of a total of 21 GW until approximately 2030, as detailed in the afore-mentioned Concept Note[1]. The following areas are considered for specifying at least 23-26 GW in the PR (Ministerie van Infrastructuur en Waterstaat 2023):

- Search Area 6/7
- Search area Doordewind (west)
- Doordewind: already designated but unused part of this area
- Lagelander: already designated but completely unused

Figure 1.1 shows a map showing the location of these areas.

[1] https://www.platformparticipatie.nl/programmanoordzee/concept-nrd-participatieplan-programmanoordzee/handlerdownloadfiles.ashx?idnv=2609791

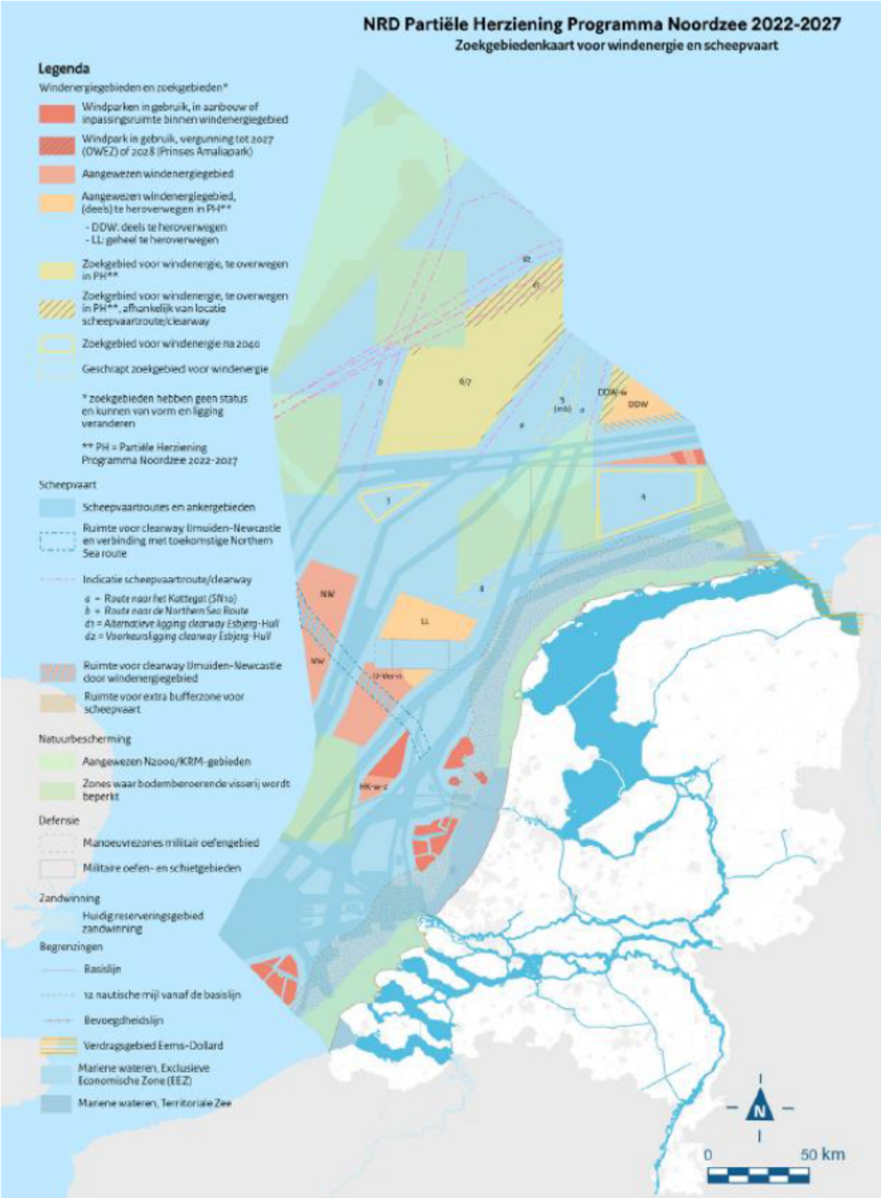

Figure 1.1: Map of wind search areas and shipping (from the Concept Note on the Partial Revision[1].

Meanwhile there are also more details available regarding the plans for offshore wind in neighbouring countries.
The previous studies indicated that the effect of several wind farms together can be different from the sum of the component parts. Hence, wind farms in other North Sea countries have an impact on the effects in and around Dutch wind farms. The German bight was in the previous Wozep studies already identified as an area that appeared to be especially sensitive (Van Duren et al 2021; Zijl et al 2023), and particularly there the plans for offshore wind have substantially increased.

1.5 Set-up of this report

It is not quite possible to describe the impacts without use of some scientific jargon. For non-specialists it is sometimes difficult to distinguish the relevance between related terms, such as the growth of algae (primary production), the amount of algae present (algal biomass) or an easily measured parameter in the field, such as chlorophyll, which is an indicator of algal biomass, but may not always translate directly. **Chapter 2** is a brief, non-technical description of the different model components. For more detail we refer to the main report (Zijl et al. 2024). **Chapter 3** describes the lay-out of the various scenarios, such as the reference scenario as used for the KEC 5.0, as well as the five different scenarios for the Partial Revision. The reference scenario results, compared to the situation without any wind farms, are described in **Chapter 4**. These are required to interpret the impact of the five Partial Revision scenarios. **Chapter 5** Describes the results of the scenarios for the Partial Revision. For each section (hydrodynamics, fine sediment dynamics and primary production and chlorophyll concentration these are split into 1) the impacts of scenarios 1, 2, 3 and 5. And 2) the impact of scenario 4. Scenarios 1, 2, 3 and 5 differ from each other only in density of turbines and energy density in Search Area 6/7. Hence these scenarios are compared to the reference scenario (i.e. the projected situation in 2033) as well as to each other. This allows assessment of the impact of pillar density on ecosystem impacts. Scenario 4 has a different lay-out from the first three and has a large open space in a north-south direction through Search Area 6/7. This scenario has the same total number of turbines and the same energy yield as scenario 1, and the same distance between turbines as scenario 5. Hence the results of scenario 4 are also explicitly compared to these scenarios. The results are discussed in **Chapter 6**. **Chapter 7** highlights knowledge gaps, data requirements for validation and potential relevance for higher trophic levels **Chapter 8** lists the literature sources.

Appendix A explains in accessible terms the most important physical and biogeochemical processes that drive phytoplankton growth and distribution, as well as explains the biological processes, and how offshore wind farms can impact these. Related to this, **Appendix B** contains a glossary with a definition of the different technical terms. **Appendix C** contains a map of the different impact areas in the North Sea as defined in previous Wozep work and **Appendix D** contains a map with the wind farm names.

2 Methodology

2.1 The hydrodynamic model

For the hydrodynamic modelling, the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) is used, which was developed in recent years as part of Deltares' strategic research. The main purpose of 3D DCSM-FM is to have a versatile model that can be used for studies on the Northwest European Continental Shelf, including the North Sea and adjacent shallow seas, such as the Wadden Sea. Earlier studies (Boon et al. 2018, Van Duren et al. 2021, Zijl and Leummens 2023) had indicated that effects on stratification are likely (at least in some parts of the North Sea) in and around wind farms. Such effects can be very far reaching for ecological processes (Ruardij et al. 1997, Große et al. 2016, Flores et al. 2017). Validation with field measurements has shown that the new DCSM-FM model is extremely good at simulating this process (Zijl et al. 2018, Zijl et al. 2020).

With a grid size of at least 900m, the piles of the OWFs are too small to explicitly include in the model schematization. The effect of the monopiles on moving water has been parameterised to an average drag function based on the size and density of monopiles.

The locations of the offshore wind farms are specified in the hydrodynamic model by means of a polygon along its boundaries. In each computational cell within this polygon the appropriate sink and source terms are computed considering the pile density (number of piles per unit of area) and mean pile diameter. Further details about the set-up and the parameterisation of wind farms in the model can be found in Zijl et al. (2024).

2.2 Waves

Since the wind forcing applied, does not yet include the impact of OWFs on the meteorological conditions, this has been included in a simplified manner by reducing the near surface wind speeds within the wind farms by 10% (Zijl et al. 2021). Other meteorological forcing parameters, such as air temperature and relative humidity, are left unchanged. Wake effects and directional changes of the wind are not considered. These wind data are the basis for a SWAN model, which is run for the different set-ups. The combined results on e.g. bed shear stress from DCSM-FM and SWAN are uses to calculate the impact on fine sediment dynamics.

2.3 Fine sediment

Coupled to the hydrodynamic model we have run models to assess the effects of wind farms on fine sediment dynamics. This module is called D-WAQ. The suspended matter in the water column is parameterised with 3 different categories with different sinking speeds.

2.4 Water quality and ecological processes

In D-WAQ also nutrient dynamics, light extinction (under the influence of suspended fine sediment), primary production and other constituents can be modelled. In this study we do not take the impact of e.g. mussels growing on the monopiles and the impact of zooplankton explicitly into account. There are studies under Wozep ongoing that also include these processes, but these are still in a developmental stage. Grazing impact and other sources of mortality are included as a mortality factor, determined in calibration runs.

Figure 2.1 gives a schematic overview of the processes in the water quality and ecology model.

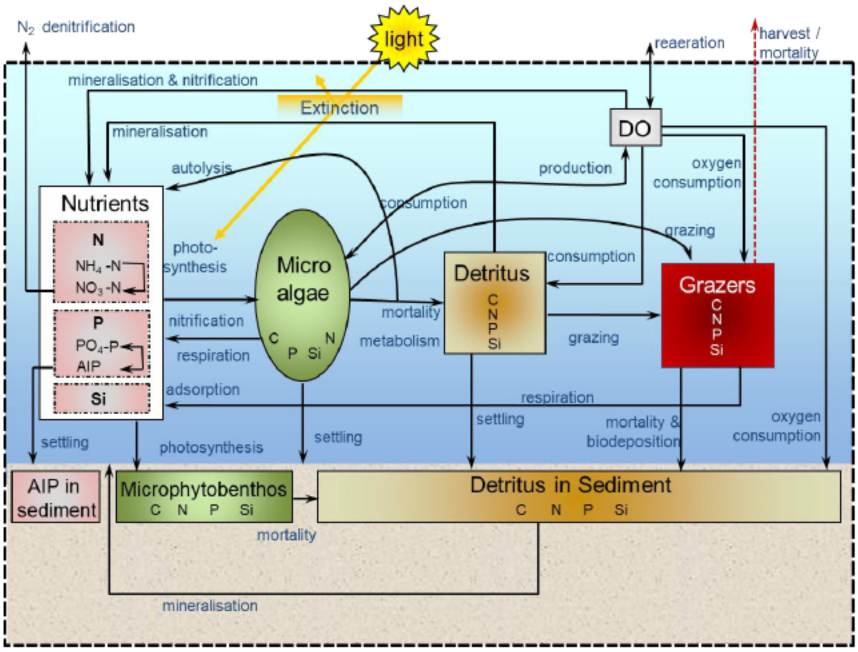

Figure 2.1: Schematic overview of processes in the water quality and ecological model. In the version of the model used in this study, grazers (zooplankton and zoobenthos) are not explicitly taken up.

For further details about the model setup, parameterisation of wind farms etc. we refer to the full technical report (Zijl et al. 2024).

3 Scenario choice

For a map with all the Dutch wind farm areas and search areas with names see Appendix D.

3.1 Reference scenario (situation 2033; used for the KEC evaluation).

The current scenario for wind farms operational in 2033 is used for the Partial Revision as a refence. This scenario includes the wind farms that are currently operational, the ones that are currently licenced (most are under construction, some in the early stages), the ones that are currently designated areas (either currently tendered or in the near future). It also includes the locations of the wind farms outside the Netherlands that are likely to be in operation by 2033. Figure 3.1 shows this scenario.

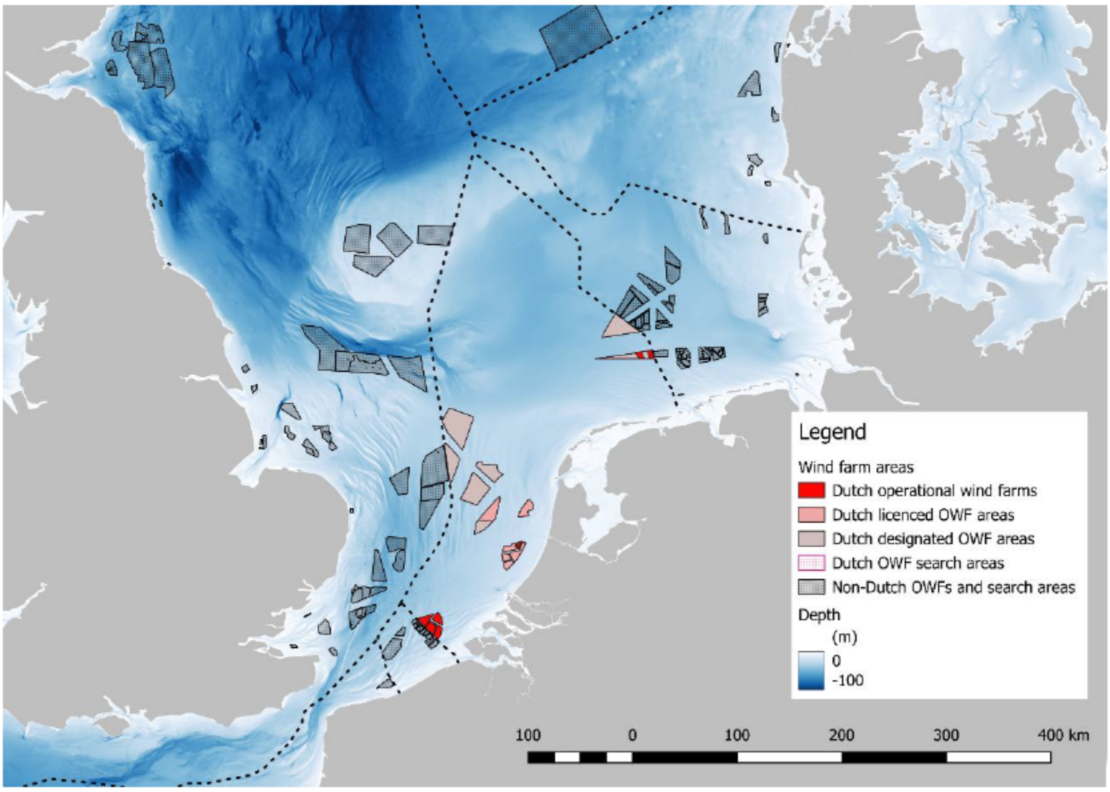

Figure 3.1: Lay-out of the reference scenario, based on the situation of 2023, when this work was initiated. The status of wind farms and search areas outside the Netherlands is not differentiated.

This scenario is used in the KEC 5.0 assessment. This is the framework for cumulative ecological impacts used by the Dutch government to assess whether ecological impacts of offshore wind remain within acceptable levels (https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/ecology/accumulation-ecological-effects/framework-assessing-ecological-cumulative-effects/).

3.2 Partial Revision scenarios

In the Partial Revision, Doordewind and Doordewind West are being investigated for a total capacity of 6 GW. The Reference scenario (used for KEC 5.0) has a total capacity of 2.3 GW in the Doordewind area, generated by 115 20 MW turbines. This deviates from the assumption in the planMER of the Partial Revision, where a capacity of 2 GW was assumed.

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In scenarios 1, 2, 3, 4, and 5 the size of the site is extended with an area called Doordewind West, forming one larger wind farm. In these scenarios the 6 GW is produced by 300 turbines of 20 MW. Hence not only is the surface area of the site larger in the Partial Revision scenarios, also the average density of turbines is substantially higher (0.4 turbines per km^2 vs 0.3 turbines / km^2 in the Doordewind area in the reference scenario). The Reference scenario has an average density of about 0.3 turbines per km^2, while the density in the Partial Revision scenarios vary in number of turbines per km^2 for area 6/7.

Also in all five scenarios there is a wind farm “Lagelander Noord” with a 2 GW capacity and 100 turbines of 20 MW each. The differences between scenarios 1, 2, 3,4 and 5 are in the configuration of the large Search Area 6/7.

3.2.1 Scenario 1, 2, 3 and 5

These are 4 scenarios in which the Search Area 6/7 is divided into 4 sections with a narrow separation. The whole area is nearly fully covered in wind farms, but with differences in the size and spacing of turbines (Figure 3.2).

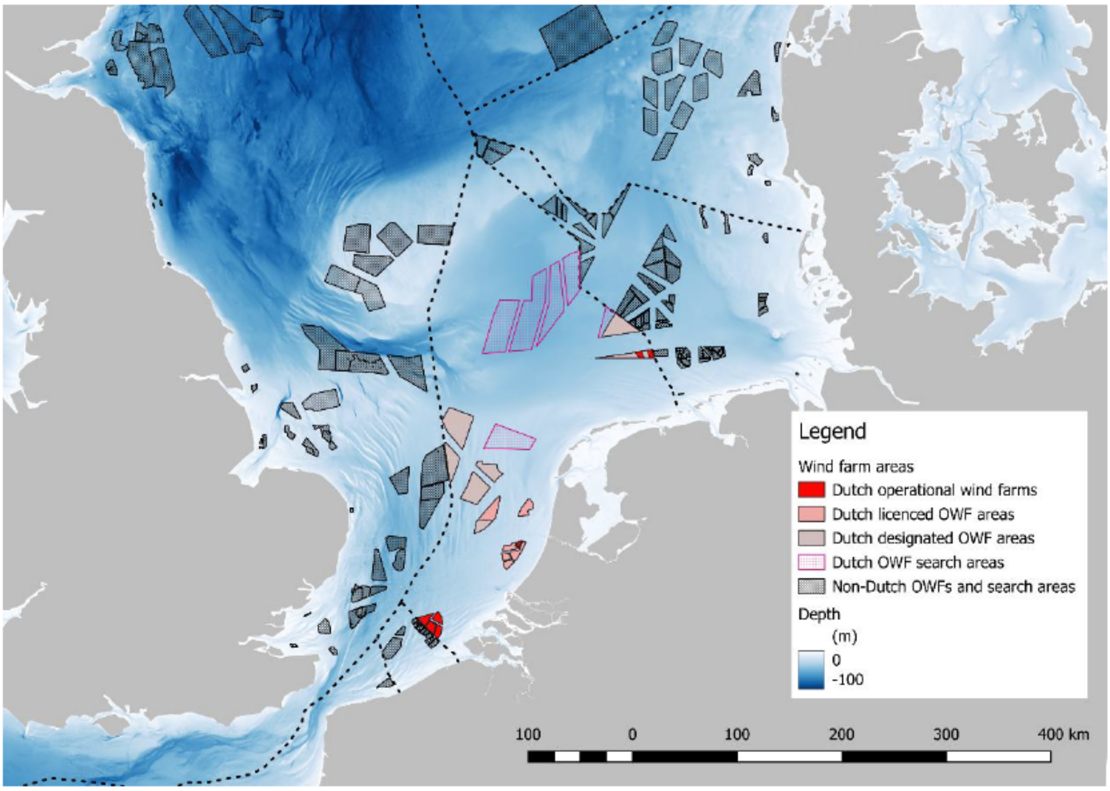


Figure 3.2: the spatial lay-out for scenarios 1, 2, 3 and 5. Colours indicate the developmental status of wind farms in 2023.

Note that scenarios 1, 2 and 3 are described and analysed in Zijl et al (2024). Scenario 5 was analysed later and the results added to this report.

3.2.2 Scenario 4

In the 4th scenario, the central part of Search Area 6/7 is left open. The gap between the 2nd and 3rd section measures between 20 and 45 km. This area coincides with the muddiest part of this search area. The mud content of this section ranges between 10 and 25%, which is high for the Dutch part of the North Sea (Figure 3.3).

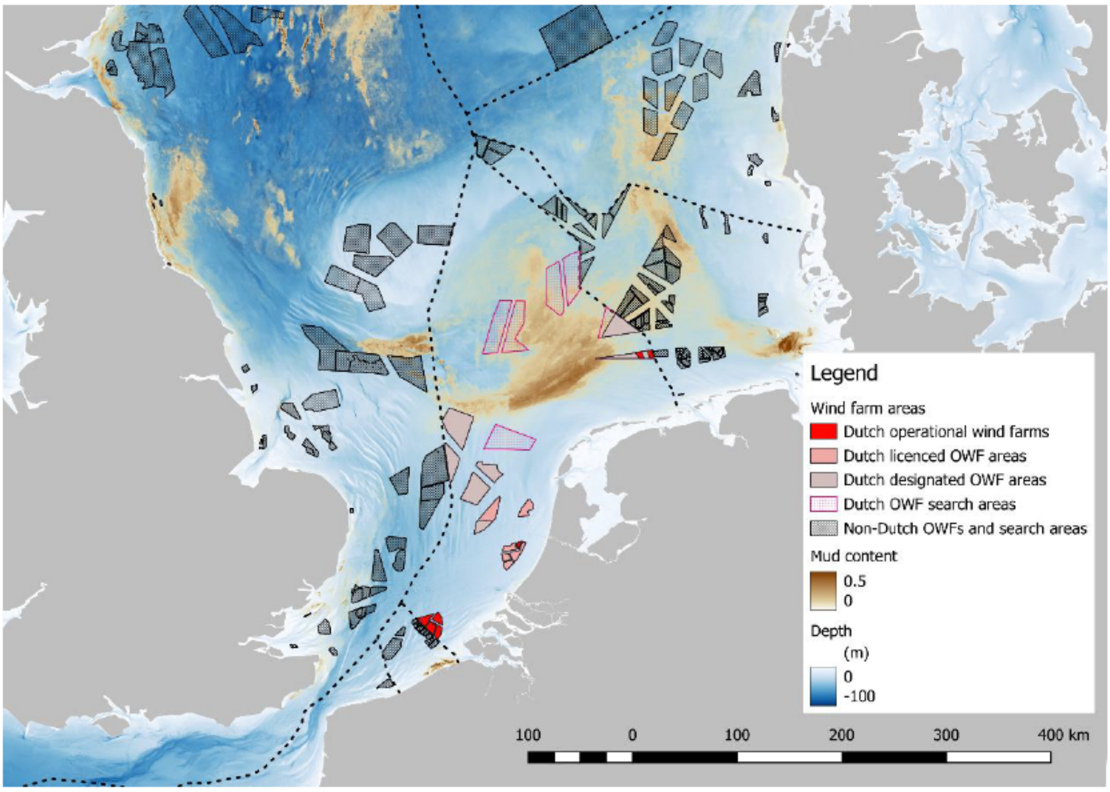


Figure 3.3: Spatial lay-out of scenario 4, with a model prediction of the mud content. The data for the mud content are based on detailed random forest models using bathymetry and bed shear stress (Stephens 2015). The lay-out of wind farms outside of this view are the same as in Scenarios 1, 2, 3 and 5. Colour coding indicates the status of planning and operation in 2023.

3.2.3 Overview of all scenarios

Table 3.1 summarises the characteristics of the wind farms Doordewind + Doordewind West and Lagelander, with respect to surface area, turbines etc. For all Partial Revision scenarios (1 to 5) these characteristics remained the same.

Table 3.1: Overview of the characteristics for Doordewind + Doordewind West and Lagelander in all scenarios

Name	Surface area with turbines	Total capacity	Energy density	Type of turbines	Turbine diameter	Number of turbines	Turbine density
	km^2	(GW)	MW/km^2	MW	m	#	$\#/km^2$
Doordewind + Doordewind West	758	6	7.9	20	11.3	300	0.40
Lagelander*	573	2	3.5	20	11.3	100	0.17

*The turbine density in Lagelander is in these scenario's rather low. When this area is designated the likely density will be higher but less surface area will be used.

Table 3.2 summarises the characteristics of all five scenarios for area 6/7. The variability in turbine sizes and densities within scenario 1, 2, 3 and 5 give a good opportunity to assess the impact of the various turbine characteristics. The scenario with the gap (Scenario 4) has the same turbines as scenario 1 and 5. The total capacity of scenario 4 is the same as scenario 1, while the local turbine density (and the energy density within the sections populated by turbines) is the same as in scenario 5. This allows a good comparison of the impact of the open space in the centre of the search area.

Table 3.2: Overview of the characteristics of the five scenarios.

Scenario	lay-out	Surface area with turbines	Total capacity	Energy density	Type of turbines	Turbine diameter	Number of turbines	Turbine density
		km^2	(GW)	MW/km^2	MW	m	#	$\#/km^2$
Scenario 1	full search area	3560	24	6.7	20	11.3	1200	0.337
Scenario 2	full search area	3560	24	6.7	25	13	960	0.270
Scenario 3	full search area	3560	37.4	10.5	15	9.9	2492	0.700
Scenario 4	central open space	2424	24	10.5	20	11.3	1272	0.525
Scenario 5	full search area	3560	37.4	10.5	20	11.3	1869	0.525

3.3 Non-Dutch OWFs

The offshore wind farms outside the Dutch EEZ were kept the same in scenario's 1-5. For the farms already operational or under construction the known number and size of turbines were used. For the search areas to be developed in the future, turbines of 20 MW were assumed with a monopile diameter of 11.3 m.

4 Reference scenario

4.1 Hydrodynamics

The monopiles in the wind farms exert drag on the flow. This reduces not just the absolute velocities, but also the residual currents. This can be seen in Figure 4.1A, where in all the wind farms residual current speeds are reduced by several cm/s. In many cases there are increases of residual currents around the wind farms, generally laterally to the main direction of the tidal flow. This will impact the horizontal transport of nutrients and particulate matter.

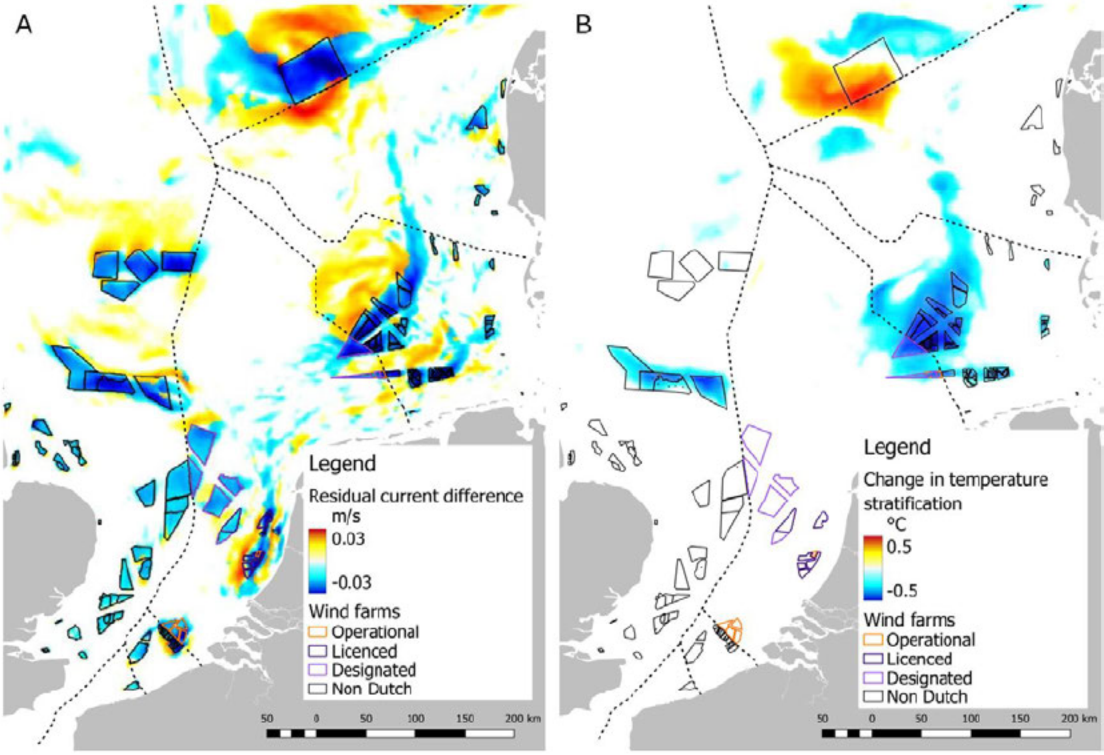


Figure 4.1: A; changes in the residual currents and B: changes in temperature stratification in the reference scenario (prognosis 2033) with a situation without any wind farms.

The drag the wind farms exert on the flow, result in increased mixing. There is no impact on temperature stratification in areas that are not stratified. The Dutch wind farms and designated areas that are located in the Holland coast therefore do not show any change in stratification (Figure 4.1B). Locations north of Nederwiek North (see Appendix D for names) do see reductions in temperature stratification (i.e. the annual average difference in temperature between the top water layer and the bottom). In the Dutch wind farms located in the German Bight area (the GEMINI farms, TNW and Doordewind) we see reductions in the temperature difference of about 0.5 °C, which amounts to a 60% reduction. Effects of these farms interact with neighbouring farms and stretch up to 50 km northwards from Doordewind.

There are impacts on salinity stratification in those wind farms that are located in areas under the influence of rivers, in the Netherlands mainly the wind farms in the Holland coast, such as HKZ (results not shown in this report).

4.2 Fine sediment

Despite the reduction in currents, the increased turbulence causes in most locations in the reference scenario an increase in the concentration of fine sediment in the top layer (Figure 4.2). This does not in all instances mean that there is more fine sediment in the water column. Earlier work has indicated that in many cases sediment that is already suspended in the water column, but has a higher concentration near the bed, is mixed more homogenously through the vertical layers. This results in more fine sediment in the upper layer and lower concentrations near the bed. The increase in the top layers is however, most relevant, as this impacts the light regime. There will be less light available for photosynthesis.

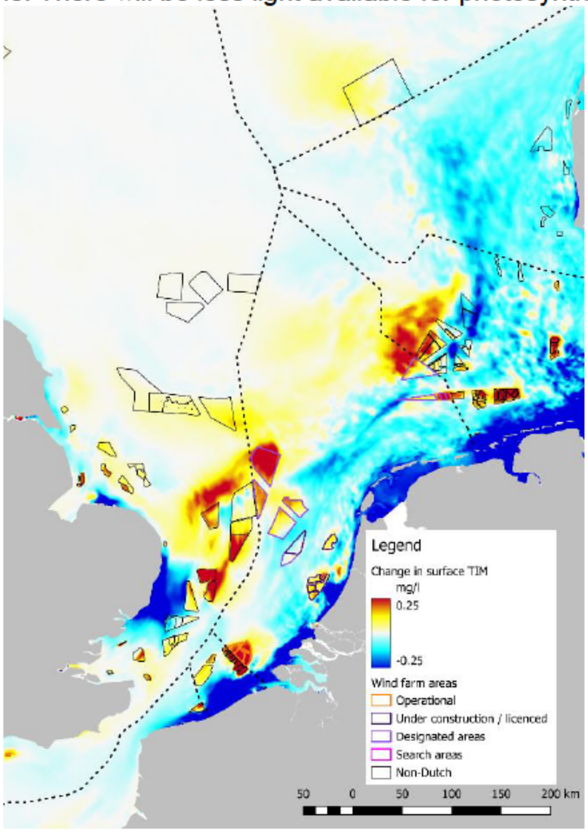


Figure 4.2: Impact of wind farms on the presence of fine sediment in the upper water layer. Reference scenario compared to a situation without wind farms. Windfarm colours in the legend indicate their status in 2023.

4.3 Phytoplankton

Table 4.1 shows for all wind farms and wind farm sections the spatially averaged value for primary production in the situation without farms and the annual average increase or decrease within the wind farm perimeter, with respect to the situation without wind farms. Note: in this table only the values and effects *within* the windfarms are given. Any changes outside the wind farms are not taken into account. Compared to the situation without wind farms, we see in the 2033 scenario a decrease of primary production in the wind farms in the Holland coast (Borssele and Hollandse Kust Zuid) and particularly in the German Bight. The local decrease in primary productivity is largest in the Ten Noorden van de Wadden (TNW) and the GEMINI farms (see Appendix C for names). Also, the Doordewind windfarm shows a clear decrease, but this is less than in the TNW and GEMINI locations and also less than in some of the adjacent German wind farms (Figure 4.3A). In these areas decreases in primary production can be up to 0.3 gC/m^2 /day, i.e. 60%, while in the Doordewind farm the decrease is around 1 µC/m^2/day (on average about 17%).

Particularly in the German Bight wind farms, there appear to be increases in primary production in the areas surrounding the farms, indicating some compensatory effects. A full overview of the changes in primary production within the perimeters of all the wind farms can be found in Table 4.1.

Table 4.1: Primary production in the situation without wind farms and changes in primary production (absolute and relative) in all the Dutch wind farms, in the reference scenario, compared to a scenario without wind farms. For names see Appendix D.

NAME	Primary production no wind farms	Primary production change absolute	Primary Production change relative
	gC/m2/day	gC/m2/day	%
Borssele Kavel I	0.24	-0.02	-10
Borssele Kavel II	0.21	-0.08	-39
Borssele Kavel III	0.28	-0.05	-18
Borssele Kavel IV	0.32	-0.06	-18
Borssele Kavel V	0.11	-0.04	-39
Doordewind	0.38	-0.07	-17
Gemini I / Buitengaats	0.45	-0.27	-60
Gemini II / ZeeEnergie	0.43	-0.19	-43
HKN Kavel V	0.53	-0.06	-12
HKZ Kavel I	0.59	-0.04	-7
HKZ Kavel II	0.62	-0.09	-15
HKZ Kavel III	0.56	-0.08	-13
HKZ Kavel IV	0.50	-0.05	-11
Hollandse Kust west noordelijk deel	0.40	-0.02	-4
Hollandse Kust west zuidelijk deel	0.45	-0.02	-4
IJmuiden Ver Noord	0.41	-0.01	-2
IJmuiden Ver versie 2021	0.45	-0.01	-2
Luchterduinen	0.53	-0.08	-15
Nederwiek noord	0.27	-0.01	-5
Nederwiek zuid	0.41	-0.01	-3
Ten noorden van de Wadden oost	0.46	-0.27	-59
Ten noorden van de Wadden west	0.38	-0.02	-5

The chlorophyll concentration is generally used as an indication of the available algal biomass. As chlorophyll is easily measured in the field and with remote sensing, this parameter is very often published. In most areas the trends in chlorophyll follow the trend in primary production, but not everywhere (Figure 4.3B). The Doordewind wind farm and the German wind farms most distant from the coast seem to show an increase in chlorophyll, instead of a decrease.

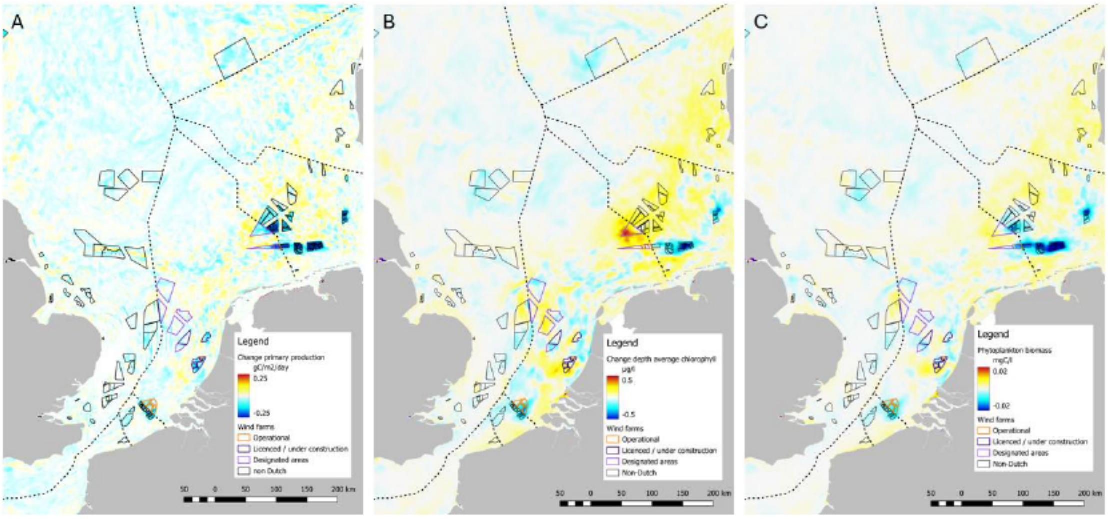


Figure 4.3. Impact of the presence of wind farms on: A: primary production (in gC/m^2/day), B: Depth averaged chlorophyll concentrations (µg/l) and C: phytoplankton biomass mgC/l. Windfarm colours in the legend indicate their status in 2023.

This seems counter-intuitive. One would expect in areas with lower primary production also a lower biomass of phytoplankton. The reasons for this discrepancy is one we have also observed in earlier model studies for the environmental impact assessment on sand mining (Van Duren et al. 2017). These areas have lower primary productivity due to the increased presence of SPM in the top layer. In this area light limitation is increased while nutrient limitation is reduced (due to the mixing of more nutrients into the top layer during stratified periods). In the model there is actually less phytoplankton biomass (Figure 4.3C), but these microalgae have a high proportion of phytoplankton, adapted to low light conditions. This results in lower algal biomass but higher chlorophyll levels. The impact patterns of phytoplankton biomass (expressed in mgC/l) are quite similar to the pattern of change in primary production (Figure 4.3C compared to Figure 4.3A).

A full overview of the changes in chlorophyll concentration per wind farm can be found in Table 4.2

Table 4.2: Average chlorophyll concentration in the wind farm areas, in the reference scenario, compared to a scenario without wind farms. For names see Appendix D.

NAME	Chlorophyll concentration no wind	Chlorophyll change absolute	Chlorophyll change relative
	µg / l	µg / l	%
Borssele Kavel I	1.83	-0.09	-5
Borssele Kavel II	1.88	-0.32	-17
Borssele Kavel III	1.89	-0.24	-13
Borssele Kavel IV	1.67	-0.06	-3
Borssele Kavel V	1.85	-0.19	-10
Doordewind	1.10	0.28	25
Gemini I / Buitengaats	2.09	0.02	1
Gemini II / ZeeEnergie	1.81	0.16	9
HKN Kavel V	3.22	0.03	1
HKZ Kavel I	3.61	0.00	0
HKZ Kavel II	3.61	0.14	4
HKZ Kavel III	3.57	0.22	6
HKZ Kavel IV	3.69	0.06	2
Hollandse Kust west noordelijk deel	1.87	-0.01	-1
Hollandse Kust west zuidelijk deel	2.04	-0.08	-4
IJmuiden Ver Noord	1.96	0.00	0
IJmuiden Ver versie 2021	1.68	0.13	8
Luchterduinen	3.65	0.00	0
Nederwiek noord	1.18	-0.03	-2
Nederwiek zuid	1.56	0.02	1
Ten noorden van de Wadden oost	1.94	0.09	4
Ten noorden van de Wadden west	1.54	0.12	8

5 Partial Revision scenario results

As indicated, the Partial Revision scenarios use the KEC scenario, with the projections for wind farms present in 2033 as a reference. The Partial Revision scenarios include these wind farms. So, comparisons between the reference scenarios and the Partial Revision scenarios show limited effect in these wind farms. Any effects in those wind farms that are visible are likely due to shifts in interactive effects between wind farms in areas of the North Sea that are very busy. This mainly occurs in the German bight where both Dutch and German farms are planned close together.

5.1 Hydrodynamics

5.1.1 General impact and effect of different turbine densities

With respect to wind farms Lagelander and Doordewind, the impact on stratification is the same in all scenarios (Figure 5.1 and Figure 5.2). This is not surprising as the lay-out of these farms is the same in these two areas. In Lagelander, which is located in an area that is not stratified, there is hardly any impact. Doordewind has (in comparison to the reference scenario) an extra (annual average) reduction of the temperature difference of 0.1 °C.

There are differences for Search Area 6/7 (Figure 5.1). Of the 4 scenarios without a gap in the middle, scenario 3 has the largest impact on average temperature stratification (Figure 5.1-3). Scenario 1 sees in this area a decrease in temperature difference between top and bottom of 0.3-0.55 °C, scenario 2 the reduction varies between 0.25 and 0.5, while in scenario 3 the reduction in temperature difference between top and bottom ranges between 0.5 and 0.9 °C. Scenario 5 is intermediate between scenario 1 and 3, ranging between 0.4 and 0.8 °C.

The differences in impact are likely mostly explained by the density of turbines. Scenario 1 has a turbine density of 0.34 monopiles per km^2, scenario 2 has a density of 0.27 monopiles per km^2, scenario 5 has 0.53 monopiles per km^2 and scenario 3 has a density of 0.7 monopiles per km^2 (see Table 3.2)

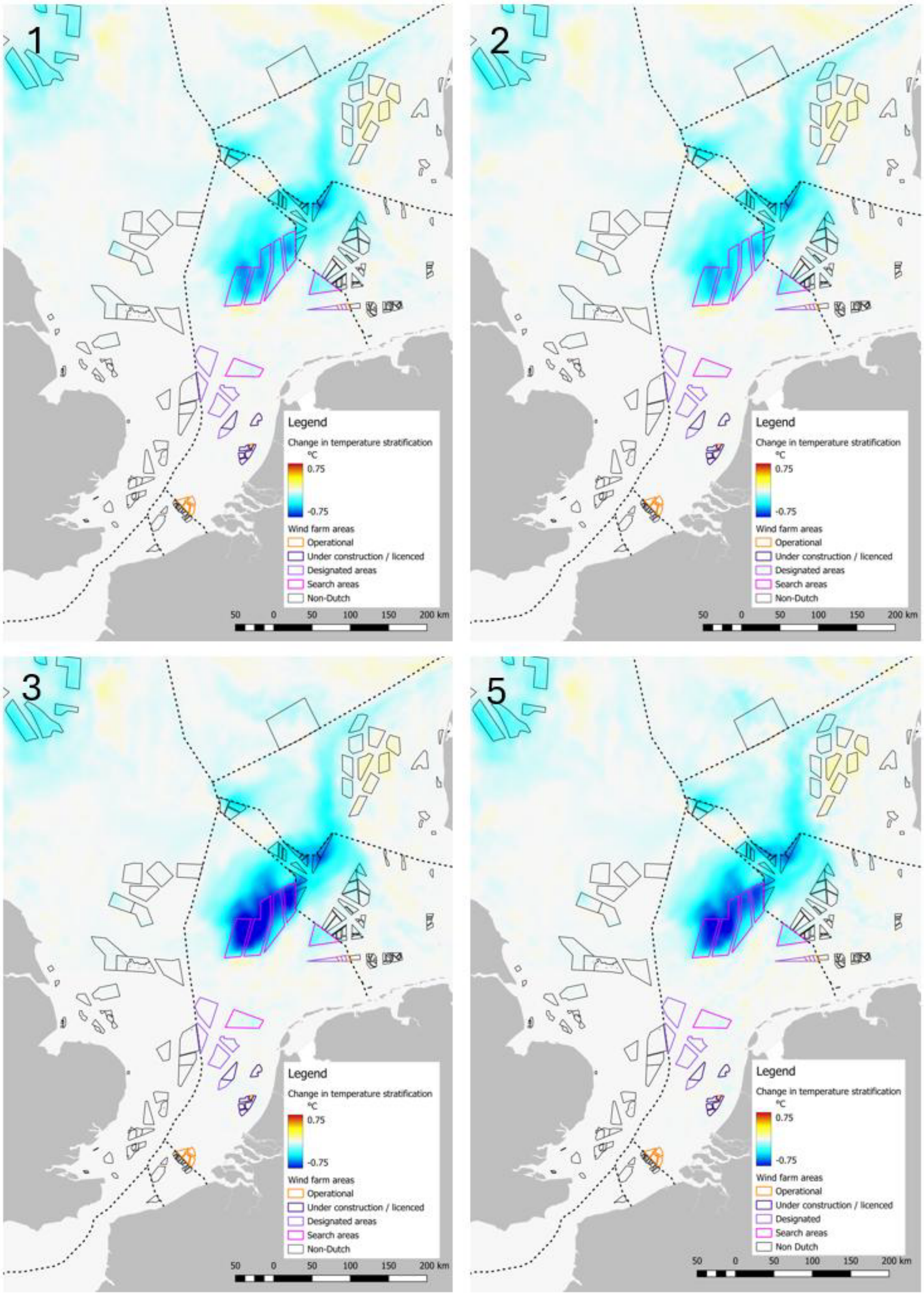


Figure 5.1: Impact on temperature stratification in the four scenarios with the full area covered by wind turbines. Numbers indicate the scenario. Windfarm colours in the legend indicate their status in 2023.

5.1.2 Effect of open space

Creating an open space in the central part of Search Area 6/7, does diminish the impact on temperature stratification in the open area Figure 5.2. Within the open space there is still some reduction of stratification, because the wakes of the turbines within the wind farm reach well beyond the perimeter of the sections with turbines. Scenario 4 has the same size of monopile as scenario 1 and scenario 5 (Figure 5.2). This leads to decreases in temperature stratification of 0.3–0.65 °C.

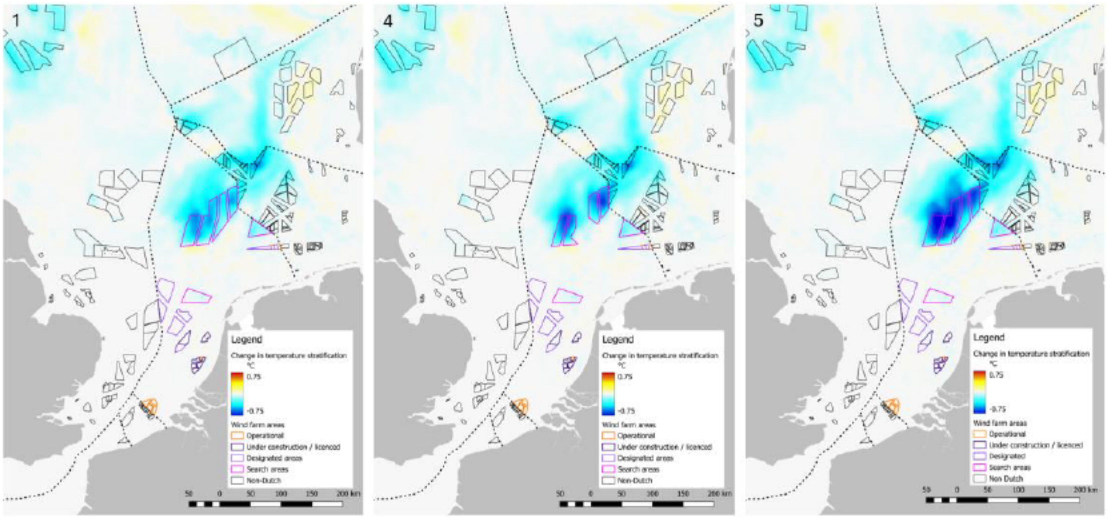


Figure 5.2: Differences in temperature stratification (difference in temperature between top and bottom of the water column) in scenarios 1, 4 and 5. Windfarm colours in the legend indicate their status in 2023.

Inside the area with turbines, the impact of scenario 4 is higher than scenario 1. Scenario 4 has the same total wind farm capacity (24 GW) as scenario 1. However, due to the fact that turbine density within the areas populated with turbines is higher, the impact within these areas is higher in scenario 4. Scenario 4 has a similar turbine density as scenario 5, although the total surface area with this density is higher in scenario 5. In the latter scenario we see effects of more than 0.5 °C, over most of the search area.

5.2 Fine sediment

5.2.1 General impacts and effects of pillars

In comparison to the reference scenario (2033) the impacts on the fine sediment concentrations in the upper water layer are mixed in areas Doordewind and Lagelander. Doordewind sees an increase of 0.05-0.1 mg/l in the extended area (the north-western part of the wind farm, that is not developed in the reference scenario (Figure 5.3). In other parts of the wind farm SPM concentrations are reduced by about 0.1 mg/l. Similarly in Lagelander, the SPM concentrations are increased in the west, but decreased in the east. Changes (increase or decrease) in these areas are maximum 5%.

Figure 5.3A shows significant increases in the fine sediment concentrations in the upper water layer occur in the western part of search area 6/7, increases of up to 0.25 mg/l are modelled for scenario 1 (i.e. up to 40%, Figure 5.3B).

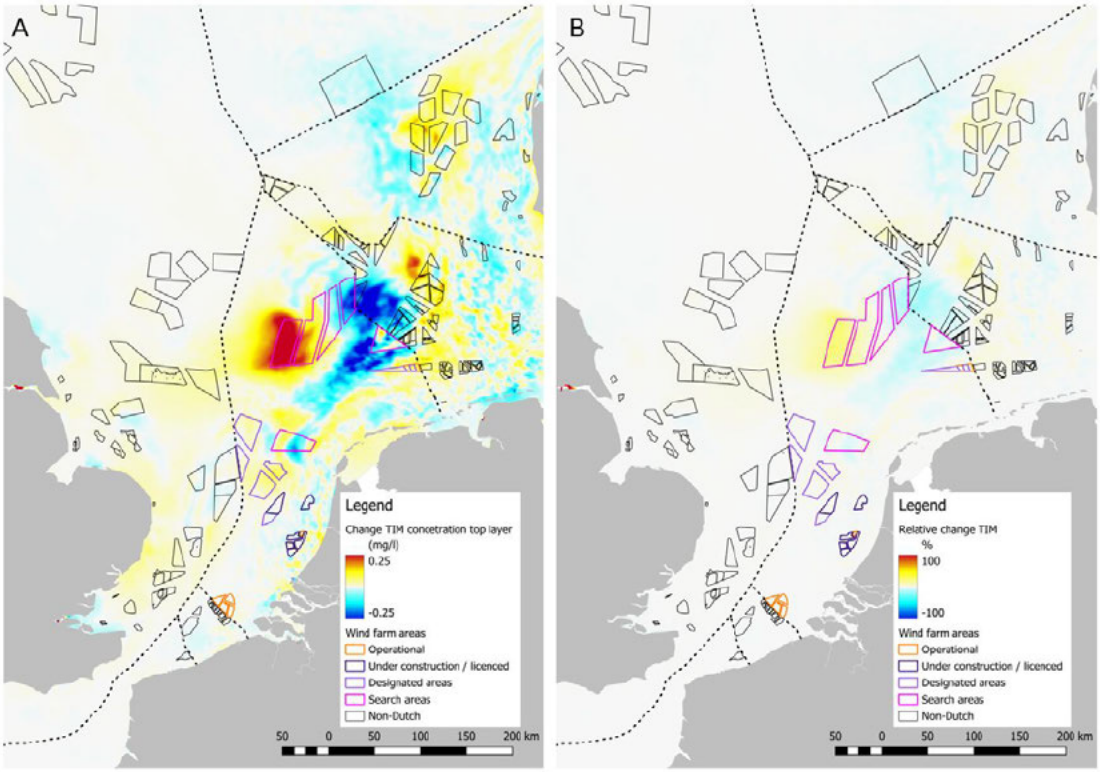


Figure 5.3: A: absolute difference in total inorganic matter in the upper water layer between scenario 1 and the reference scenario. B: relative difference in total inorganic matter in the upper water layer between scenario 2 and scenario 1. Windfarm colours in the legend indicate their status in 2023.

This pattern is similar in scenarios 2, 3 and 5 that differ in turbine density. The differences in absolute terms are difficult to see if scenarios 1, 2, 3 and 5 are compared to the reference scenario side by side. The differences are best assessed when scenarios 2, 3 and 5 are compared to scenario 1 (Figure 5.4). The results for Doordewind and Lagelander are similar, as these lay-outs do not differ between these scenarios.

Scenario 2, with fewer, larger turbines has on average 0.01-0.03 mg/l less SPM in the top layer than in scenario 1, while scenario 3 (with a higher turbine density and a higher energy capacity) has 0.05-0.1 mg/l more SPM than scenario 1. Scenario 5, which has a turbine density intermediate to 1 and 3 but the same total capacity as scenario 3, shows 0.02 – 0.5 mg/l SPM more in the top layer than scenario 1. Hence with the same energy density but fewer (larger) turbines, the impact is less.

Note, the differences between these four scenarios are minor in comparison to the impact of the scenarios with reference to the scenario projected for 2033.

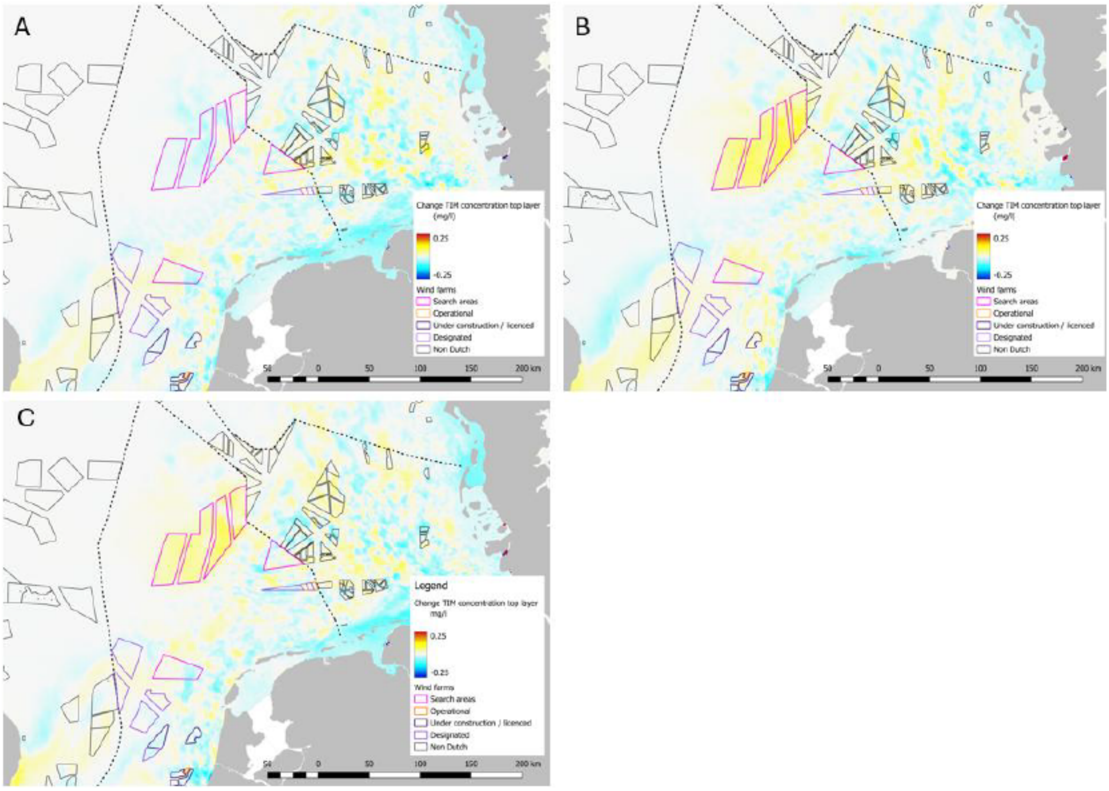


Figure 5.4 A: Difference in total inorganic matter in the upper water layer between scenario 2 and scenario 1. B: Difference in total inorganic matter in the upper water layer between scenario 3 and scenario 1. C: Difference in total inorganic matter in the upper water layer between scenario 5 and scenario 1. Windfarm colours in the legend indicate their status in 2023.

All the figures shown so far are annual averages. However, stratification has a significant impact on the penetration of fine sediment into the upper water layers. Figure 5.5 shows the changes in fine sediment concentration in the upper water layers for Scenario 1, relative to the reference scenario in winter (October to March, A) and in summer (April to September, B). The large increase in search area 6/7 is clear in winter, but in the summer months the difference in sediment concentration between scenario 1 and the reference scenario are very minor. The explanation is that, although stratification is diminished in this area, it is not absent in summer. The pycnocline in summer is a very effective barrier for suspended particles. So even if there is resuspension of fine sediment in the near-bed layers, once stratification sets in (generally around April), it no longer reaches the top layers. This is very relevant for the growth of phytoplankton, as most of the growth takes place in summer. So, in the growing season there is no reduced light availability due to increased particulate matter. In winter there is reduced light availability. However, as the productivity in winter is small, the impact on the annual average primary production is minor (see also section 5.3). The Doordewind wind farm area does show on average a more than 0.2 mg/l increase in the summer months.

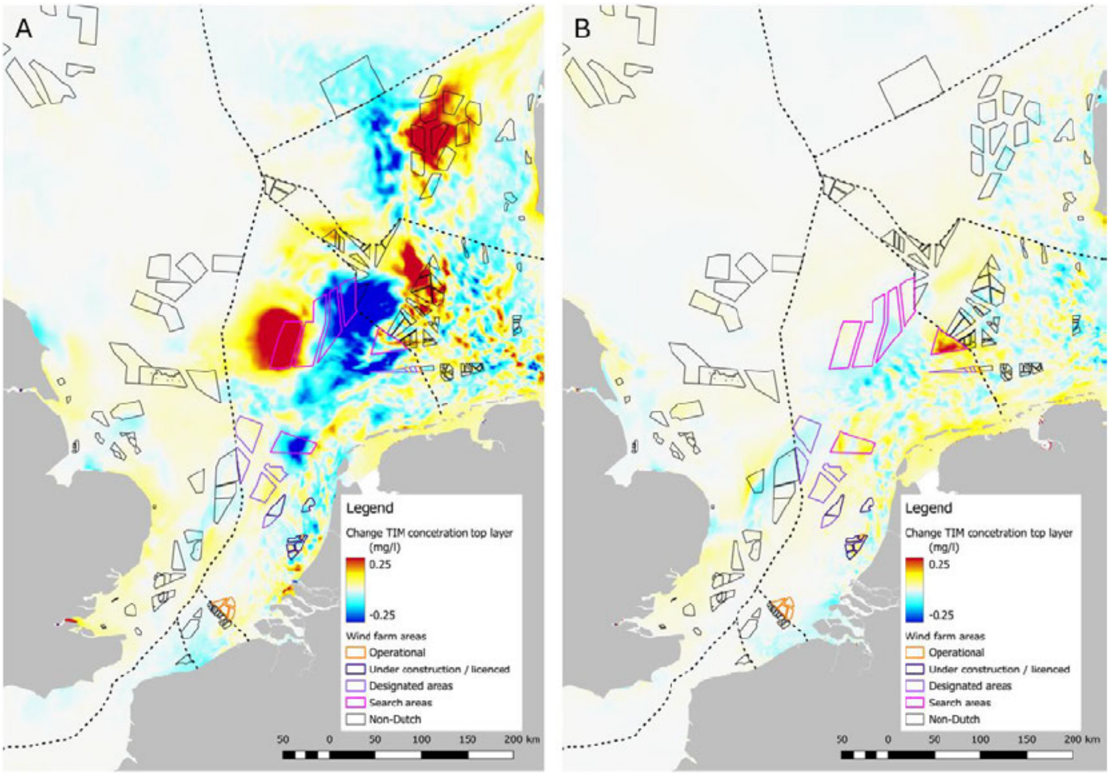


Figure 5.5: Changes in fine sediment concentration in the top layer for scenario 1 compared to the reference scenario. A: winter months, B: summer months. Windfarm colours in the legend indicate their status in 2023.

5.2.2 Effect of open space

If we compare the impact of scenario 4 to the reference scenario, we see increases from 0.10-0.18 mg/l in the western parts of the search area 6/7 (Figure 5.6). In the open space itself the impact is patchy and smaller (+ or – 0.05 mg/l), while in the western parts of the area the impact is also patchy (between an increase of 0.15 mg/l in the north and a decrease of 0.15 mg/l in the south-eastern corner).

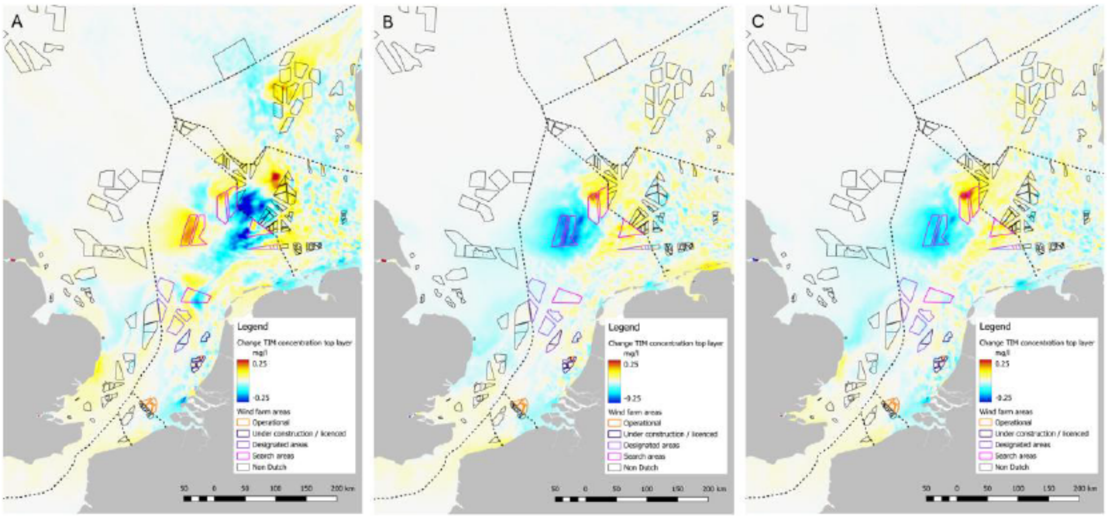


Figure 5.6: A: Absolute differences in fine sediment concentration in the top layer of the water column between scenario 4 and the reference scenario, B: Absolute differences in fine sediment concentration in the top layer of the water column between scenario 4 and scenario 1, C: Absolute differences in fine sediment concentration in the top layer of the water column between scenario 4 and scenario 5. Windfarm colours in the legend indicate their status in 2023.

The differences between scenario 4 and scenario 1 (same turbine size and similar total wind farm capacity) are more outspoken than the differences between scenarios 2, 3 or 5 and scenario 1 (Figure 5.6B). In the western sections of the search area, as well as in the open space, concentrations are between 0.1 and 0.18 mg/l lower than in scenario 1, while in the northern part of the eastern sections SPM concentrations increase with 0.2-0.25 mg/l, while in the southern part of the eastern sections the increases are limited to 0.05 – 1 mg/l, in comparison to scenario 1. Comparing scenario 4 to scenario 5 (same turbine sizes and density within areas populated by turbines, but in total fewer turbines due to the gap) we see that scenario 4 has lower fine sediment concentrations in the western areas than scenario 5 (between 0.15 and 0.2 mg/l) while in the north eastern part the increase is locally about 0.15-0.2 mg/l, hence slightly less than compared to scenario 1.

5.3 Phytoplankton

5.3.1 General impacts and effects of pillars

With respect to primary productivity the impact of the wind farms is a decrease in Lagelander and an even larger one in Doordewind in all five scenarios (Table 5.1 shows the spatially averaged changes). In Search Area 6/7 the impact with respect to the reference scenario is positive. The general effects are similar in all 5 scenarios, but the amount differs. As an example, Figure 5.7 shows the absolute and relative changes for Scenario 1 with respect to the reference scenario and also with respect to the situation without any wind farms. In Lagelander, the decrease with respect to the reference scenario is 0.02-0.03 $gC/m^2/day$ for scenario 1 (on average 6.8%; Figure 5.7A and B). For Lagelander the decrease in primary production is the same in comparison to the reference scenario (i.e. the scenario projected for 2033 and the situation without any wind farms (Figure 5.7C).

The impact is higher in Doordewind, where productivity is decreased on average by 0.09 gC/m^2 (about 26%), in scenario 1 compared to the reference scenario (Figure 5.7A and B). This reduction is on top of the reduction from 0.4 $gC/m^2/day$ to 0.3 $gC/m^2/day$ in base scenario, compared to the situation with no wind farms. The total difference between Scenario 1 and the situation without wind farms is 0.2 – 0.3 $gC/m^2/day$ (Figure 5.7C).

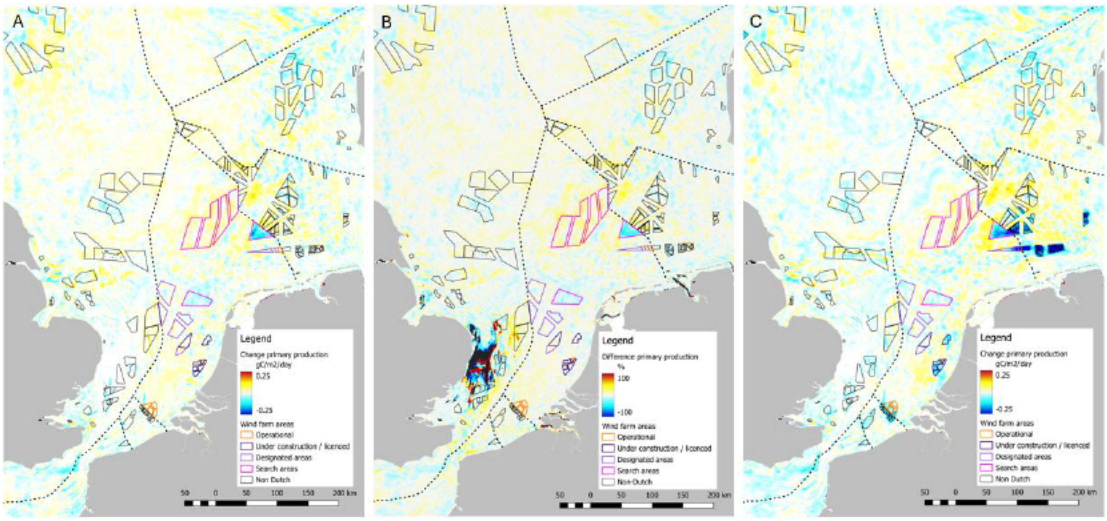


Figure 5.7 A: absolute differences in primary production between scenario 1 and the reference scenario (prognosis 2033). B: relative differences in primary production between scenario 1 and the reference scenario. C: absolute differences in primary production between scenario 1 and a situation without any wind farms. Windfarm colours in the legend indicate their status in 2023.

On the contrary, simulated primary production increases in Search Area 6/7. In scenario 1 the increase varies within the wind farm between 0 and 0.1 gC/m^2/day, but is more than 0.025 gC/m^2/day on average over the total farm area (i.e. 10.4%) increase, with respect to the reference scenario (Figure 5.7).

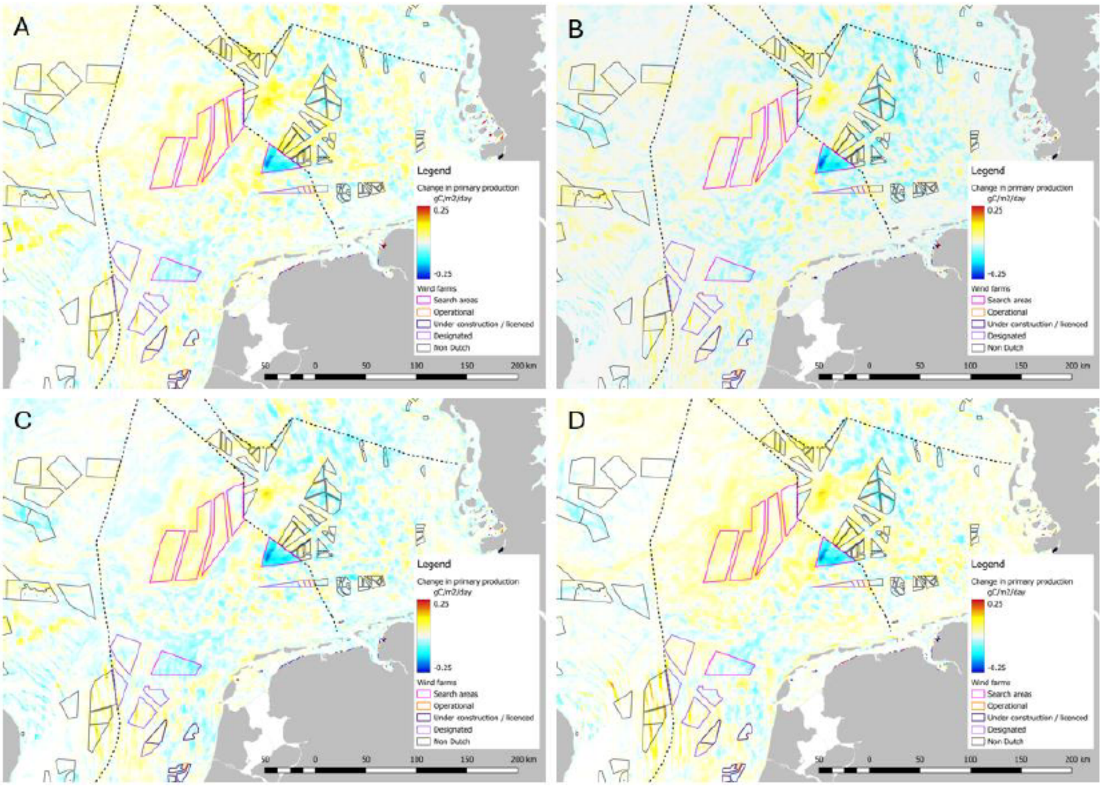


Figure 5.8 A: absolute differences in primary production between scenario 1 and the reference scenario, B: absolute differences in primary production between scenario 2 and the reference scenario, C: absolute differences in primary production between scenario 3 and the reference scenario, D: absolute differences in primary production between scenario 5 and the reference scenario. Windfarm colours in the legend indicate their status in 2023.

As with the modelled impacts for fine sediment, the differences between scenarios 1, 2, 3 and 5 are subtle, certainly in comparison to the difference between these scenarios and the reference scenario (Figure 5.8 and Table 5.1). The changes in Search Area 6/7 are slightly less in scenario 2 (with the lower turbine density) and higher in 5 with the same turbine size but a higher turbine density and total capacity. In the modelled primary production fields, there appears to be some variation in the background values (values outside the wind farms). Scenario 1 and particularly Scenario 5 appear to have slightly higher background levels than Scenarios 2 and 3.

The changes in phytoplankton biomass concentrations show a similar pattern as primary production and are fully in line with the changes in stratification and fine sediment in the upper layers (Table 5.2). Chlorophyll also shows decreases in Lagelander and Doordewind and increases in Search Area 6/7 in all 4 scenarios with the full site covered in turbines (Table 5.3). What is striking is that the relative changes in primary production and phytoplankton biomass tend to be larger in Doordewind + Doordewind West, in comparison to Search Area 6/7. However, for chlorophyll concentrations the changes in are proportionally larger in Search Area 6/7. This is again a consequence of the fact that in Doordewind + Doordewind West, the presence of turbines increases fine sediment concentrations in the upper layer. This not only causes lower primary production and lower phytoplankton biomass, but also causes a shift in the composition of the microalgae. The proportion of phytoplankton adapted to low light intensity is increased. These types have more chlorophyll per unit biomass. The reduction in phytoplankton in that area is therefore not proportional to the reduction in chlorophyll.

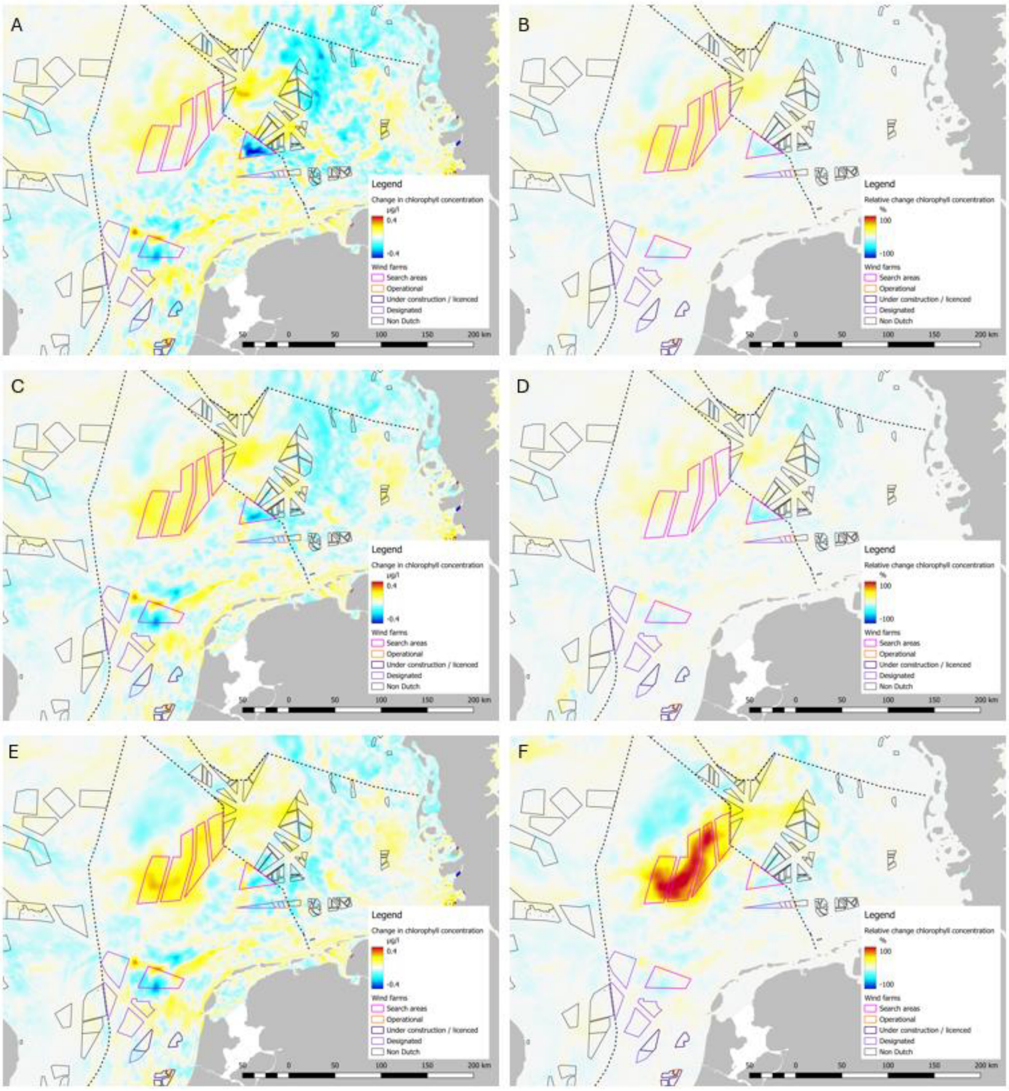


Figure 5.9 Differences between scenario 1 and the reference scenario, A: top layer absolute change, B: top layer relative change, C: depth averaged, absolute change, D: depth averaged, relative change, E: bottom layer, absolute change, F: bottom layer relative change. Windfarm colours in the legend indicate their status in 2023.

With respect to chlorophyll concentrations there are not only large differences in horizontal effects, but also in the vertical. Figure 5.9 shows the results for scenario 1, compared to the reference scenario for the top (A and B), depth averaged (C and D) and the bottom layer (E and F.

For wind farm Lagelander the difference between top and bottom is both in absolute as in relative terms is negligeable. This area is and remains fully mixed. The depth averaged / wind farm averaged effect is a decrease of 0.02 to 0.04 µg Chla /l, i.e. around 2% in most scenarios. However, locally decreases may be 10 times higher (0.3 µg Chla /l). There is some variability between the scenarios, that appears to be caused by slight variabilities in the background primary production between the model runs. E.g. primary production well away from the influence of wind farms appears to be a bit higher in scenarios 1 and 5, and a bit lower in 2 and 3. The impact of the wind farms is much larger that this background variability. It is not immediately clear what the causes of this background variability between model runs is.

In wind farm area Doordewind (+ Doordewind west) the difference with the reference scenario ranges between 0.09 and 0.12 µg/l depth averaged and wind farm averaged. In scenario 1 this is 0.09 µg Chla /l. In the top layer the decrease is larger (0.2 – 0.4 µg/l), while at the seabed there is actually an increase in the northwestern part of about 0.1 µg/l. Note: this is the section that is added to the wind farm in the PR scenarios. In the reference scenario this area does not have turbines. There is a decrease in the south eastern part (i.e. in Doordewind, where in the reference scenario there are also wind turbines).

In Search Area 6/7 the impact on chlorophyll concentration is on average positive. Depth averaged values show an increase of about 0.15 µg/l (on average a 10% increase). However as Figure 5.9A and Figure 5.9B show, the increase at the surface is only a few percent, while the relative increase at the seabed is more than 100% (0.2µg/l in absolute terms).

As with primary production and fine sediment concentrations, the differences among scenarios 1, 2, 3 and 5 are relatively subtle and best assessed with respect to each other (Figure 5.10). Depth averaged differences in Lagelander and Doordewind are patchy and small. In Search Area 6/7 the differences in chlorophyll a concentrations vary between + and – 0.02 µg/l. Over the whole wind farm the average effect is nearly 0 (Figure 5.10A). Both scenario 3 and scenario 5 show larger increases in chlorophyll a in the western two sections and decreases, or near-zero effects in the eastern parts (Figure 5.10B). Averaged over the full wind farm areas both scenario 3 and scenario 5 have a larger decrease than scenario 1 (Table 5.1). Scenario 3 appears to have a lower increase in primary production than scenario 5. Based on the impacts on stratification and fine sediment, the opposite was expected, as scenario 3 has a higher turbine density. This is almost certainly caused by the fact that scenario 5 appears to have a higher background primary production, than scenario 3. It is unclear what the cause of this background variability is. The difference between 15 and 20 MW turbines is not large – the distance between the turbines is larger than the extent of the wake (Hendriks et al 2024). However, we would still expect a slightly larger impact from scenario 3 than from scenario 5.

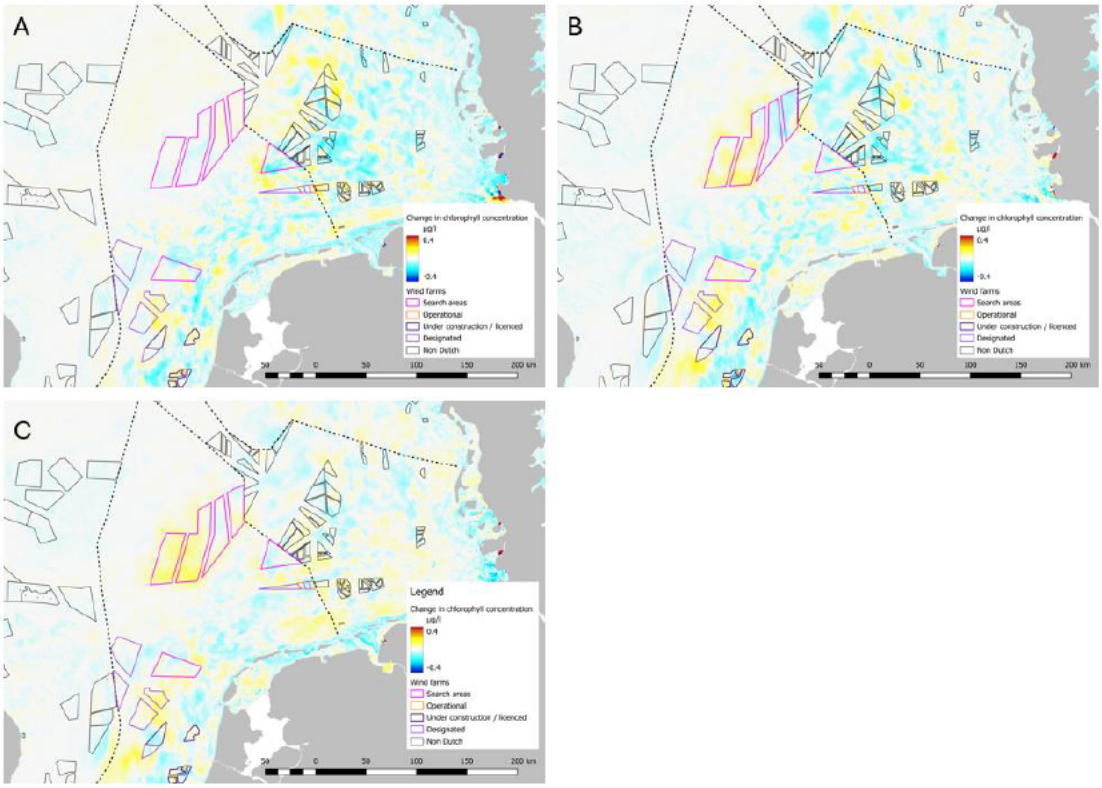


Figure 5.10: Absolute differences in chlorophyll a concentration between scenario 2 and scenario 1, B: absolute differences in chlorophyll a concentration between scenario 3 and scenario 1, C: absolute differences in chlorophyll a concentration between scenario 5 and scenario 1. Windfarm colours in the legend indicate their status in 2023.

5.3.2 Effect of open space

For search Area 6/7 the effects on primary production are quite similar for scenarios 1, 2, 3 and 5. The average amounts differ, due to the density and size of turbines, but the patterns are similar. The differences for scenario 4 are more substantial. Compared to the reference scenario average increases in primary production are around 0.02 gC/m^2/day (varying between 5 and 20%, Figure 5.11A, Table 5.1), which is about 0.01 gC/m^2/day less of an increase as in scenario 1 (Figure 5.11B, Table 5.1), the wind farm with similar sized turbines, a similar total energy capacity but larger distances between turbines. Scenario 4 shows about 0.02 gC/m^2/day less of an increase in Search Area 6/7 as in scenario 5 (Figure 5.11C, Table 5.1). This wind farm has also the same turbine sizes, a similar distance between the turbines, but with the whole area covered, and hence a higher energy capacity.

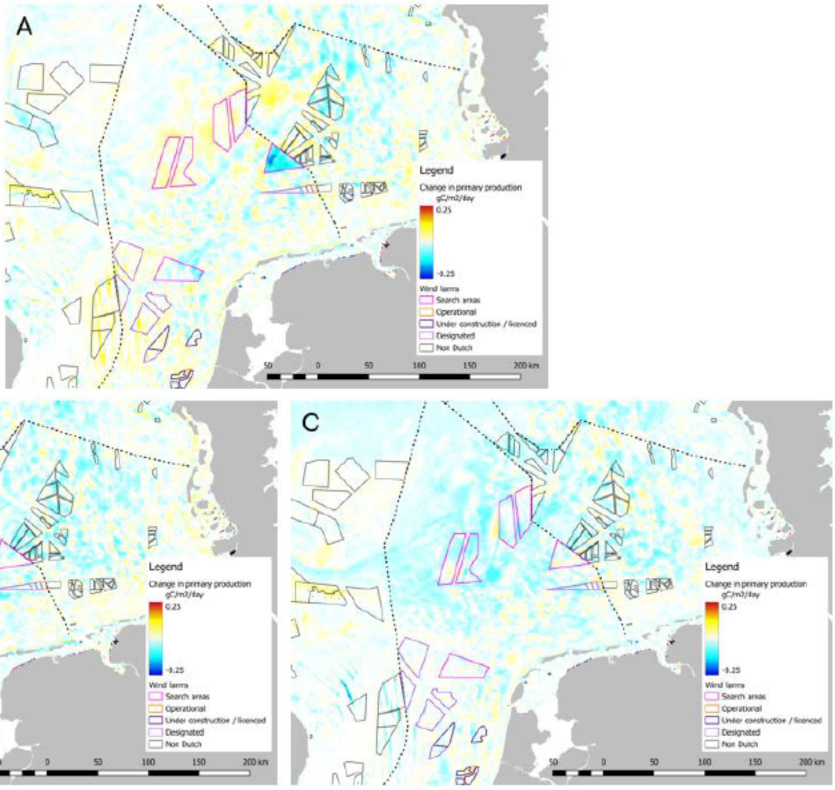


Figure 5.11: A: Differences in primary production between scenario 4 and the reference scenario; B: differences in primary production between scenario 4 and scenario 1; C: differences in primary production between scenario 4 and scenario 5. Windfarm colours in the legend indicate their status in 2023.

With respect to depth averaged chlorophyll a concentrations, there are increases within the sections with turbines of just over 0.15 µg/l, while in the open space the concentrations only increase with about 0.05 µg/l (Figure 5.12A). The average over the whole area (including the gap) is 0.09 µg/l (Table 5.3). If we compare the values to those from scenario 1, it is also clear that the impact in the sections with the turbines is similar or slightly higher than in scenario 1, but that chlorophyll a concentrations in the open space are about 0.05 µg/l lower (Figure 5.12B). Comparing scenario 4 results to scenario 5, we see that over the whole of the wind farm area (including the gap) the average concentrations are 0.05 µg/l lower (Figure 5.12C). While the turbines and the turbine densities are the same (within areas with turbines) in the western two sections of the wind farm scenario 4 shows a decrease of about 0.07 µg Chla/l, in comparison to scenario 5, while the eastern section, adjacent to the gap shows increases of about 0.03 µg Chla/l. Inside the gap the chlorophyll concentrations even further decreased (about 0.08 µg/l over the whole of the gap, in comparison to scenario 5).

Note: the net effect of scenario 4, compared to the reference scenario, is an increase in primary production, phytoplankton biomass and chlorophyll. Hence, as here scenario 4 is compared to scenarios 1 and scenario 5, a reduction in chlorophyll concentration compared to these scenarios means “less increase” with respect to the reference scenario.

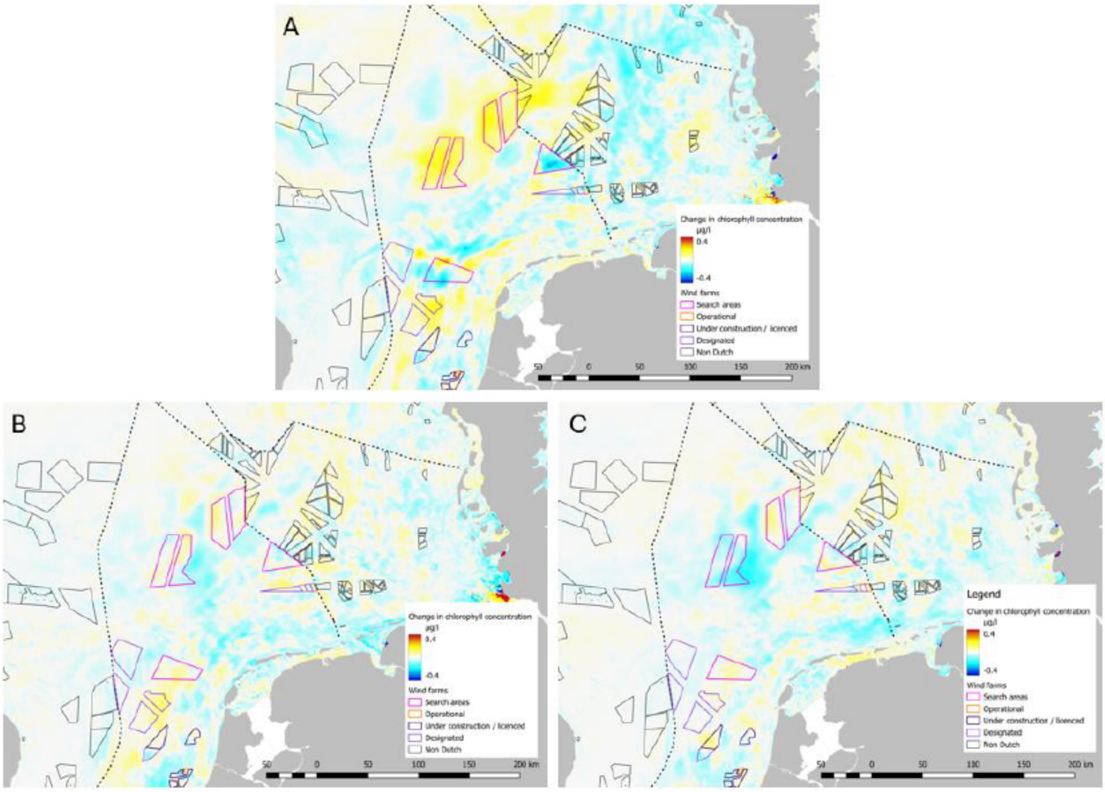


Figure 5.12: A: Differences in depth averaged chlorophyll a concentration between scenario 4 and the reference scenario; B: differences in depth averaged chlorophyll concentration between scenario 4 and scenario 1; C differences in depth averaged chlorophyll concentration between scenario 4 and scenario 5. Windfarm colours in the legend indicate their status in 2023.

5.3.3 Overview of average effects within the wind farms

In the tables below (Table 5.1, Table 5.2 and Table 5.3) overviews are presented on the impacts on primary production, phytoplankton biomass and chlorophyll concentration in all scenarios averaged over the total surface area of the respective wind farms. Note that for Scenario 4, this is the impact over the total area, including the gap, in order to keep the results comparable between wind farms. Averaging over the surface area with turbines (excluding the gap) would clearly give other numbers.

Table 5.1: Overview of the average primary production in the reference scenario, within the 3 wind search areas that are added to the reference scenario and absolute and relative changes in each scenario in each wind farm.

NAME	Primary production reference 2031	Scenario 1 Change absolute	Scenario 1 Change relative	Scenario 2 Change absolute	Scenario 2 Change relative	Sceanrio 3 Change absolute	Sceanrio 3 Change relative	Scenario 4 Change absolute	Scenario 4 Change relative	Scenario 5 Change absolute	Scenario 5 Change relative
	$gC/m^2/day$	$gC/m^2/$ day	%	$gC/m^2/$ day	%	$gC/m^2/$ day	%	$gC/m^2/$ day	%	$gC/m^2/$ day	%
Doordewind + Doordewind West	0.34	-0.09	-26	-0.10	-29	-0.10	-28	-0.10	-28	-0.09	-27
Lagelander	0.36	-0.02	-7	-0.01	-4	-0.03	-8	-0.01	-4	-0.01	-3
Search area 6/7	0.26	0.03	10	0.01	5	0.03	12	0.02	7	0.04	14

Table 5.2: Overview of the annual average phytoplankton biomass in the reference scenario, within the 3 wind search areas that are added to the reference scenario and absolute and relative changes in each scenario in each wind farm.

NAME	Phytoplankton biomass reference 2031	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
		Change absolute	Change relative	Change absolute	Change relative	Change absolute	Change relative	Change absolute	Change relative	Change absolute	Change relative
unit	mlC/l	mlC/l	%	mlC/l	%	mlC/l	%	mlC/l	%	mlC/l	%
Doordewind + Doordewind West	0.0447	-0.0054	-12	-0.0067	-15	-0.0058	-13	-0.0024	-5	-0.0061	-14
Lagelander	0.0710	-0.0015	-2	-0.0018	-3	-0.0019	-3	-0.0003	0	-0.0015	-2
Search area 6/7	0.0273	0.0022	8	0.0020	7	0.0027	10	-0.0013	-5	0.0025	9

Table 5.3: Overview of the average chlorophyll concentration in the reference scenario, within the 3 wind search areas that are added to the reference scenario and absolute and relative changes in each scenario in each wind farm.

NAME	Chlorophyll concentration Reference	Scenario 1		Scenario 2		Sceanrio 3		Scenario 4		Scenario 5	
		Change absolute	Change relative	Change absolute	Change relative	Change absolute	Change relative	Change absolute	Change relative	Change absolute	Change relative
	µg / l	µg / l	%	µg / l	%	µg / l	%	µg / l	%	µg / l	%
Doordewind + Doordewind West	1.32	-0.09	-7	-0.12	-9	-0.09	-7	-0.10	-7	-0.10	-8
Lagelander	2.07	-0.04	-2	-0.05	-2	-0.03	-1	-0.02	-1	-0.04	-2
Zoekgebied 6/7	0.51	0.10	19	0.09	17	0.15	28	0.09	17	0.14	27

5.3.4 Temporal effects

In stratified areas, the onset of algal growth (the spring bloom) is linked to the onset of stratification, temperature and the light regime. Stratification is not only diminished in many areas, but due to the increased mixing in the wind farms, the onset of stratification is also delayed. Combined with the higher fine sediment concentration in the water this also leads to a delay of the spring bloom. Scenarios 1-5 also have different effects on temporal dynamics of phytoplankton (Figure 5.13). Simulated time-series of near-surface chlorophyll a concentrations in different sections of Search Area 6/7 shows that the presence of OWFs in this area leads to a delay of the spring bloom compared to the reference situation. This delay occurs in all scenarios. It is however clearly larger in Scenario 3, where the spring blooms occurs around half a month later than in a scenario without OWFs. This is probably due to a combination of drivers: the increased mixing of the water column leads to lower near-surface temperature in the early spring and lower light availability. Also the onset of stratification is delayed, due to the presence of turbines in Search Area 6/7. This causes a delay in the occurrence of optimal conditions for phytoplankton growth.
On the contrary, the presence of an open space in the centre of the Search Area 6/7 seems to reduce that effect. Simulated time-series, particularly the ones inside the open space (location centre, Figure 5.13) are closer to the situation without OWFs compared to Scenarios 1-3, and 5.

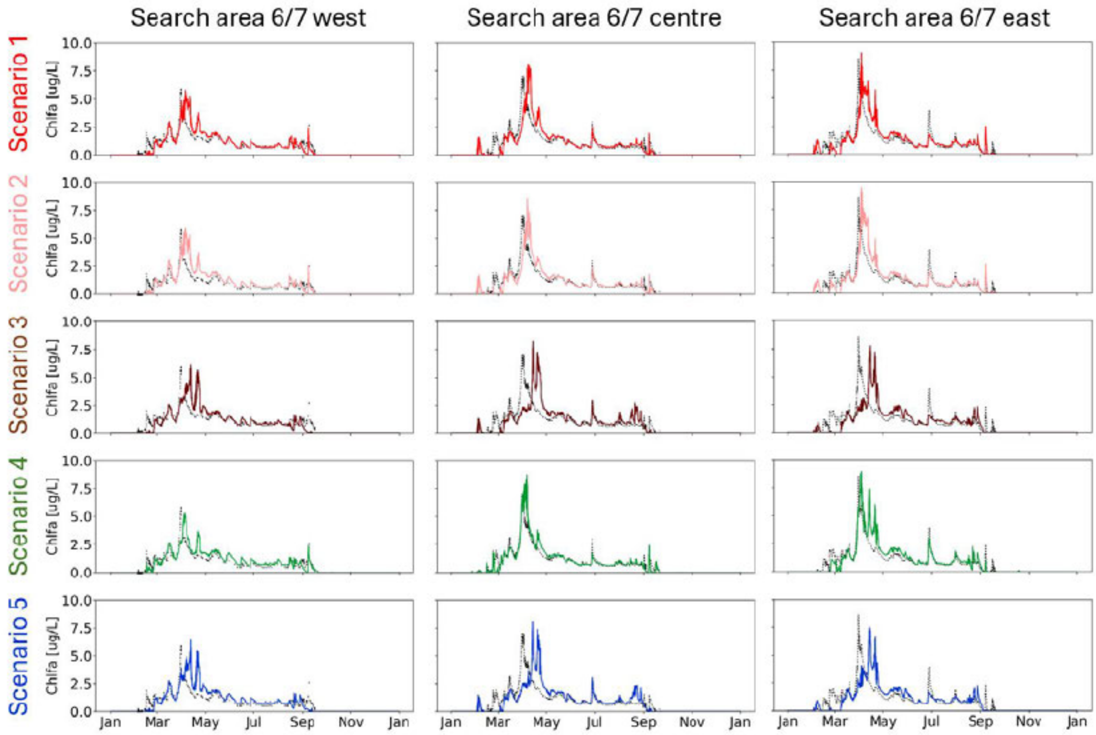


Figure 5.13: Changes in timing of the spring bloom in scenarios 1, 2, 3 and 4 with respect to the reference scenario. Location 'centre' is located in the open space in Scenario 4. Black dotted line represents the reference scenario at that location.

6 General discussion

6.1 Regional patterns in environmental effects of offshore wind farms

The current set of scenarios broadly give the same type of environmental effects due to the presence of offshore wind farms in the different regions as were identified in the previous studies (Van Duren et al. 2021, Van Kessel et al. 2022, Zijl et al. 2023). A summary of the impacts in the different regions can be found in Appendix C.

6.2 Reference scenario

6.2.1 Wind farms in the Holland Coast

The scenario for wind farms expected to be operational in 2033 shows relatively minor impacts in the Dutch EEZ with respect to temperature stratification. This is not surprising, since the majority of the wind farms are in areas that either are not stratified, or have limited, intermittent stratification. The wind farms in the Holland coast tend to be further apart, particularly in the main direction of the flow, than those in e.g. the German Bight. The Holland Coast areas have limited temperature stratification, and only some (mainly HKZ) have salinity stratification. Most of the Holland Coast area has a relatively low concentration of fine sediment in the seabed. Hence, although any extra sediment that is resuspended, will immediately impact the top layers, the concentration increases are not large here. Hence in the Holland Coast the direct impacts on primary production are limited, particularly in search areas IJmuiden Ver, IJmuiden Ver Noord and the Nederwiek farms.

6.2.2 Wind farms in the German Bight

The scenario for wind farms expected to be operational in 2033 shows impacts on and effects of stratification changes in the OWFs in (or near) the German Bight (Gemini, TNW and Doordewind). Combined with the effect of the German wind farms that are planned before 2033 these ones have a marked effect on temperature stratification, on SPM in the top layer and on primary productivity. The impact in the German Bight is fairly widespread, while in the Holland coast, effects on SPM and on primary production are more confined to the wind farm locations.

It appears that the decreases in primary production in the German Bight impact area (Appendix C) differ per wind farm. Some of these differences may be due to the fact that certain farms are older and turbines are closer together than assumed in the scenarios for future farms, but it also appears to be the case that the wind farms nearer the shore (i.e. in shallower parts) have larger effects. E.g. the Doordewind location appears to give markedly lower impacts on increased SPM in the top layer than the neighbouring German farms Deutsche Bucht, Veja Mate and BARD. These German farms are already operational and have 6 MW turbines, while the scenario for Doordewind has been run with 15 MW turbines.

However, it is also clear that the wind farms in the southern part of the German Bight (TNW, the GEMINI farms and the German ones, such as Borkum Riffgrund and the ones further to the east), have very pronounced effects, with reductions of over 60% in primary production. The older GEMINI farms have smaller turbines and hence a much higher density of turbines, but the adjacent Borkum Riffgrund has 11 MW turbines and sees similar effects. This area is around 30 meters deep, while the more Northerly farms, such as Doordewind are about 40 meters deep. The smaller depth means that SPM from near-bed layers is easily mixed up to the top, where it reduced light penetration.

Finally the Wind farms in the German Bight appear to be in each other's zone of influence with respect to impact on temperature stratification (Figure 4.1) as well as sediment plumes in the growing season (Figure 4.2).

6.3 Partial Revision scenarios (in comparison to the reference scenario)

6.3.1 Lagelander area

Comparing scenarios 1-5 to the reference scenario, the additional impact of the 2GW farm Lagelander area is relatively minor, considering the modelled parameters. The area is not stratified (temperature or salinity), the seabed contains in most of the area relatively little mud. In comparison to the reference scenario, the primary production changes by about 5%. Phytoplankton biomass is decreased around 2% in most scenarios. Decreases in chlorophyll are percentagewise slightly larger, due to the fact that decreases are caused by increased light limitation. Hence, phytoplankton will increase its chlorophyll to carbon ratio.

6.3.2 Doordewind area

The total capacity of Doordewind+ Doordewind West is 6 GW, as opposed to 2.3 GW for Doordewind. In the five Partial Revision scenarios there is a clear impact of the additional 3.7 GW in Doordewind + Doordewind West on the SPM concentration in the upper layers and on primary production. The Doordewind West part has a slightly higher mud content in the seabed than the main Doordewind area. The combination of extending the area and increasing the density of turbines leads to an additional 25-30% decrease in primary production in this area in comparison to the reference scenario. The Doordewind area is directly adjacent to German wind farms (some already operational, but many planned to be operational before 2045). In order to assess what impact can specifically be attributed to the Dutch farms and which are the combined effects might need some extra scenario runs to tease the effects apart. However, the physics of the area combined with the high density of German and Dutch wind farms mean that the German Bight part of the North Sea appears to be susceptible to substantial decreases of primary production. Particularly in this area, we see in the results some compensatory effects in primary production. Nutrients not being used inside areas with elevated SPM levels can boost productivity outside these areas, but this does not appear to be sufficient to compensate the reduction in primary productivity completely. Mass balance analyses on regional and subregional scales can give better insight in this.

6.3.3 Search Area 6/7 variants

In general, a windfarm in this area causes an increase of primary production. In this area there is clear summer stratification, which when reduced, is mixing more nutrients to the higher water levels, but due to the fact that stratification is not removed altogether, SPM is still confined to the lower water layers in summer, even though in winter SPM levels are clearly elevated in all scenarios. However, due to the fact that phytoplankton growth takes place in the summer half year, the net effect is in all scenarios an increase in productivity. Not only is production higher, but also the distribution of chlorophyll throughout the water column is more even, so availability of food for grazers near the bed is disproportionally higher. The near-bed chlorophyll concentrations can be more than doubled in comparison to the reference scenarios (Figure 5.9).
In this area the spring bloom appears to be delayed, due to the fact that the onset of stratification is later and temperature in the upper layer is lower. The impact is most marked in scenario 3, with the highest density of turbines.

The size of the turbines (inversely relating to the density) appears to have some effect on mixing, stratification and hence on fine sediment. However, the differences between scenarios 1 and 2 (both with a similar total production capacity of 24 GW, only differing in turbine size (20 or 25 MW turbines) was relatively small, while the impacts in scenario 3 (smaller turbines, but a much higher total capacity of the wind farm) was much more pronounced. This appeared to be consistent with impacts on stratification, SPM and primary production. Search Area 6/7 also directly borders German wind farms and within this area there are differences between impacts in the western part and the eastern part, that are likely associated with the fact that the area to the west is free from other wind farms.

The scenario that does appear to have less impact on SPM and particularly on stratification is the one with the open zone, scenario 4. Primary production is still increased in this area, but less so, than in Scenarios 1, 2, 3 and 5. There is a slight reduction on both primary production and chlorophyll *a* levels in the central part of the wind farm at the location of the open zone, in comparison to scenario 1. However, the effect is patchy and proportionally less than the impacts on stratification, which is likely the main driving force to boost productivity. In scenario 4 the delay in spring bloom is clearly less in the centra area, so that is also a mitigating impact of the open zone. Also, for this scenario mass balance analyses on a regional and subregional scale can give more insight in the importance of the different impacts.

7 Knowledge gaps and uncertainties

The ecosystem effects investigated in the Wozep project and assessed for a number of policy-relevant scenario in this report are assessed with numerical models. Such models are basically the only tool available to get an idea about effects of situations that currently do not exist and can therefore not yet be measured. However, numerical models are associated with uncertainties. The most important ones are highlighted below.

7.1 Validation data

The background scenario, without wind farms is well validated with respect to patterns of stratification, patterns of SPM concentrations in the top layers and primary production. However, we still lack substantial validation of the modelled impacts of offshore wind on these parameters. Qualitatively the results match with observations in Germany (Floeter et al. 2017) and in the project “Effects of windfarms on the marine ecosystem, and implications for governance” (Hendriks et al. 2024). However, we lack validation data for areas that are seasonally stratified, since there are currently no wind farms present there.
Gradually there are more data becoming available. In follow-up projects (either Wozep or the recently submitted NWA proposal No-Regrets) it will be important to substantiate various aspects of the model much better. These projects will have measurements in the GEMINI wind farms, where the model predicts strong impacts on primary production. For the physical impacts of the monopiles on the water movement there are some measurements and also CFD models that can be used. At present we particularly lack data on primary production.
As the simulations on chlorophyll show, using this as a proxy for algal biomass (and hence food concentration for grazers) has its drawbacks. Concentrations of biomass may decrease when chlorophyll concentrations remain the same or even increase, if decreases are caused by a reduction in light. Chlorophyll is relatively easily detected using earth observation techniques. These will yield a good areal cover. However, as Figure 5.9 illustrates, looking only at the top layers of the water column is in stratified areas not sufficient to fully assess impacts of wind farms. Impacts near the bed may differ in magnitude and in direction.

7.2 Wind

In the current model we include a reduction of 10% of wind speeds inside the wind farms, but depending on atmospheric stability the wakes behind wind farms can reach many tens of kilometres (Hasager et al. 2015, Boon et al. 2018), which can affect the wave field and hence resuspension. In a Wozep study we analysed the relative importance of these wind wakes relative to the impacts of tidal current interaction with turbine monopiles. That study indicated that instantaneous effects can be large, but annual averaged effects are moderate in comparison to the enhanced mixing from tidal current interaction (Zijl and Leummens 2023). However, the subsequent impact on primary production still has to be assessed. Particularly in areas with interactive effects between wind farms (such as in the German Bight), this may be important. We are also aware that within wind farms lower turbines and a higher density will also impact the wind speed within a wind farm. The 10% reduction currently taken for all wind farms should also be evaluated and possibly be made dependent on turbine design and lay-out.

7.3 Grazers

In the modelling suite used in this study there is mortality of phytoplankton, which is determined by calibrating the reference scenario model, based on observations. In reality there will be feedback processes from pelagic and benthic grazers (zooplankton and zoobenthos) on phytoplankton. The first modelling results in Wozep from a suite including observed biomasses of mussels on the wind farm turbines (Van Kessel et al. 2022, Zijl et al. 2023) indicate that this predominantly has effects on the biomass of phytoplankton (i.e. on the chlorophyll concentration). Impacts on primary production were relatively low. Grazers reduce the standing stock of phytoplankton (for which chlorophyll concentrations are used as a proxy). In areas with high grazer concentrations, there can also be feedback impacts on productivity due to the faster remineralisation of faecal material (Troost et al. 2010, Troost 2011). The same was true for the first modelling efforts on including dynamic grazing pressure of zooplankton (Rienstra 2023). However, the latter study only considered 1D column models (where environmental conditions from the 3D Wozep model we used as boundary conditions) and this was done with Dynamic Energy Budget model parameters from a copepod species that is not typical for the North Sea. Future Wozep work on the impacts on grazers as well as the grazer impacts on primary production and on chlorophyll concentrations should shed more light on these impacts.

7.4 Impacts on higher trophic levels

This study only assesses the impacts on primary production. The framework for cumulative ecological impacts, predominantly assesses whether impacts are within acceptable limits based on the impact on species with targets under Natura 2000. These are all apex predators such as birds, marine mammals and some iconic fish species such as sharks and rays, the latter are protected under the Marine Strategy Framework Directive. On a large scale there are obviously links between e.g. primary production and fish (Chassot et al. 2010, Capuzzo et al. 2018), but with the current level of knowledge and the currently available models it is not yet possible to translate any impacts at the base of the food web on target species such as harbour porpoises, kittiwakes or gannets. Internationally there are programmes running such as PELaGIO (https://ecowind.uk/projects/pelagio/) where changes in physical forcing and food web structure and their consequences for higher trophic levels are researched. However, all this work is still very much in its infancy.

7.5 Interaction with other human impacts

In this study only the impacts of offshore wind on the ecosystem are studied. The presence of offshore wind will also impact other human activities, such as the location of high fishing intensities (Dunkley and Solandt 2022). The modelling suite is calibrated on a situation with limited presence of wind farms. So lack of bottom trawling within the wind farms, or increased fishing in certain areas outside wind farms, is not taken into account. For most areas this is probably a limited impact, as the Holland coast area is relatively sandy and bottom trawling frequencies in most areas are limited to once or twice a year. This might still impact the composition of benthic biota but will have limited impact on e.g. fine sediment concentrations in the water column. For changes (reductions or concentrations) in bed disturbance in and around Search Area 6/7 the net impact may be larger, due to the fact that this area has little natural bed mobility and has in certain areas an elevated amount of fine sediment in the seabed.

8 References

Boon, A. R., S. Caires, I. L. Wijnant, F. Zijl, J. J. Schouten, S. Muis, T. Van Kessel, L. A. Van Duren, and T. Van Kooten. 2018. Assessment of system effects of large-scale implementation of offshore wind in the southern North Sea. 11202792-002-ZKS-0006, Deltares, Delft.

Capuzzo, E., C. P. Lynham, J. Barry, D. Stephens, R. M. Forster, N. Greemwood, A. McQuatters-Gollop, T. Silva, S. M. van Leeuwen, and G. H. Engelhard. 2018. A decline in primary production in the North Sea over 25 years, associated with reductions in zooplankton abundance and fish stock recruitment. Global Change Biology **24**:e352-e364.

Cazenave, P. W., R. Torres, and J. I. Allen. 2016. Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. Progress in Oceanography **145**:25-41.

Chassot, E., B. S., N. K. Dulvy, F. Mélin, R. Watson, D. Gascuel, and O. Le Pape. 2010. Global marine primary production constrains fisheries catches. Ecology Letters **13**:495-505.

Dunkley, F., and J.-L. Solandt. 2022. Windfarms, fishing and benthic recovery: Overlaps, risks and opportunities. Marine Policy **145**:105262.

Floeter, J., J. E. E. van Beusekom, D. Auch, U. Callies, J. Carpenter, T. Dudeck, S. Eberle, A. Eckhardt, D. Gloe, K. Hänselmann, M. Hufnagl, S. Janßen, H. Lenhart, K. O. Möller, R. P. North, T. Pohlmann, R. Riethmüller, S. Schulz, S. Spreizenbarth, A. Temming, B. Walter, O. Zielinski, and C. Möllmann. 2017. Pelagic effects of offshore wind farm foundations in the stratified North Sea. Progress in Oceanography **156**:154-173.

Flores, R. P., S. Rijnsburger, A. R. Horner-Devine, A. J. Souza, and J. D. Pietrzak. 2017. The impact of storms and stratification on sediment transport in the Rhine region of freshwater influence. Journal of Geophysical Research: Oceans **122**:4456-4477.

Große, F., N. Greenwood, M. Kreus, H. J. Lenhart, D. Machoczek, J. Pätsch, L. Salt, and H. Thomas. 2016. Looking beyond stratification: A model-based analysis of the biological drivers of oxygen deficiency in the North Sea. Biogeosciences **13**:2511-2535.

Hasager, C. B., P. Vincent, R. Husson, A. Mouche, M. Badger, A. Peña, P. Volker, J. Badger, A. Di Bella, A. Palomares, E. Cantero, and P. M. F. Correia. 2015. Comparing satellite SAR and wind farm wake models. Institute of Physics Publishing.

Hendriks, E., K. Langedock, L. A. van Duren, J. Vanaverbeke, W. Boone, and K. Soetaert. 2024. Near-field measurements around offshore wind turbines show how they enhance hydrodynamics in their direct environment. EGU General Assembly 2024, Vienna.

Ministerie van Infrastructuur en Waterstaat. 2023. Kamerbrief Partiële Herziening van het Programma Noordzee.

Rienstra, J. 2023. Potential effects of upscaling of offshore wind in the North Sea on zooplankton. MSc. thesis. Wageningen University / Deltares, Wageningen.

Ruardij, P., H. Van Haren, and H. Ridderinkh. 1997. The impact of thermal stratification on phytoplankton and nutrient dynamics in shelf seas: A model study. Journal of Sea Research **38**:311-331.

Sharples, J., O. N. Ross, B. E. Scott, S. P. R. Greenstreet, and H. Fraser. 2006. Inter-annual variability in the timing of stratification and the spring bloom in the North-western North Sea. Continental Shelf Research **26**:733-751.

Stephens, D. 2015. North Sea and UK shelf substrate composition predictions, with links to GeoTIFFs.*in* Pangaea, editor.

Troost, T. A. 2011. Draagkracht voor mosselen in de Oosterschelde. 1203038, Deltares, Delft.

Troost, T. A., J. W. M. Wijsman, S. Saraiva, and V. Freitas. 2010. Modelling shellfish growth with dynamic energy budget models: An application for cockles and mussels in the Oosterschelde (southwest Netherlands). Philosophical Transactions of the Royal Society B: Biological Sciences **365**:3567-3577.

Van Duren, L. A., T. Van Kessel, T. A. Troost, A. N. Blauw, L. Kramer, J. A. G. van Gils, J. W. M. Wijsman, J. A. M. Craeymeersch, P. M. J. Herman, and M. T. Villars. 2017. Scenariostudies ter ondersteuning van de MER zandwinning Noordzee 2018 – 2027. Winning van suppletiezand voor RWS. 1230888-000-ZKS-0025, Deltares, Delft.

Van Duren, L. A., F. Zijl, V. T. M. van Zelst, L. M. Vilmin, J. Van der Meer, G. M. Aarts, J. Van der Molen, K. Soetaert, and A. W. Minns. 2021. Ecosystem effects of large upscaling of offshore wind on the North Sea - Synthesis report. 11203731-004-ZKS-0010, Deltares, Delft.

Van Kessel, T., V. T. M. van Zelst, J. Hanssen, L. M. Vilmin, and L. A. van Duren. 2022. Environmental effects of large-scale implementation of offshore wind farms. Further analyses. . 11208071-001-ZKS-0006, Deltares, Delft.

Zijl, F., S. C. Laan, A. Emmanouil, V. T. M. van Zelst, T. Van Kessel, L. M. Vilmin, and L. A. Van Duren. 2021. Potential ecosystem effects of large upscaling of offshore wind in the North Sea. Final report model scenarios. 11203731-004-ZKS-0015, Deltares, Delft.

Zijl, F., S. C. Laan, and J. Groenenboom. 2020. Development of a 3D model for the NW European Shelf (3D DCSM-FM). report 11205259-015-ZKS-0003, Deltares, Delft.

Zijl, F., S. C. Laan, L. Leummens, T. Zijlker, T. van Kessel, V. T. M. van Zelst, L. Jaksic, L. M. Vilmin, L. Schneider, and L. A. van Duren. 2023. Scenario studies on potential ecosystem effects in future offshore wind farms in the North Sea. 11208071-001-ZKS-0010, Deltares, Delft.

Zijl, F., and L. Leummens. 2023. The effect of wind wakes on hydrodynamic parameters. Coupling 3D DCSM-FM to WINS50 Harmonie results. 11209248-003-ZKS-0001, Deltares, Delft.

Zijl, F., L. Leummens, N. Alexandrova, T. van Kessel, L. Jaksic, V. T. M. van Zelst, L. M. Vilmin, S. Heye, and L. A. van Duren. 2024. Impact of offshore wind farms on the North Sea ecosystem. Scenario study for the Partial Revision of the Dutch offshore wind planning. 11209248-007-ZKS-0001, Deltares, Delft.

Zijl, F., J. Veenstra, and J. Groenenboom. 2018. The 3D Dutch Continental Shelf Model - Flexible Mesh (3D DCSMFM) : setup and validation. 1220339, Deltares, Delft.

A Important processes and terminology

This appendix provides some background information about essential physical and ecological processes in the marine environment, that are impacted by the presence of offshore wind farms and have a knock-on effect on the ecosystem. Appendix B contains a glossary of technical terms used throughout this report and their definitions.

A.1 Currents waves and stratification

The support structures for wind turbines (in the Dutch part of the North Sea generally monopiles) will exert a drag force on the tidal current. This results in a slowing down of the current in the vicinity of the structure and in the development of whorls and eddies behind the structure. The impact decreases with distances but can extend for hundreds of meters (Cazenave et al. 2016). In wind farms with turbines that are relatively close together, the wakes can start interacting. Within a wind farm therefore the flow velocities are smaller, but the level of turbulence is higher.

The turbines remove energy from the wind. This results on average in lower wind speeds within a wind farm, than outside farms. This wind reduction inside wind farms is in order of 10%. The length of wind wakes depends on the state of the atmosphere, but can under certain conditions reach for more than a hundred kilometres. In more turbulent atmospheres the reach in only a few kilometres (Hasager et al. 2015, Zijl and Leummens 2023). Wind drives waves. If waves reach the seabed, this also causes turbulence.

Stratification (when two distinct layers exist in the vertical water column) occurs when water with a lower density (generally either warmer water or less saline water) ‘floats’ on top of water with a higher density. The layers are separated by a “pycnocline” a thin layer with a strong density gradient. This is an important factor in marine ecological processes. In a fully mixed, (not stratified) system, nutrients, fine sediment, phytoplankton and zooplankton are easily transported throughout the water column. In a stratified system, algae can grow in the top layer, where there is enough light, but can only access the nutrients that are dissolved in the top layer. Nutrients in the lower layer cannot be used for algal growth.
In the North Sea temperature stratification occurs in a large part of the system in summer (Figure 8.1 shows annual average temperature stratification). Some areas are stratified during the whole summer, other areas on a regular basis, but can get mixed during storms. The southern part of the North Sea is permanently mixed. Close to where rivers discharge into the sea, salinity stratification occurs. The biggest region of freshwater influence (ROFI) is near the mouth of the Rhine, as this is by far the largest river discharging into the North Sea. These areas are permanently stratified, but can vary over the year in size. As the river water contains very high levels of nutrients, stratification in these ‘ROFI’s does not lead to reduced algal growth.

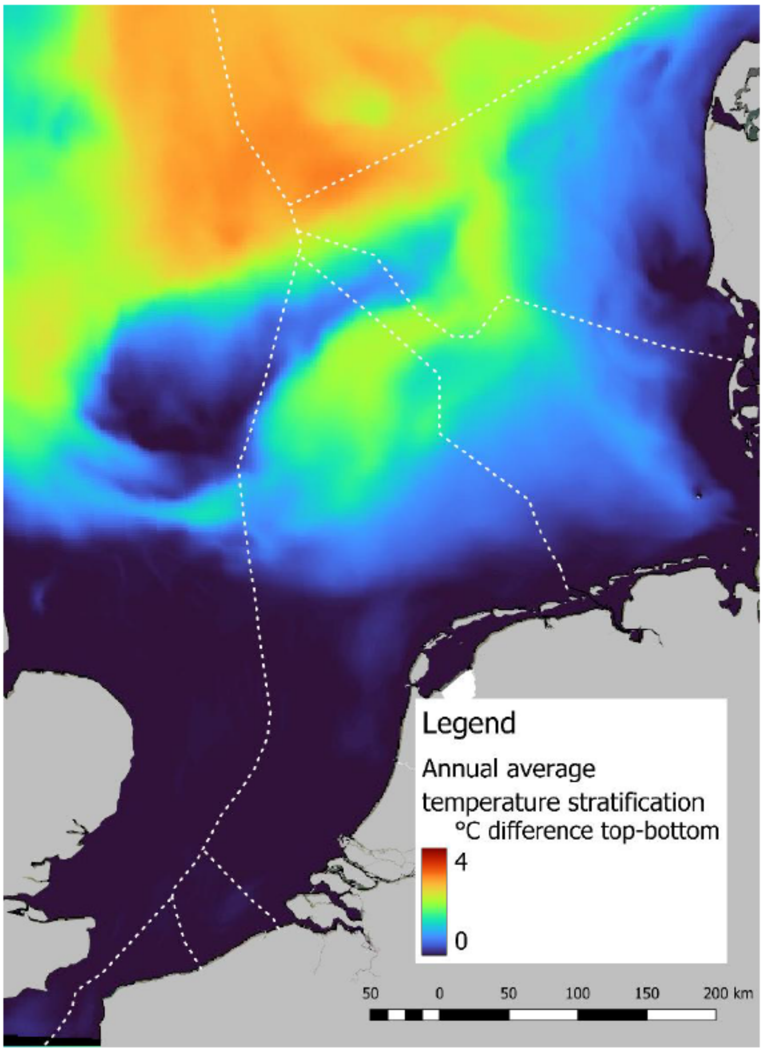


Figure 8.1: Annual average difference in temperature between top water layers and the seabed. In summer these differences are larger, in winter they are virtually non-existent.

A.2 Algae, biomass and primary production

The bulk of the plant-like material in the sea consists of small unicellular algae. They are called microalgae or phytoplankton. They are transported by sea currents and grow under the influence of light and nutrients such as nitrogen compounds and phosphate. They produce organic material by photosynthesis, using pigments such as chlorophyll. These organisms are the foundation of the whole of the marine food web. Ultimately also the top predators (sharks, birds, marine mammals) depend on how much organic material is produced by phytoplankton. The biomass of phytoplankton is best expressed in either grams dry weight or grams carbon. Because phytoplankton is often measured by the amount of chlorophyll, the biomass is often approximated by the chlorophyll concentration, as this is relatively easily measured. This is not always a good approximation. Phytoplankton that is adapted to low light conditions tends to have more chlorophyll per unit biomass.

The growth rate of phytoplankton is called “primary production”, i.e. the production of algal material per square meter of sea per year. It is important not to confuse biomass and primary production. Phytoplankton biomass is the result of primary production and mortality. Highly productive systems with high amounts of animals that eat phytoplankton (grazers) will have a low standing stock of phytoplankton, but a high turn-over.

In winter primary production is low. There are a lot of free nutrients in the water, but not enough light. Primary production starts in spring, when there is enough light. This fast build-up of algal biomass is called the spring bloom. In seasonally stratified areas the spring bloom is linked to the onset of stratification (Sharples et al. 2006). This is followed by a quick growth in zooplankton, reducing the phytoplankton biomass. Many fish and other animals time their spawning and migration patterns in tune to the spring bloom.

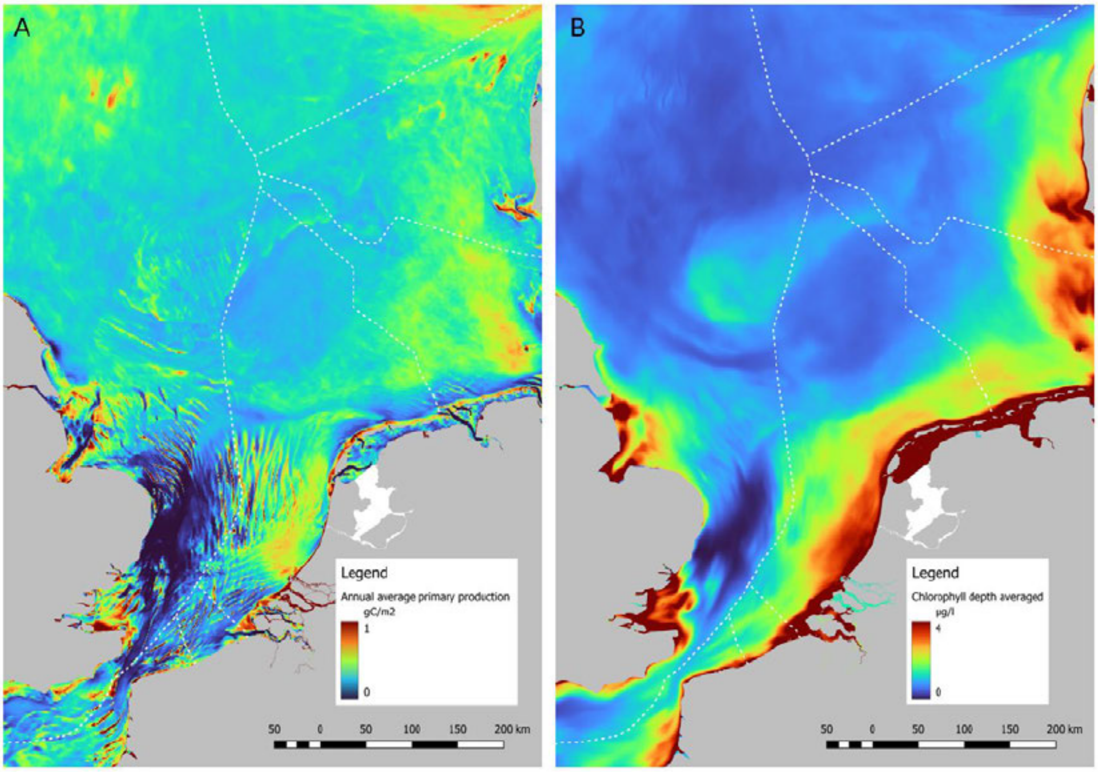


Figure 8.2 A: annual mean primary production in the North Sea, B: Annual mean depth averaged chlorophyll concentration in the North Sea. While dashed lines indicate the delineation of the different national EEZs.

Phytoplankton primary production is highest in areas closer to the shore, receiving nutrient inputs from river plumes, and where light availability isn't limiting, reaching yearly-average values of ~1 $gC/m^2/day$ (Figure 8.2A). Offshore primary production is lower (~0.2-0.3 $gC/m^2/day$), with slightly higher values in the more shallow and better mixed area of the Dogger Bank. Near-surface and depth-averaged chlorophyll a concentrations show sharp spatial gradients from near-shore, nutrient rich areas to offshore (Figure 8.2B).

In areas with very low primary production, such as the Thames plume, even a tiny change in productivity in absolute terms, can lead to a very large relative change, and vice versa. In order to fully understand the impacts it is often good to consider both.

A.3 Offshore wind farm effects

Previous work (Van Duren et al. 2021, Zijl et al. 2021, Zijl et al. 2023) on ecosystem effects of offshore wind has indicated that the presence of wind farms has two effects:

1. The reduction in wind reduces waves and wave mixing
2. The presence of turbine foundations causes more mixing

On balance the second effect (interaction with tidal flows) appears to be dominant (Zijl and Leummens 2023).

The extra mixing and reduction in stratification, due to the presence of wind farms will have location-specific effects on the growth of algae.

- In dynamic, relatively shallow areas, that are fully mixed or with limited, intermittent stratification, enhanced turbulence will increase the amount of fine sediment (SPM) in the top layer, but will not affect the distribution of dissolved nutrients. In these areas the net effect tends to be a reduction of primary production due to reduction of light. Often the spring bloom is delayed.
- In coastal ROFIs, the extra mixing tends to reduce primary production and delay the spring bloom, generally due to the increased fine sediment in the top layer. These areas are not nutrient limited due to the excess nutrients coming from land.
- In offshore seasonally stratified areas, stratification is reduced but not eliminated. In these areas extra mixing does increase the amount of nutrients in the upper water layers, but fine sediment does not get above the pycnocline. In these areas onset of stratification tends to be delayed due to the presence of wind farms. In such areas, primary production is increased, but the spring bloom delayed.

There are also areas in the North Sea such as the German Bight, where the system is physically very complex. There is regular temperature and salinity stratification, but the system is relatively shallow and there is a lot of fine sediment in the seabed. Earlier work showed that these areas tend to show a negative impact of offshore wind on primary production and quite a severe (up to 4 weeks) delay in the onset of the spring bloom.

An overview of the different impact areas of offshore wind from previous model studies can be found in Appendix C.

B Glossary

Term	Definition / explanation	Common unit
Bed shear stress	The force exerted on the seabed due to water movement	N m^2
Benthic	Relating to the seabed	
Chlorophyll	Pigment used by algae for photosynthesis; is often used as a proxy for algal biomass, as it is easy to measure	µg l^{-1} or g m^{-3}
Detritus	Dead organic material	
Energy density	Energy production of a farm per unit surface area	W km^{-2}
Phytoplankton	Small unicellular algae, transported by currents. These are the main marine primary producers	
Phytoplankton biomass	Dry weight of algae	g C l^{-1}
Pelagic	Relating to the water column	
Primary production	The growth rate of algae	g C m^{-2} $year^{-1}$
Pycnocline	The boundary, separating two water layers in a stratified system	
Secondary production	Growth rate of animals feeding directly on algae. Secondary producers can be benthic (e.g. shellfish or worms) or pelagic, such as zooplankton	g C m^{-2} $year^{-1}$
SPM	Suspended particulate matter; suspended particles	mg l^{-1} or g m^{-3}
Spring bloom	Period in spring when phytoplankton starts to grow rapidly. Many species time their migration or their spawning in relation to the spring bloom	
Stratification	Separated layers of fluid or gas, with different densities. In seawater generally due to either temperature or salinity differences. In scientific literature stratification is quantified as the density anomaly (the amount of energy it takes to mix the water column). In this report we tend to indicate the differences in temperature (or salinity) between top water layer and the bottom.	For density anomaly: W m^3
TIM	Total inorganic matter; suspended sediment	mg l^{-1} or g m^{-3}
Zooplankton	Small animals that do not have sufficient swimming capacity to move independent of the flow. Many feed on phytoplankton. The vast majority of zooplankton consists of copepods – very small crustaceans	

C Regional difference in the North Sea in impact of offshore wind.

Earlier work (Van Duren et al. 2021), identified a number of different impact regions in the North Sea, where the effect of offshore wind on primary production differed. For the explanation of processes governing these differences see section A.3.

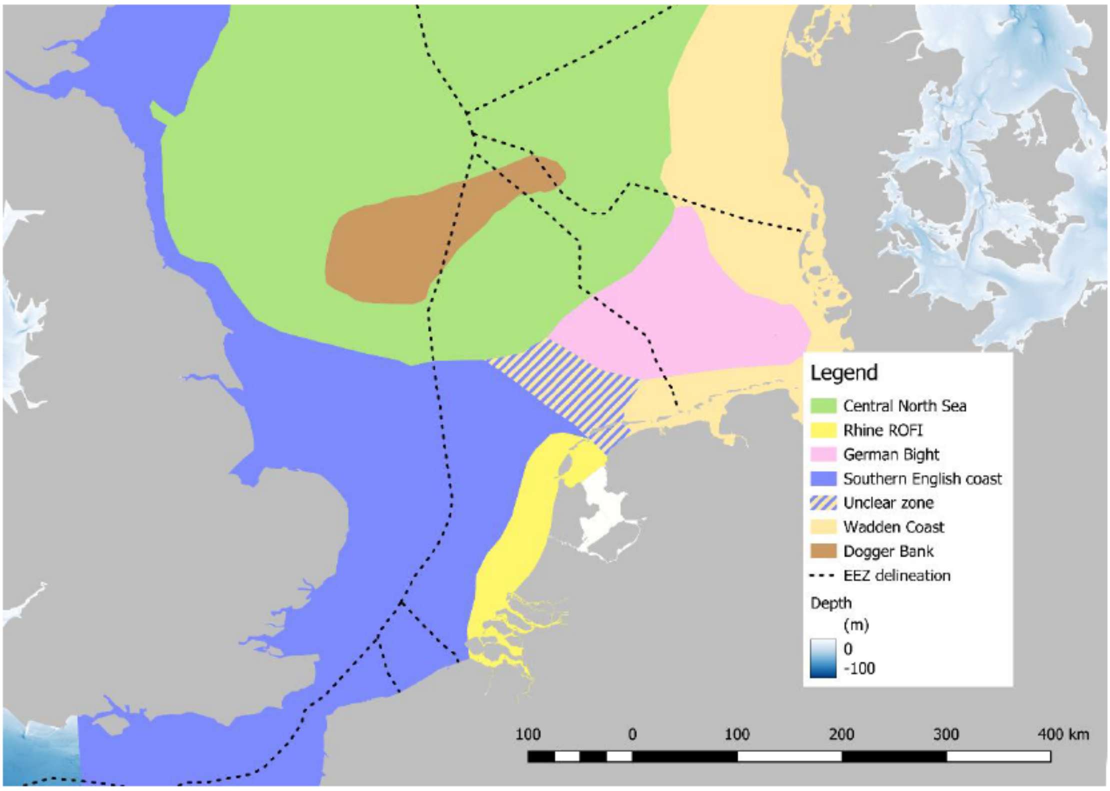


Figure 8.3: the effect areas identified in earlier Wozep studies.

C.1 Central North Sea

This area is intermittently to seasonally stratified due to temperature. Enhanced mixing in the wind farms has the effect to weaken stratification and enhance vertical exchange of heat, SPM and nutrients. SPM concentrations in the upper layer are elevated in winter, but when stratification sets in, SPM is confined to near-bed layers. This area tends to see an increase in primary production and a delay in the onset of the spring bloom.

C.2 Rhine ROFI

This is an area with high nutrient availability and without temperature stratification, but some salinity stratification. It is a highly dynamic area with strong tidal currents. In this area primary production is more light-limited than nutrient-limited. Nutrient availability in upper layers is high due to riverine input. The net effect of wind farms in this region is that higher fine sediment concentrations in the upper layers decrease primary production, but increased mixing does not enhance productivity. The changes in mixing in this area (in horizontal and vertical direction) are likely to have some effect on the transport of fine sediment along the Dutch coast and towards the Wadden Sea.

C.3 German Bight

This area is characterised by frequent but not very strong stratification. Temperature stratification is dominant, but also salinity plays a role here. The model runs (Zijl et al. 2023) suggest that SPM effects of wind farms tend to be dominant in this area. Leading on average to a suppression of primary production in and around wind farms. Due to the high density of planned wind farms in the German and Dutch part, effects of wind farms tend to interact and effects on primary production can extend well beyond wind farm perimeters.

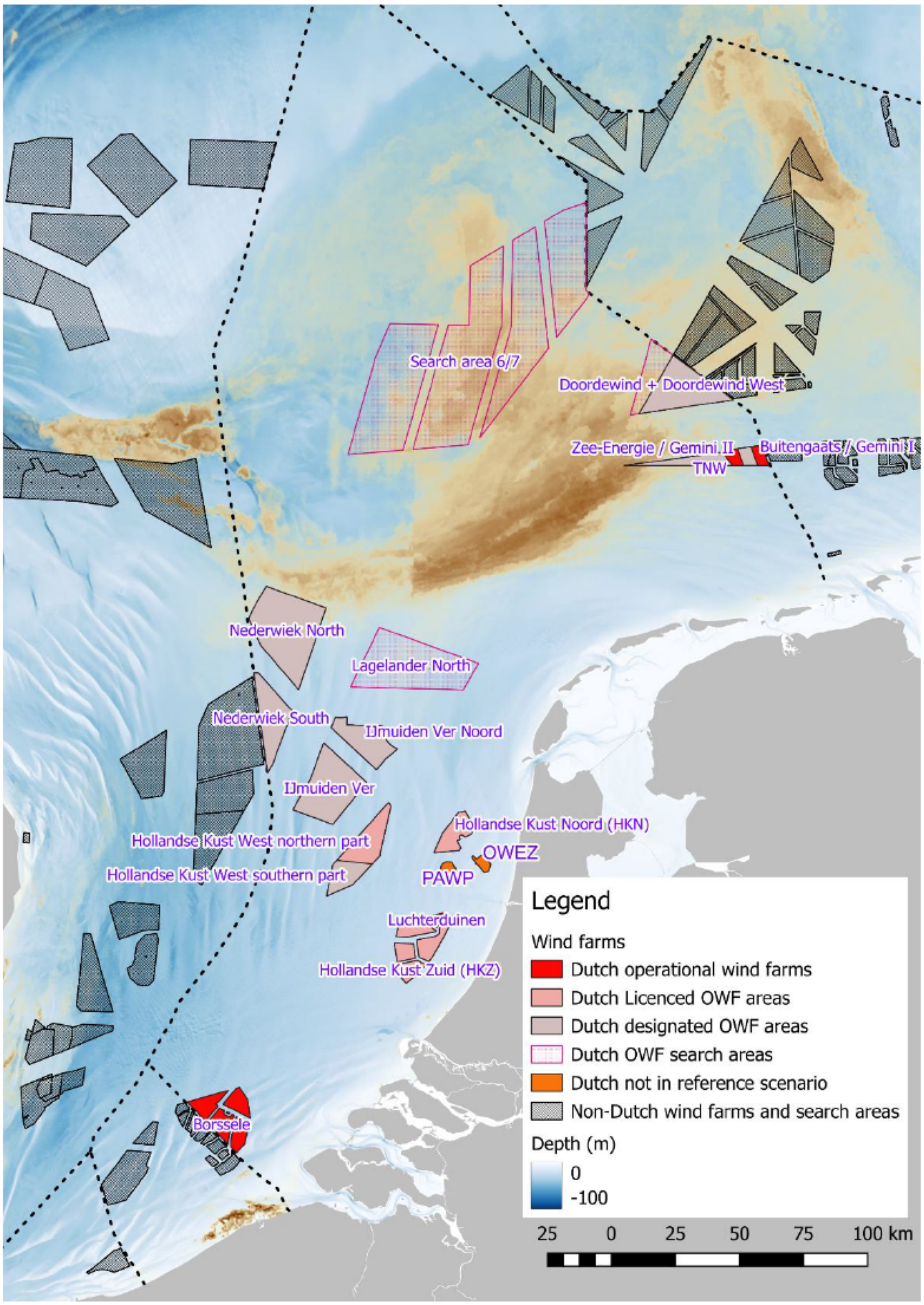
C.4 Southern English coast and western part of the Dutch Continental Shelf and the German and Danish Wadden coast

These are the areas that are fully mixed or nearly always fully mixed. Changes in stratification do not occur here, depending on the amount of fine sediment in the seabed. The main effect of windfarms is the increase in turbidity in the top layers of the water column. In some parts, e.g. close to the Thames estuary, the system without wind farms is extremely turbid and hence very low in productivity. In absolute terms, any increase in SPM in the top layers does not decrease productivity much further, although in relative terms the decrease may be large. In all other areas, increased turbidity due to wind farms reduces production. In Van Duren et al (2021) an unclear area was identified between the western part of the Dutch Continental Shelf and the Wadden Coast. As mixing regimes and depth are similar to the two former areas we assume this area would respond in the same way. As we have not had any wind farms in that area, that has not been tested.

C.5 Dogger Bank

This is an isolated shallow area surrounded by deep seasonally stratified waters. It has a unique composition of ecological communities. The Dogger Bank has some areas that occasionally have some intermittent (not very strong) temperature stratification, other parts are nearly always fully mixed. The bed consists predominantly of medium sand and coarse-grained material, so even though waves easily reach the bed, resuspension of fine sediment from the bed is limited. The resulting effects of offshore wind farms on the Dogger Bank on primary production are limited.

D Map with names of different wind farm areas in the Dutch EEZ



Note the status of the wind farms is the situation in 2023, when this research was initiated. Meanwhile wind farms indicated here as licenced will be operational and areas that are indicated as ‘designated’ may be licenced or operational.

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