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Regional mass balances of ecosystem effects of offshore wind farms on the North Sea

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Summary

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 on the North Sea. Previous studies under this program indicated that ecosystem effects of large-scale offshore wind on primary and secondary productivity can be profound. These effects are due to interactions of the wind turbines with the ambient flow, resulting in changes in spatio-temporal patterns of currents, stratification, changes in fine sediment dynamics and consequently changes in primary production, phytoplankton biomass and chlorophyll. The results also indicated that in some areas, there may be significant reductions of primary production within wind farms, which may be compensated on a larger scale by increases outside wind farms. In order to get a better idea about the regional relevance of these changes we have performed mass balance analyses based on the OSPAR pelagic assessment areas.

The mass balance analyses showed different responses in different areas, but also showed that within some OSPAR assessment areas there are sub regions with increases and others with decreases in primary production within wind farms. Based on these results, this report presents a new definition of “Wozep impact areas”, that starts from the OSPAR assessment areas and modifies them where needed to provide a meaningful image of the large scale impacts of wind farm developments. This new definition replaces the impact areas that were used in previous studies.

The way assessment areas are defined has a major impact on the perception of average impacts on primary production and phytoplankton biomass. The newly defined Wozep impact areas were used to quantify the impacts of the “Partial revision scenario 1”. Particularly in the eastern part of the North Sea (bordering the German EEZ) average impacts are possibly large enough to expect impacts on higher trophic levels. The analyses also highlighted strong spatial differences in the impact of wind farms on phytoplankton biomass and on chlorophyll, reinforcing the conclusion that chlorophyll may not always be the best proxy to monitor changes in phytoplankton availability. However, as chlorophyll is easily measurable, including from remote sensing, it is still an important parameter

Having assessment frameworks for human exploitation of marine resources on lower trophic levels (e.g. primary production) rather than only on individual species with conservation targets, is going to be important for future sustainable use and management of marine space. Analyses such as here can be a first step towards such a framework.

Contents

1 Introduction

1.1 Background

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 on the North Sea. Previous studies under this program at Deltares have indicated that ecosystem effects of large-scale offshore wind can be profound. These effects are due to interactions of the wind turbines with the ambient flow, resulting in changes in spatio-temporal patterns of currents, stratification, changes in fine sediment dynamics and consequently changes in primary production (Zijl et al. 2023, Zijl et al. 2024).

Some effects are limited to a wind farm or its immediate vicinity, in some cases we see impacts well beyond wind farms and interactive effects between neighbouring wind farms. This is particularly the case in the German Bight area where the density in wind farms is high (Zijl et al. 2024). With respect to primary production and phytoplankton biomass, we often see so called “compensation effects” around wind farms. An illustration of a compensation effect can be seen in Figure 1.1. This shows the impact on an offshore wind scenario on primary production. In the German Bight wind farms, including those in the Dutch EEZ, we see clear decreases in algal growth (blue colours).

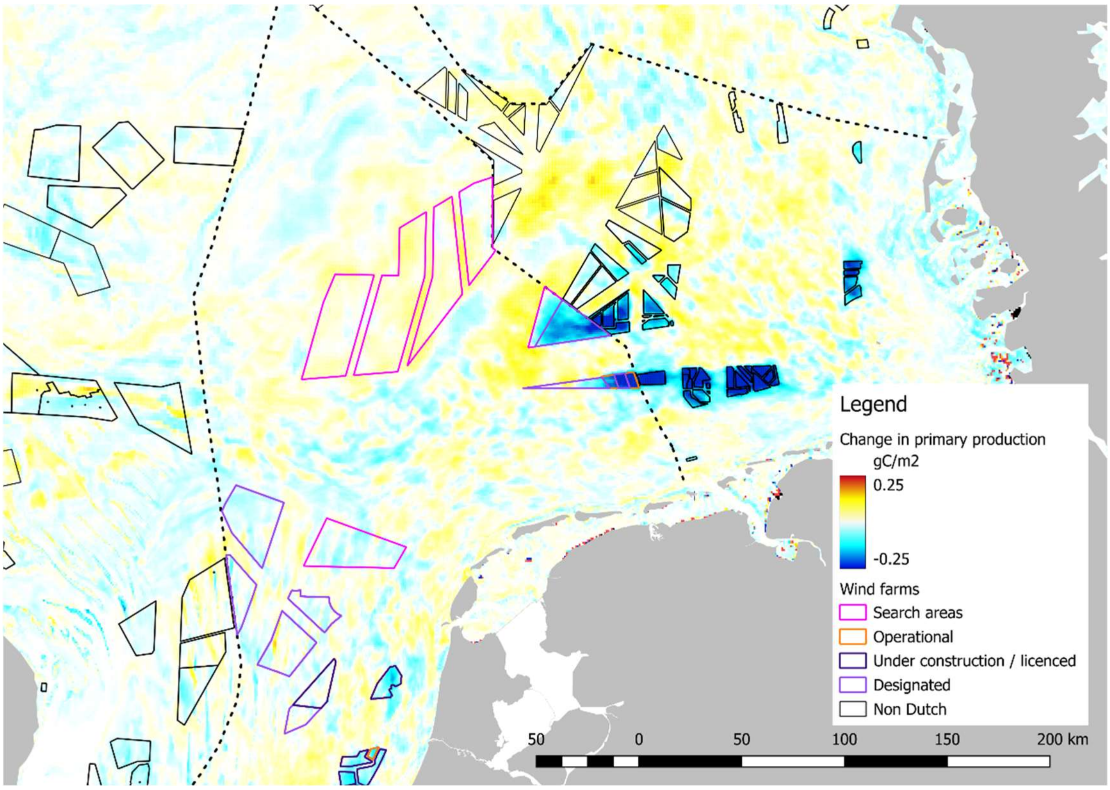

Figure 1.1: Model results of changes in yearly average, depth-integrated primary productivity in and around wind farms. Results shown are the difference between a wind farm scenario and a reference situation without wind farms. Modified figure based on model runs reported in an earlier Wozep scenario report (Zijl et al. 2024). The status of the wind farm areas (operational, under construction, designated or search area) is the status of 2023. In the meantime some wind farms that were under construction have become operational and areas that were designated have been tendered.

This effect is due to increased presence of fine sediment in the top layers of the water, which reduces light availability. These increased fine sediment concentrations are confined to the windfarms. In surrounding areas we see yellow colours, indicative of an increase of primary production. Nutrients that cannot be used inside the wind farm are boosting phytoplankton growth outside the farm.

1.2 Towards an assessment framework

In the previous Wozep studies on ecosystem effects of offshore wind farms, it was not always easy to indicate whether effects were deemed “positive”, “neutral” or “negative”. Wozep was developed to assess whether protected species with targets under the European Habitat and Bird Directive would be affected, directly or indirectly, by the establishment of large-scale offshore wind farms. If there are substantial changes at the base of the foodweb, such as changes in primary production, this is likely to impact higher trophic levels. However, exactly how such changes cascade up the food web and impact specific policy relevant species, is very complex. The Marine Strategy Framework Directive (MSFD) was put in place to protect the marine ecosystem and includes 11 descriptors, of which several directly relate to the base of the foodweb. Any future impact assessment framework for offshore wind (or any other human activities that impact water quality and ecology) clearly must be aligned with the MSFD.

A first step to assessing whether or not changes in primary production are likely important or not, is to carry out mass balance assessments on a more regional scale. This would indicate if changes are important on a larger scale than only the wind farms. Choosing regions of a meaningful size, requires significant consideration (Graves et al. 2023). Different areas of the North Sea have different abiotic characteristics (such as depth, stratification regime, seabed composition) and will also respond differently to implementation of offshore wind farms (Van Duren et al. 2021, Zijl et al. 2023). The regions should be large enough to have relevance for certain species, but not so large that impacts are averaged over regions with different responses to implementation of wind farms. The assessment scales should be linked to the drivers of change (Graves et al. 2023).

This report presents an assessment using the OSPAR pelagic assessment areas (OSPAR 2023), which are based on the eutrophication assessment regions (Enserink et al. 2019). These regions are based on depth, stratification, salinity and seasonal patterns of chlorophyll concentration. The latter is influenced by light availability and hence fine sediment dynamics. The most important factors determining how fundamental functions, such as primary production are impacted by offshore wind farms, are stratification, fine sediment dynamics and depth[1]. Therefore, we expect different OSPAR eutrophication assessment areas to show different responses to the deployment of offshore wind farms.

1.3 Lay-out of this report

Chapter 2 describes the OSPAR assessment regions and compares these to the earlier defined impact areas, as determined in earlier Wozep reports (Van Duren et al. 2021). Chapter 3 describes the methods to perform the analyses. Chapter 4 shows the results of the mass balance analyses on the OSPAR assessment areas. Chapter 5 proposes a new definition of the impact areas in the North Sea and chapter 6 discusses the potential use for a future evaluation framework.

[1] https://www.ospar.org/documents?v=49366

2 Description of regions and comparison to earlier Wozep impact regions.

For the purpose of eutrophication, pelagic habitats and food webs indicator assessments OSPAR divided three of its subregions (Greater North Sea, Celtic Seas and Bay of Biscay and Iberian Coast) into 64 eutrophication assessment areas, based on depth, stratification regime, impact of fresh water and seasonal patterns of chlorophyll concentrations. . In the Greater North Sea this amounts to 22 assessment areas (**Error! Reference source not found.**).

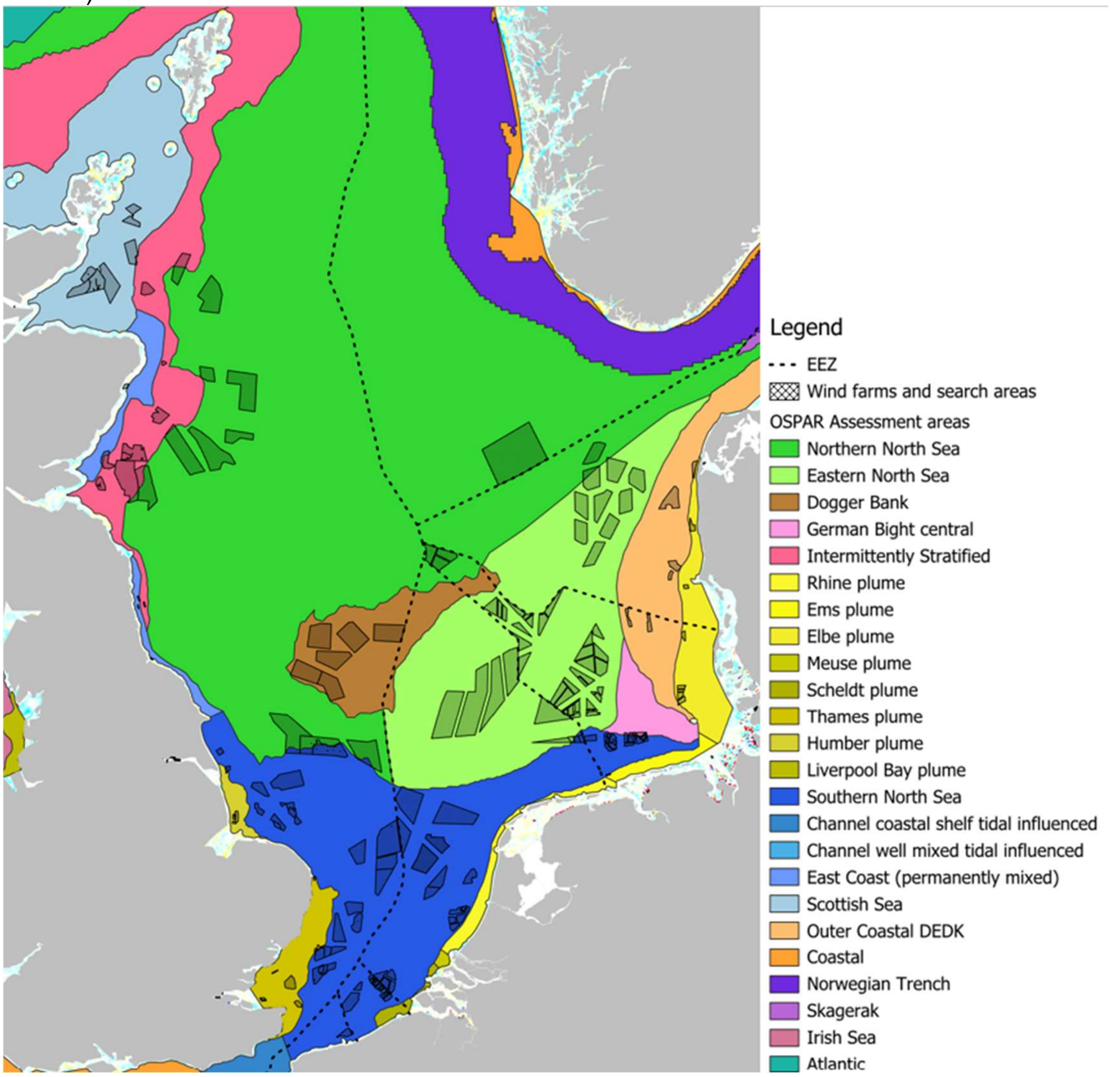

Figure 2.1: OSPAR eutrophication assessment areas in the North Sea, with the wind farms used in the scenario studies.

There are obvious similarities between this classification and the impact areas identified in previous Wozep reports (Figure 2.2). This is not surprising as freshwater influence and stratification regimes are important underlying elements in both. These parameters, together with factors such as seabed composition, are important determining factors in how offshore wind farms influence the marine environment. However, there are also differences. The delineation of the German Bight Central (pink area) is in the OSPAR eutrophication assessment areas smaller than the Wozep impact area. Note that in the delineation of the

OSPAR assessment areas, the German Bight area only contains the very northern edge of some German wind farms, but is otherwise open.

The original impact area map as indicated in Figure 2.2, was made, focussing on the Dutch EEZ. Hence areas such as the Norwegian Trench were not identified and possibly too little attention was paid to effects in e.g. the Thames and Humber plumes. Although the 'English coastal area' was drawn up into Scotland, at the time this area was not really well assessed.

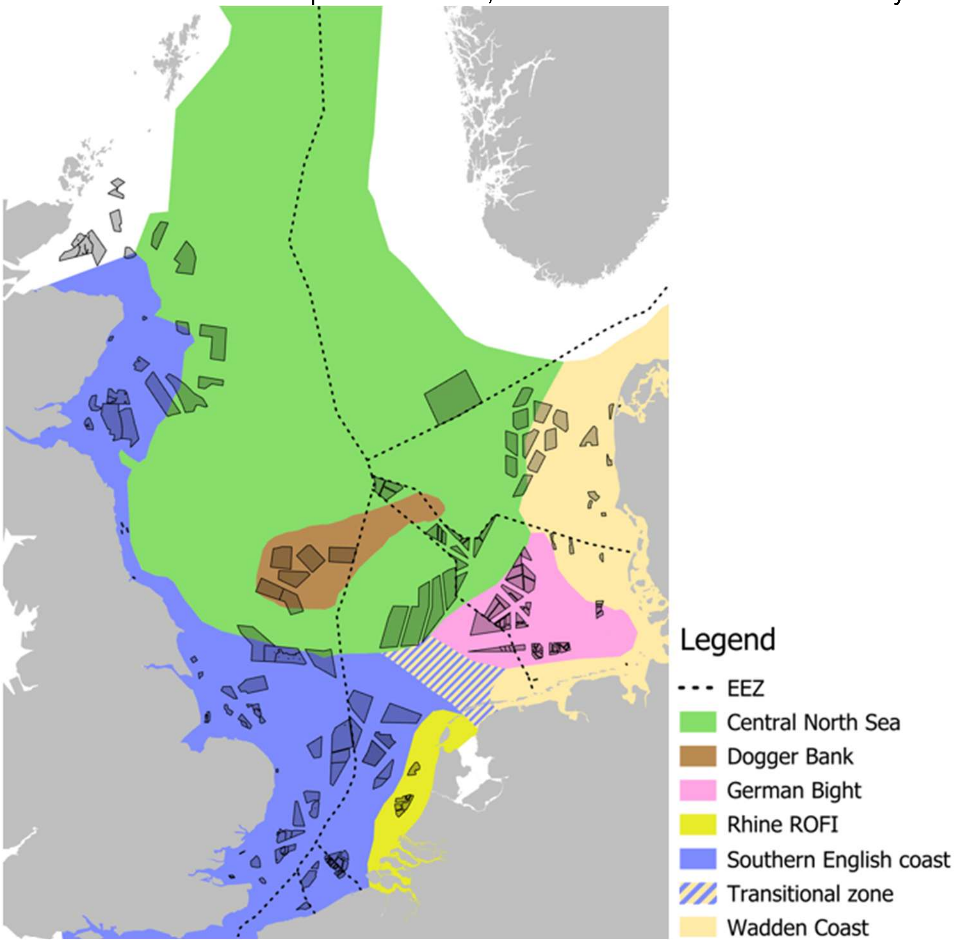

Figure 2.2:The different "impact areas" for Wozep, where impacts of offshore wind differ from each other. (ROFI = Region Of Freshwater Influence)

It was already clear from the previous studies (Van Duren et al. 2021, Zijl et al. 2023, Zijl et al. 2024), that the 'West part of the Dutch EEZ and English coast' (the blue section) and the coastal part along the Wadden Islands are relatively similar in their responses to the implementation of wind farms. The "transitional zone" was inserted in between these areas, where we expect impacts to be similar as in the Wadden Coast and Southern English coast, but it could not really be assessed as in none of the earlier studies this area ever had any wind farms.

3 Method

3.1 Scenario

We used the results from the ‘Partial Revision scenario 1’ from the most recent Wozep scenario report (Zijl et al. 2024) as a basis for the mass balance analyses. This scenario represents the current vision of a posible lay-out of wind farms, operational around 2024. The lay-out of the wind farms is indicated in Figure 3.1. The wind farms are parameterised in this model as a drag force, based on the density and the size of the turbines. The names of the different wind farm and search areas can be found in Appendix A.

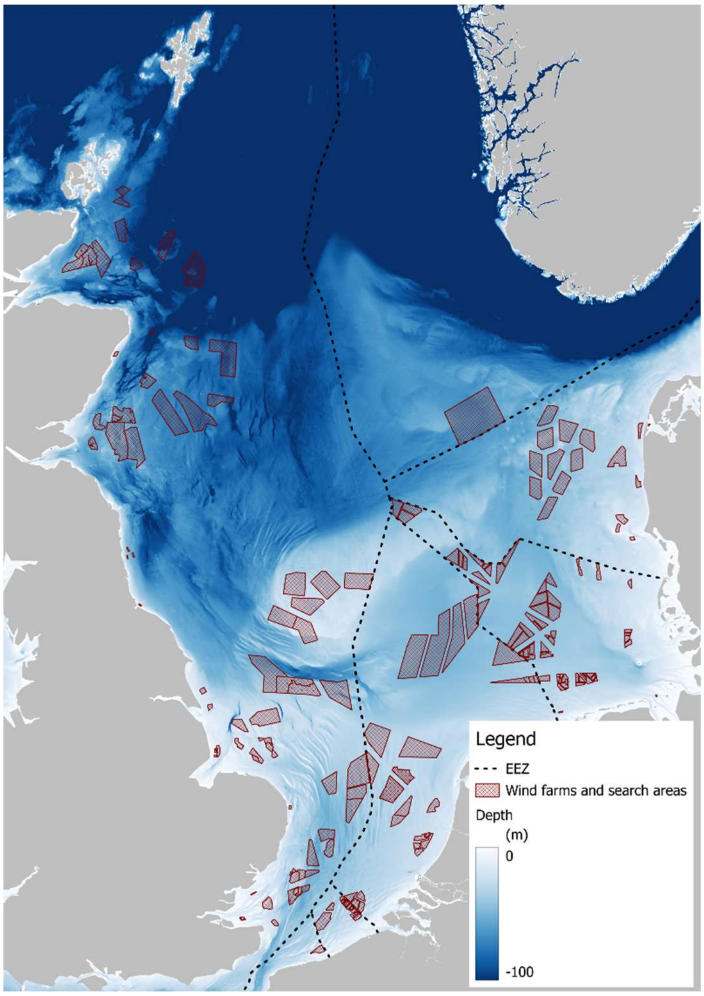

Figure 3.1: Wind farm scenario used for the mass balance analyses.

3.2 Mass balance analyses based on OSPAR regions

The original model yields spatial data on primary production (expressed in gC/m^2/day, phytoplankton biomass (expressed in mg C/l and chlorophyll concentration (expressed in µg/l). North Sea phytoplankton consists of over 30 taxa and hundreds of species (Reid et al. 1990). Each species has a different affinity for different nutrients and light. It is not possible to model each individual species explicitly. In order to capture some of the variability, model includes three dominant species groups (diatoms, green flagellates and dinoflagellates) and each group has algal types that are adapted to low nitrogen concentrations, low phosphate concentrations and low light levels. On top of these nine types, *Phaeocystis globosa* is modelled explicitly as individual species. So, not only overall primary production may vary with environmental conditions, also the species composition may vary, although clearly not the full variability in species diversity is captured. Chlorophyll is often used as a proxy for phytoplankton biomass. However, with shifts in species composition, also changes may occur in the chlorophyll to biomass ratio. Hence both variables are shown and analysed.

These model outputs were transformed into shape files, readable by georeferencing programmes such as QGIS. These data were subsequently spatially averaged over 1) the wind farm outlines and 2) the different OSPAR assessment areas, using the '*Join attributes by location*' function in the QGIS toolbox.

3.3 New Wozep impact area definition

Primary production is the most important factor for ecosystem functioning, as this is the basis for the marine food web. Phytoplankton biomass (expressed as grams carbon) is ultimately the resultant of primary production and phytoplankton mortality (generally the main cause is grazing, but starvation due to lack of nutrients and senescence also contribute).

Using the impacts seen in the wind farms, as well as back ground information on temperature and salinity and depth, we updated the Wozep impact areas. Where appropriate the delineation of the OSPAR assessment areas were followed, as these areas are used for broad scale assessments of Good Environmental Status (OSPAR assessments are used as the basis for MSFD Article 8 reporting) internationally. However, in a few instances it was deemed sensible to deviate from these. The aim of the Wozep impact areas is to communicate which areas respond to the implementation of offshore wind farms in a similar way (due to similarities in the underlying physics).

Where we see fundamental differences in environmental responses within OSPAR areas, the cause of these differences are discussed.

4 Results on the OSPAR assessment areas

4.1 Primary production

4.1.1 Annual average, compared to original model resolution

Figure 4.1A shows the original model results, at the model resolution, of differences in yearly average, depth-integrated primary production between a scenario with offshore wind farms and a situation without. In general, it is possible to see impacts of the presence of wind farms and the far field effects outside the wind farms.

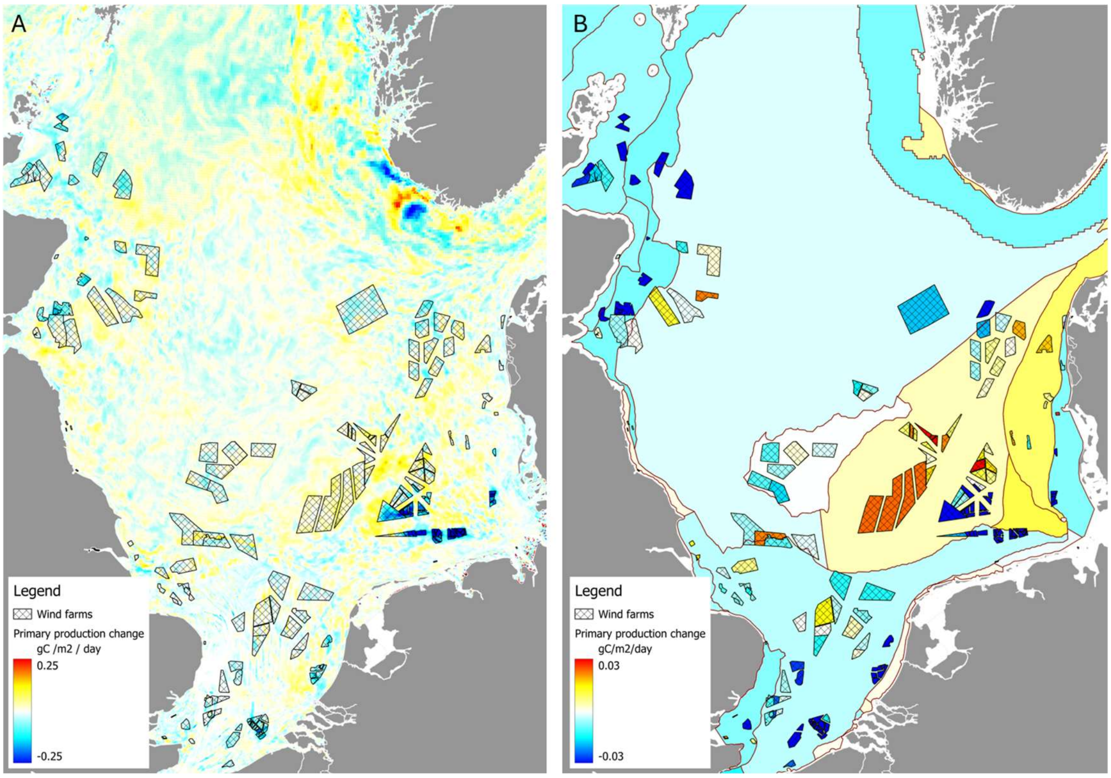

Figure 4.1: A: Original model results on yearly average, depth-integrated primary production, B: Averages within wind farms and averages within OSPAR assessment areas.

Figure 4.1B shows the averages per wind farm and per OSPAR assessment area. Note that the colour scales within figure B are the same for the wind farms and the assessment areas, but differ from the model resolution results in Figure 4.1A. In individual grid cells, impacts on primary production can be very large, but if averaged out over many cells in a region, the differences are much less extreme. Per area the highest increase in primary production can be seen in the German Bight Central area (an increase of 0.01 gC/m^2/day). This is a highly productive area, with an annual average production of 0.47 gC/m^2/day, so the increase in relative terms amounts to about 2%. Note that this is an area that does not contain any wind farms (Figure 2.1) , but is very close to wind farm areas with a strong decrease in primary production. This area appears to profit from compensatory effects, from these nearby wind farms

The seasonally stratified area Eastern North Sea” has on average a small increase (0.004 gC/m^2/day, i.e. a 1% increase). This is an area that contains large offshore wind areas with strong increases (e.g. Search Area 6/7, which increases of 0.024 gC/m^2/day, i.e a 10% increase on average over the total wind farm), but this area also has wind farms with substantial decreases, e.g. the Doordewind+Doordewind West area, which has an average decrease of 0.12 gC/m^2/day (which is a 32% decrease). An overview of all the changes in primary production per wind farm are given in appendix B.1 and the impacts per OSPAR Assessment area are given in Appendix C.1.

Areas with a relatively large decrease in primary production are the intermittently stratified areas near the East Coast of Scotland (0.008 gC/m^2/day, i.e. a 2% decrease over the whole area). The large Northern North Sea area sees a small decrease (0.002 gC/m^2/day, which is only 0.4%). This area is very large. It does contain a few wind farms, some with increases and some decreases in primary production.

The Southern North Sea shows an average decrease of primary production of 0.004gC/m^2/day, i.e. just over 1%. The average primary production rate over the whole area is 0.3 gC/m^2/day, but it is very varied. In the Thames plume, there are large areas with near zero productivity, while in the vicinity of wind farm HKZ, production rates often top 0.75 gC/m^2/day. Impacts within wind farms are mostly decreases of primary production, with a few exceptions, such as IJmuiden Ver (+0.004 gC/m^2/day) and the UK Wind farm Norfolk Boreas (+0.014 gC/m^2/day).

In the OSPAR assessment areas, the Rhine plume, which does not contain any wind farms, sees a small increase (0.001 gC/m^2/day, which amounts to only 0.002%).

On the Dogger bank, the wind farm scenario appears to induce no substantial change in primary production (-0.00007 gC/m^2/day).

4.1.2 Variability over seasons

If we look at the impact of wind farms over different seasons, the most obvious differences can be seen in the Eastern North Sea area (Figure 4.2).

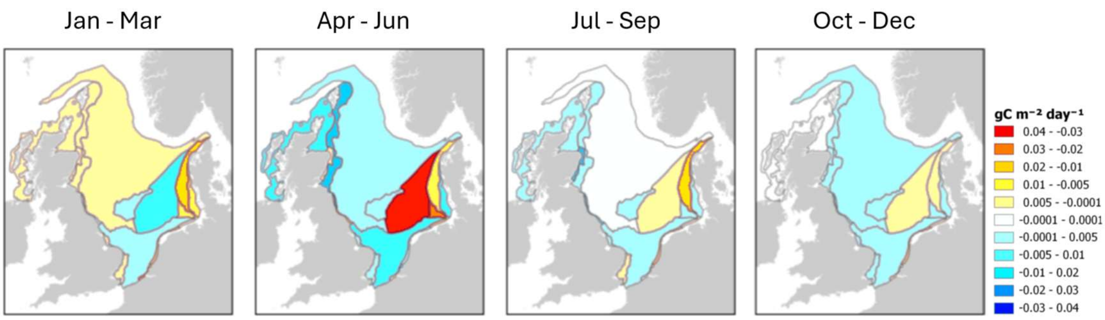

Figure 4.2: Average impacts of offshore wind farms on depth-integrated primary production over the seasons in the different OSPAR assessment areas.

This area shows decreased production in the first three months of the year, when the water column is fully mixed. In this period we see substantial increases of fine sediment in the top layers in this area, increasing light limitation. Once stratification sets in, this switches to a strong increase In primary production (>0.04 gC/m^2/day) in the period of the spring bloom. Once stratification sets in in this part of the North Sea, fine sediment no longer is able to get through the pycnocline and impact the light climate. The increased mixing in and around the wind farms does increase nutrient availability in the upper layers, where there is enough light for photosynthesis, boosting primary production.

The Northern North Sea, Scottish East Coast and adjacent intermittently stratified area all have a slight increase in the first quarter, but see decreases in the other nine months of the year.

Impacts in the Southern north Sea show a decrease year-round and in the outer coastal Danish waters show an increase year-round.

4.2 Total Phytoplankton biomass

4.2.1 Annual average, compared to original model resolution

The pattern of increases and decreases of phytoplankton biomass due to the presence of offshore wind farms (Figure 4.3A and B) more or less follows the pattern of primary production. The main exception is the German Bight, where an annual average decrease can be seen of more than 0.001 mgC/l, which is a nearly 2% decrease over the whole of the area. The highest increases can be found in the German regions with fresh water influence, such as the Ems plume (+ 0.002 mgC/l, i.e. a 2% increase).

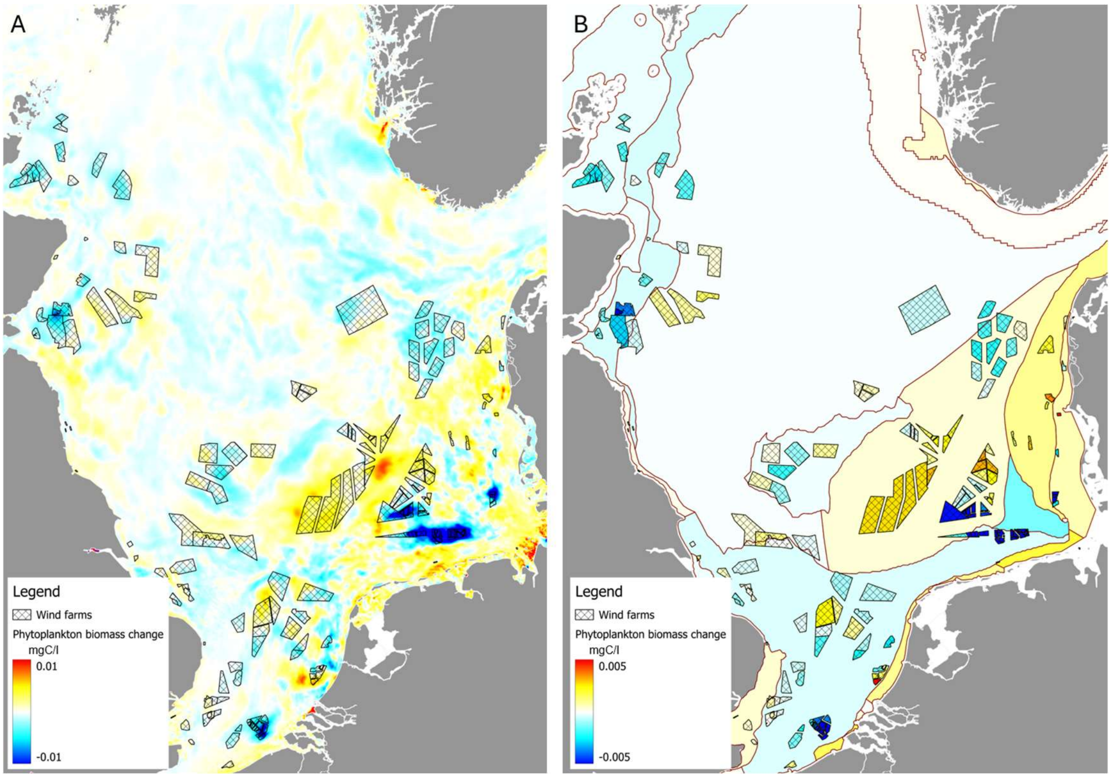

Figure 4.3: A: Original model results on yearly average, depth-averaged phytoplankton biomass concentrations, B: Averages within wind farms and averages within OSPAR assessment areas.

As for the primary production, the Eastern North Sea contains wind farms with strongly differing impacts within the wind farms, but the area on average shows an increase of 0.0004 mgC/l, amounting to about 1%. The central North Sea hardly sees any change on average, while the Southern North Sea has widely differing impacts within the wind farms, but overall sees a decrease of 0.0003 mgC/l (on average 0.6%).

The full details of the absolute and relative changes in phytoplankton biomass in individual Dutch wind farms can be found in Appendix B.2. The full details of the absolute and relative changes in phytoplankton biomass in all OSPAR assessment areas within the North Sea can be found in Appendix C.2.

4.2.2 Variability over seasons

Impacts on phytoplankton biomass (Figure 4.4) show the same seasonal pattern in the Eastern North Sea as it does for primary production. This also goes for the Outer Coastal area of Denmark. However, in most other regions we see decreases in the first, second and last quarter of the year, but an increase in the 3rd quarter of the year (Figure 4.4).

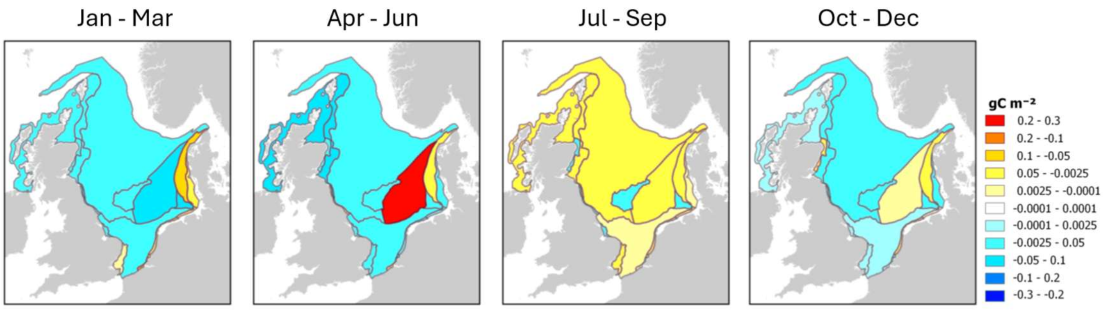

Figure 4.4: Variability of the impact of offshore wind farms on depth-averaged phytoplankton biomass in the OSPAR assessment areas

4.3 Chlorophyll

Chlorophyll is often used as a proxy for phytoplankton biomass, as it is easy to measure, both in the field as well as by e.g. remote sensing. However, the previous Wozep report already indicated that chlorophyll does not always show the same impact patterns as phytoplankton biomass (Zijl et al. 2024).

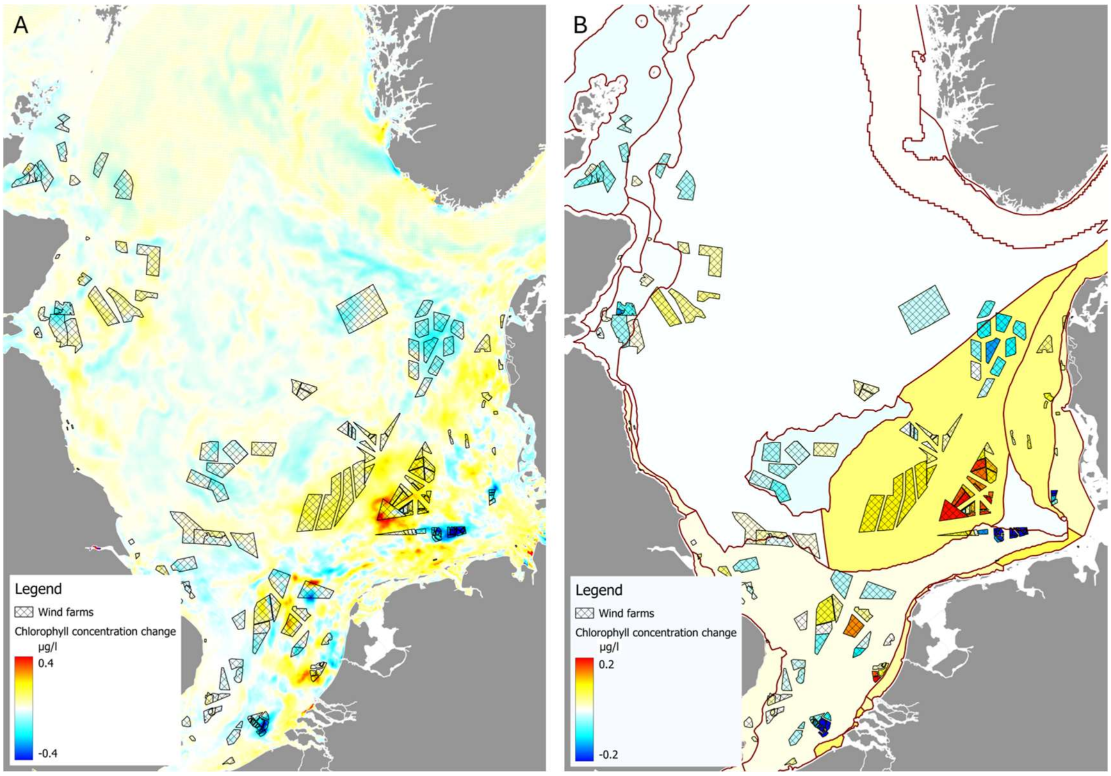

Figure 4.5: A: Original model results on yearly average, depth-averaged chlorophyll concentration, B: Averages within wind farms and averages within OSPAR assessment areas. Note: the changes in chlorophyll concentration in the OSPAR assessment areas and the wind farms in B are on the same scale.

There are clear differences in impacts of wind farms on chlorophyll compared to phytoplankton biomass. While the biomass in the southern North Sea decreases (just like the primary production), the chlorophyll shows an increase of 0.009 µg/l. In relative terms this is a fairly small change of about 0.5%, in comparison to the 5% increase in the Eastern North Sea, but it is opposite. Overall in this offshore wind scenario,chlorophyll concentrations appear to increase the south and south-eastern part of the North Sea and decrease in the north-west.

The full details of the absolute and relative changes in chlorophyll concentration in individual Dutch wind farms can be found in Appendix B.3. The full details of the absolute and relative changes in chlorophyll concentration in all OSPAR assessment areas within the North Sea can be found in Appendix C.3.

5 Impact areas defined on effects of offshore wind farms

5.1 New delineation of Wozep impact areas

A new delineation of the impact areas has been devised. The delineation of the OSPAR assessment areas was the starting point. Based on the results presented above, there are a few areas where there are significant differences.

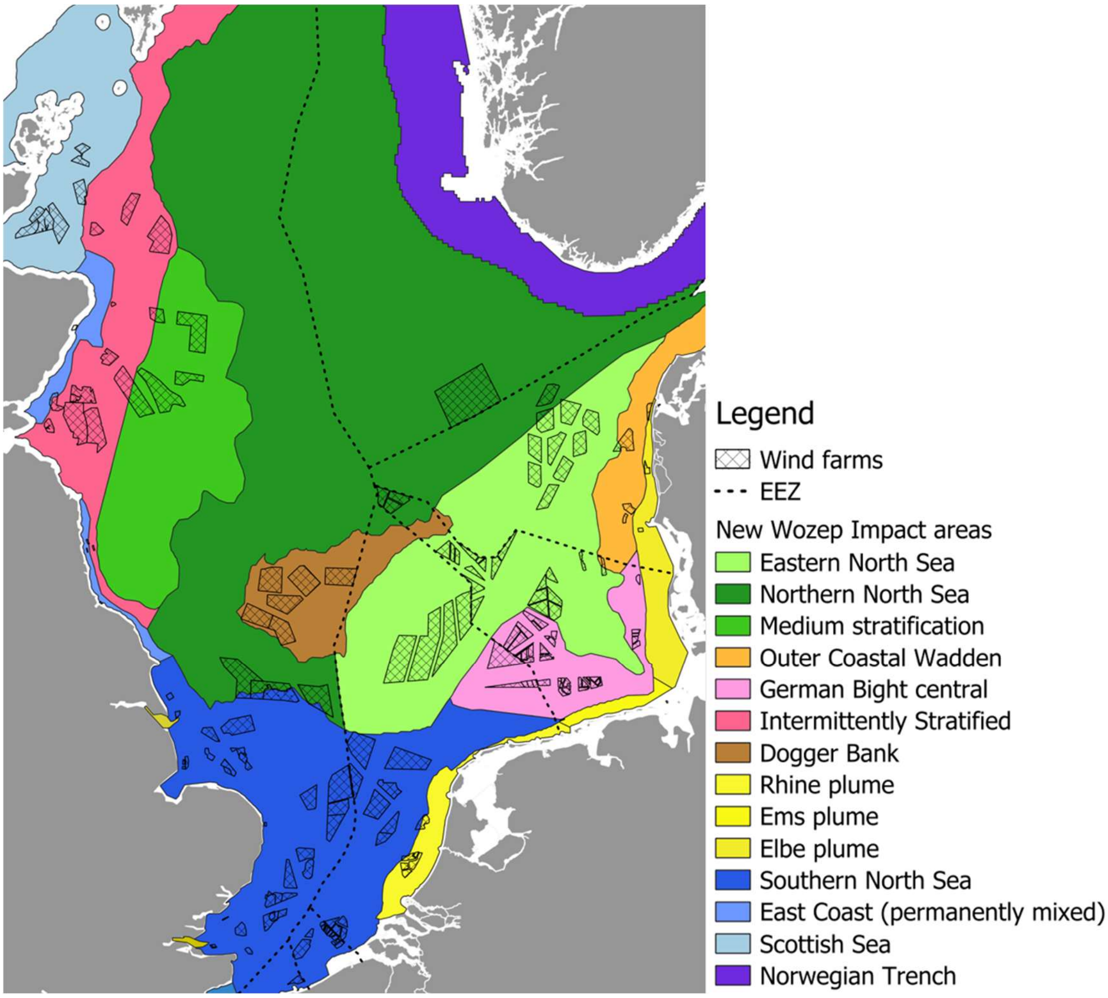

Figure 5.1: New definition of Wozep impact areas.

The most important difference is the separation between the Eastern North Sea and the German Bight. This separation deviates from the OSPAR assessment areas. As seen in Figure 4.1 and Figure 4.3, within the OSPAR assessment area Eastern North Sea there are large differences in impacts of the wind farms. Some areas (such as the Dutch search area 6/7 and some of the northern German wind farms in that area) show increases in both primary production as well as phytoplankton biomass, while some others (e.g. in the Dutch Doordewind and the Gemini farms) impacts are substantial decreases. In the OSPAR assessment areas, the delineation is based on a methodology that involves chlorophyll a, physical conditions such as depth, salinity, stratification and other factors. Appendix E is an excerpt of the common procedure of the Eutrophication Status of the OSPAR maritime area (OSPAR 2022). The underlying model used is the same, although the method for defining regimes is different. The OSPAR method for determining stratification regimes is based on monthly averages. This leads to a typification of the German Bight as seasonally stratified. In animations of day-to-day images of temperature stratification we see in the summer season (e.g. during storms) regular break down of stratification, in the German Bight, while the Eastern North Sea remains stratified throughout the whole summer season. As the Wozep model is based on a finer grid, is more recent and is well validated on stratification, we used this as a basis for delineating the impact areas (mainly along the 0.75 °C annual difference; Figure 5.2A). As we have seen in the analyses in the most recent Wozep scenario report (Zijl et al. 2024), in the areas with stronger stratification (such as search area 6/7), there is more resuspension of fine sediment, but in summer, the stratification is there sufficiently strong to prevent fine sediments to be transported up in the upper water layers. Hence in summer, when primary production is highest, there is no extra light limitation. In the German Bight areas (in the new Wozep impact areas) stratification is diminished far enough by the joint impact of the wind farms, to allow fine sediment to be mixed up into the upper layers and diminish primary production.

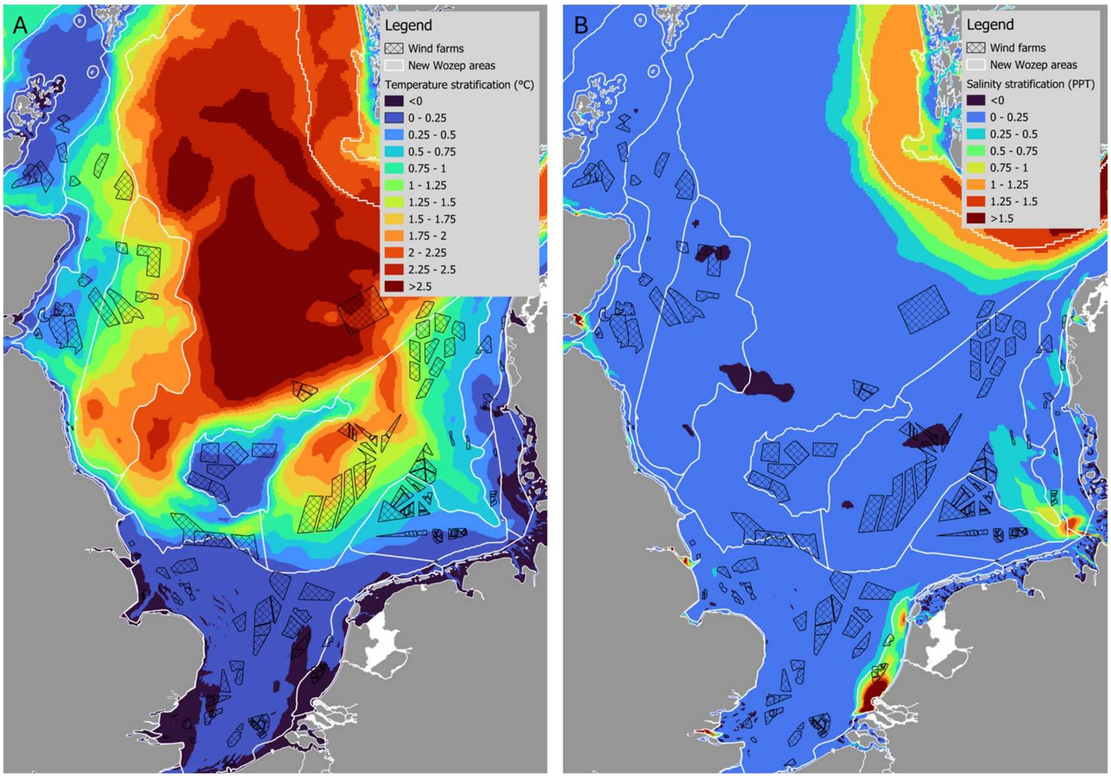

Figure 5.2: A: Annual average temperature stratification (difference in temperature between top and bottom in °C); B: Annual average salinity stratification between top and bottom (difference between bottom and top in PPT). White lines indicate the new Wozep Impact areas.

Also, on the Scottish east coast we had to divert from the OSPAR assessment areas definition. Between the Northern North Sea area (which shows very heavy summer stratification) and the intermittently stratified section (which appears to behave similarly to the German Bight) we introduced an area named Intermittently stratified. The area is summer stratified, but not as extreme as the central part of the Northern North Sea. In behaviour it is similar to the eastern North Sea.

The new Wozep impact areas also differ in the regions of freshwater influence (ROFIs) (i.e. the river plumes. In the impacts we see, effects appear to be related to salinity stratification, rather than vertically averaged salinity. In ROFIs, the water coming in from rivers contains high concentrations of nutrients. If the plume is stratified, the nutrient-rich water is retained in the top layers where there is enough light for primary production. The impact of the wind farms is to increase mixing. This results in nutrients being rapidly distributed in the water column, as well as more fine sediment reaching the upper layers. Hence both light and nutrient limitation are increased, decreasing primary production. The OSPAR assessment areas are delineated on the 32 PSU salinity contour (Louchart et al. 2022, OSPAR 2022), resulting in a definition of the Rhine/Meuse plumes very close to the coast. Their separation is defined on the extension of the WFD water bodies. In the Wozep model we see still significant differences in salinity between bottom and surface up to 50 km offshore, so beyond the wind farms HKZ and HKN (Figure 5.2B). The extent of the plumes of English rivers defined in the OSPAR assessment areas reaches tens of kilometres into the North Sea. The Thames plume is in the OSPAR systematic delineated by the 25 mg/l SPM contour, as this is in those areas most relevant to the eutrophication status. Most of these rivers have a very small discharge in comparison to the Rhine/Meuse, and this is reflected in hardly any salinity stratification in the Wozep model in these plumes. Hence in the Wozep impact areas, we reduced the size of these plumes from English rivers and extended the Rhine ROFI area. The English rivers Thames and Humber can be distinguished in the figure (both mustard yellow), but they are not taken up in the result tables, on account of their tiny size and lack of wind farms.

5.2 Averages per impact area.

5.2.1 Primary production

As in Figure 4.1, Figure 5.3 shows the average impact on primary production per wind farm area and then the average impact per new Wozep Impact area, both on the same colour scale. Note that in the impact areas, as defined in **Error! Reference source not found.**, we have not assessed the impacts in the Norwegian trench. This is an area which does not have any bottom-based offshore wind. Modelled impacts in this area are relatively small but may also partially be caused by model artefact in this area of the North Sea.

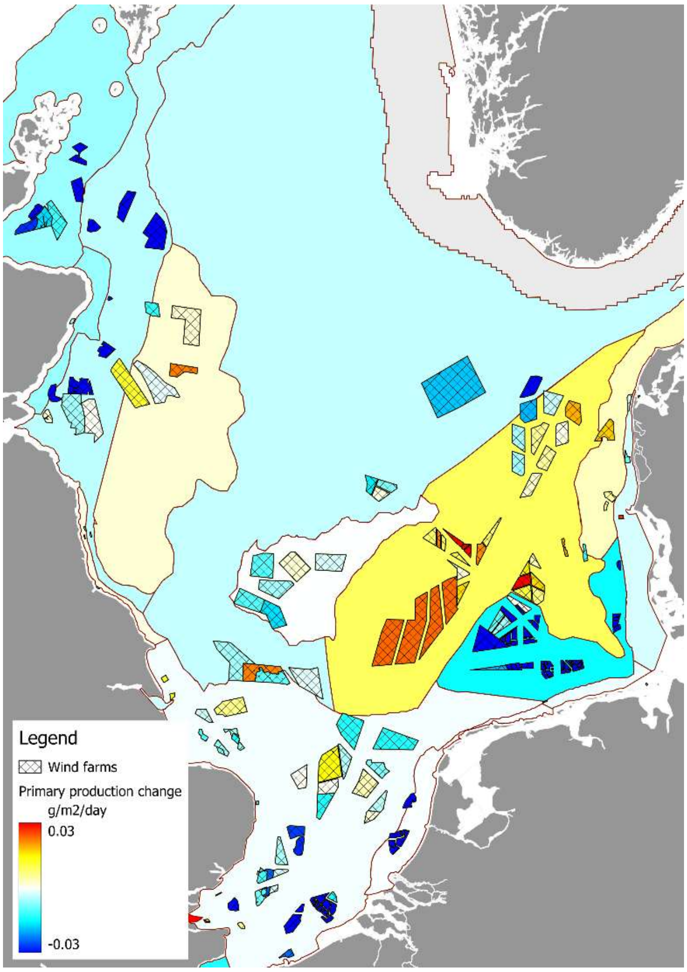

Figure 5.3: Average changes in yearly average, depth-integrated primary production in the wind farms and in the new Wozep impact areas.

Similar to the previous assessments, the Dogger bank shows on average relatively limited effects of the wind farms. Another area where primary production on average is not strongly affected is the Southern North Sea area, despite the fact that most wind farms in this area (with exception of one English wind farm) show moderate to strongly reduced primary production. Although this area is generally not stratified, there is still increased turbulence inside the wind farms, resuspending extra fine sediment and redistributing it is the water column.The average reduction in the whole area is 0.0005 gC/m^2/day, which is less than 0.2%. This area typically sees clear compensation effects outside of the wind farms, which result in relatively minor area-wide impacts, despite some strong local impacts.

In contrast with the southern North Sea impact area, the German Bight impact area, where in nearly all wind farms the impact is a substantial decrease in primary production, on average shows decreased primary production. Averaged over the whole 16718 km^2, the reduction is 0.015 gC/m^2/day (nearly 4% for this area). Clearly in this area compensatory effects of increased production outside the wind farms are not sufficient to outweigh the reduction in and around the wind farms.

The Eastern North Sea area is dominated by wind farms causing an increase in primary production. This also translates in an increase over the whole impact area of 0.01 gC/m^2/day (i.e. a 3% increase). In these seasonally stratified waters, stratification is lessened by the presence of offshore wind farms, but not removed altogether. Dissolved nutrients can more easily penetrate the pycnocline and boost primary production, while particulate material, such as fine sediment cannot transgress the pycnocline and reduce light availability while the system is stratified.

Average impacts in areas in the Northern part of the North Sea are less extreme, but still in the newly defined Medium stratification area, the impact an increase (0.0025 gC/m^2/day, about 0.7%). In the areas closer to the Scottish coast, where in most wind farms reduced productivity is predicted, the averages over the whole impact area is also a decrease (0.0038 gC/m^2/day, i.e. 0.7%.

Full results of absolute and relative changes in primary production in the new Wozep impact areas within the North Sea can be found in Appendix D.1.

5.2.2 Phytoplankton biomass and chlorophyll concentration

Figure 5.4A shows the area-averaged changes in the new Wozep impact areas for depth-averaged phytoplankton biomass. With respect to biomass, area with the largest decrease in primary productivity is the German Bight. Average reduction in phytoplankton biomass amount there to 0.002 mgC/l (nearly 3%).

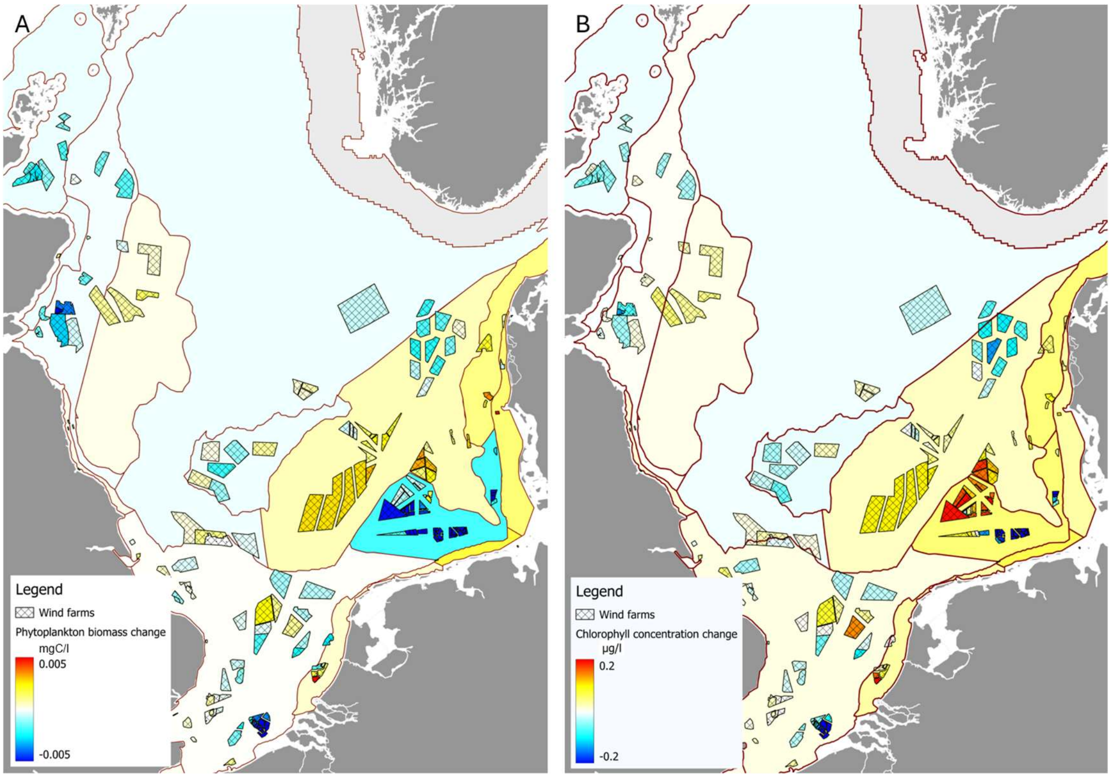

Figure 5.4: A: Average changes in yearly average, depth-averaged phytoplankton biomass in the wind farms and in the associated new Wozep impact areas. B: Average changes in yearly average, depth-averaged chlorophyll concentrations in the wind farms and in the associated new Wozep impact areas.

Neighbouring areas without windfarms, such as the Ems plume, see an increase of a similar magnitude, although that area is clearly much smaller.

The Eastern North Sea area sees an average increase in phytoplankton biomass of about 0.0007mgC/l (1.5%). Although the average change is still an increase, it is notable that in the north-eastern part, the cluster of wind farms there shows a decrease in phytoplankton biomass. Another area where a relatively substantial increase is predicted is the Outer Coastal Wadden area off the Danish coast. This area shows an increase inside the wind farms, as well as an average increase in the area of 0.0012 mgC/l (about 1.3%).

Most other areas show both in absolute and in relative terms much smaller average changes. In the Southern North Sea this is near 0, while most wind farms in the area show clear decreases. Also in the phytoplankton biomass we see clear compensation effects.

In Figure 5.4B we can see that the German Bight area with clear reductions in both primary production and on phytoplankton biomass, has a marked average increase in chlorophyll concentration (0.05 µg/l, close to 3%). While primary production and phytoplankton biomass in the Southern North Sea are very minor, there is still a discernible increase in chlorophyll concentration in this area. Not as large as e.g. in the German Bight, but an increase of 0.01 µg/l, i.e. 0.6%. All other areas show changes in chlorophyll content that are more or less proportional to the changes in phytoplankton biomass.

Full results of absolute and relative changes in phytoplankton biomass in the new Wozep impact areas can be found in Appendix D.2. Full results of absolute and relative changes in chlorophyll concentrations in the new Wozep impact areas can be found in Appendix D.3.

6 Discussion

6.1 Mass balance based on OSPAR assessment areas

The mass balance analyses based on the OSPAR assessment areas did show differences in the responses of different areas. As there is quite some overlap between the previously defined Wozep impact areas and the OSPAR assessment areas, the results are mostly as expected. However, particularly in the southeastern part (German bight and surrounding area) and offshore from the Scottish coast we observed that within the same OSPAR areas we see substantial differences in effects between wind farms. The OSPAR area Eastern North Sea includes wind areas such as Search Area 6/7 and nearby German farms (Appendix A) show in these wind areas strong increases in primary production, while offshore wind farms such as Doordewind, the Gemini farms and some of the German farms immediately east of these show strong reductions. On average over the whole area, the impact is still an increase, but clearly, the conditions in this area are not uniform.

The area that is in OSPAR defined as the German Bight contains no wind farms. The fact that this area sees a (small) increase in primary production is due to compensation effects of wind farms in neighbour areas.

East of Scotland there is an area with moderately strong seasonal stratification, where within the wind farms the impact on primary production is an increase, while in wind farms in adjacent areas effect is a decrease (both in the OSPAR areas Intermittently stratified area and Northern North Sea).

In the Eastern North Sea assessment area, the response of the local system to the presence of windfarms in terms of primary production is a very delicate balance between areas with

1) Sufficiently strong stratification, such that fine sediment is no longer able to penetrate through the pycnocline in the spring and summer months when phytoplankton growth is largest. Here primary production is boosted, because dissolved nutrients can still more easily penetrate into the upper layers.
2) Areas with slightly less strong stratification, where the extra mixing of the wind farms is strong enough to increase fine sediment in the top layers

The demarcation between the two appears to be very sharp.

On the East coast of Scotland we also see in the Northern North Sea section areas with increases of productivity in wind farms and other sections with decreases in wind farms. It appears that fine sediment plays less of a role here – this area of the North Sea sees fewer strong increases in suspended particulate matter (SPM) in the upper layers than the Eastern North Sea/German Bight region, most likely because this area is also supplied with large amounts of fine sediments from riverine origin. Some differences in this area may be caused by the very strong stratification and relatively low flow velocities. In the moderately strongly stratified regions we still see a boost of primary production, but in regions further east in this assessment area, it is possible that stratification is so strong that due to the low velocities, the extra turbulence is not enough to mix enough extra dissolved nutrients up into the upper layers to boost productivity. To further investigate this hypothesis, we would need to investigate changes in vertical gradients of nutrients over time.

6.2 Proposed new impact areas

Because within some OSPAR assessment areas there were sections with contrasting environmental responses, we could not directly use these areas as assessment areas where impacts of offshore wind are similar. However, to easily link with future assessments within the OSPAR framework we used these delineations where possible and made some adjustments where appropriate, for environmental impacts of offshore wind. The most important factor for ecology, particularly for higher trophic levels is primary production. Hence this was the prime impact to delineate the new Wozep impact areas. In most cases changes in primary production in assessment areas are also reflected in phytoplankton biomass. However, not in every case.

Every delineation is to a certain extent arbitrary, and there may be arguments to separate areas differently, or merge areas.

In the newly defined impact areas we see in nearly all wind farms in the Eastern North Sea an increase in primary production, apart from a couple of Danish wind farms, which are close to the delineation between the Eastern North Sea and the Northern North Sea areas. In the annual average stratification contours and the depth contours there were no immediate arguments to change the delineation. However, all the Danish wind farms in that cluster in the eastern North Sea section show decreases in the phytoplankton biomass. Perhaps a closer inspection of seasonal stratification patterns could provide an explanation for this and give arguments to split this impact area in a north-eastern and a southwestern section.

The current delineations in the new Wozep assessment areas are predominantly based on annual average patterns of temperature and salinity stratification. Further assessments should include more attention to seasonal patterns and temporal shifts.

6.3 Impacts in different areas, linked to physical characteristics

As was already found in earlier Wozep studies, the way offshore wind farms impact the lower part of the food web (such as primary production and phytoplankton biomass), is strongly related to the physics of the environment. The impact of the turbines on currents and mixing affect the horizontal and vertical distribution of nutrients and fine sediment, and hence the light regime. Whether there is a net stimulation or a net reduction in primary production by the presence of wind turbines, is highly location dependent.

6.3.1 Stratification

Stratification is an important characteristic, determining amount and timing of phytoplankton growth (Lozier et al. 2011). In salinity stratified areas, fresh water with high nutrient concentrations is kept near the surface and in the light. Increased mixing reduces the nutrient concentration in the upper layer and may also increase the fine sediment concentration, resulting in a decrease of productivity. This is particularly visible in areas such as the Rhine ROFI, where there is still some salinity stratification. In wind farms in these areas we see a strong decrease in primary production and phytoplankton biomass.

Temperature stratification tends to take place in deeper waters, quite often further offshore and hence in areas with more nutrient limitation. In seasonally stratified waters, where stratification is lessened by the presence of offshore wind farms, but not removed altogether, dissolved nutrients can more easily penetrate the pycnocline and boost primary production, while particulate material, such as fine sediment cannot transgress the pycnocline and reduce light availability. This is particularly visible in the Eastern North Sea. In this area the model shows strong increases in SPM concentrations in winter, when the system is fully mixed. As soon as stratifications sets in in April, the resuspended fine sediment is confined to the layers below the pycnocline (Zijl et al. 2024).

An important issue we have not really yet examined, is the impact of changing stratification patterns on the vertical distribution of phytoplankton biomass. In Zijl et al. 2024 we already demonstrated that in Search Area 6/7, where moderate changes in chlorophyll in the upper water layer were seen, the near-bed layer saw nearly a doubling of chlorophyll concentrations. In the stratified areas of the North Sea, commonly deep chlorophyll maxima are observed (Weston et al. 2005), which in turn attract concentrations of zooplankton and also fish (Sharples et al. 2006). Changes in stratification therefore can influence how easily higher (pelagic) trophic levels can capture food, even if impacts on average productivity are minor. We have not yet validated the performance of the model on reproducing the vertical distribution of phytoplankton. Once this has been done, it would be a useful exercise to see how distributions of phytoplankton are affected at larger spatial scales.

One important factor that is at the basis of the delineation of the OSPAR assessment areas is oxygen depletion near the bed. In stratified conditions, oxygen is produced in the upper layers with sufficient light. If this does not get mixed down towards the bed, and respiration rates near the bed (e.g. due to decaying organic material) are high, oxygen can get depleted in the near-bed layer. The OSPAR assessment area “Eastern North Sea” is particularly prone to low oxygen concentrations (OSPAR 2023). The impact of increased mixing, due to the presence of wind farms has until now not yet been explicitly examined, but this ought to be part of future impact assessments. On one hand, the increased mixing should also get more food towards the seabed, but the higher local productivity will increase near-bed respiration. The temporal and spatial scales of these processes is very relevant for ecosystem functioning.

Another issue that would be interesting to examine further is the changes in rates of carbon and nutrient cycling in the different impact areas. The observed changes in primary production indicate that we can also expect changes in rates of carbon fluxes towards the seabed and potentially in sequestration rates. Examination of the remineralisation rates and mass balances of particulate and dissolved carbon (POC and DOC) could provide more insight into this.

6.3.2 Fine sediment, phytoplankton biomass and chlorophyll

The reason for the discrepancies between impacts on chlorophyll and impacts on phytoplankton biomass in some of the regions, lies in the fact that phytoplankton, that is well adapted to growing under light limited conditions, has much higher chlorophyll contents per gram dry weight in comparison to algae that are adapter to e.g. low nitrogen or low phosphate conditions (Geider et al. 1997). In areas where light availability is decreased, we may either see a shift in species that are have a higher chlorophyll content, relative to carbon, or phytoplankton cells can increase their chlorophyll content. Producing a higher chlorophyll to carbon ratio under more light limited conditions is called photo-adaptation (Baumert 1996). This process is also captured in the model (Zijl et al. 2024). However, there is still uncertainty on how well, it is captured in the model. This is one of the processes that still need further validation. This shift in composition is the main explanation why in the new Wozep impact area German Bight we see a clear (and fairly strong) reduction in phytoplankton biomass (in keeping with the impacts on primary production) but an increase in chlorophyll concentrations. Also in e.g. the Southern North Sea, we see on average a near-neutral impact on phytoplankton biomass concentrations, but an increase in terms of chlorophyll. Indeed, any reduction in primary production in wind farms in the southern North Sea can be attributed to an increase in fine sediment in the upper water layers, and hence more light

limitation (Zijl et al. 2024). In the Northern part of the North Sea, the impact on fine sediment in the upper layers is relatively minor.
The fact that we see these discrepancies between phytoplankton biomass and chlorophyll concentration, also on the larger scales and not only within or in the immediate vicinity of certain wind farms, underlines that future monitoring efforts should take into account that chlorophyll is not always a perfect proxy for biomass. However, it is a parameter that can be measured effectively using satellite imaging and other forms of remote sensing, yielding data with higher temporal and spatial resolution than is possible to obtain for carbon biomass observations. Hence chlorophyll will still be an important parameter to evaluate.

The model includes three different main phytoplankton groups, diatoms, green flagellates and dinoflagellates. Shifts between these main groups have not been extensively analysed nor validated in the current model. Shifts between these groups can be very relevant, as some algal groups tend to have more nutritional value than others (Canavate 2019).

6.3.3 Wind farm density and physical properties of the environment

It is clear that the regional impact of wind farms does not only depend on the physical characteristics of the area, but also very much on the turbine density in the wind farms (van Duren et al. 2025), and on the regional density of wind farms. The German Bight area has a very high proportion of wind farm area to total area and indeed sees the strongest reductions. However, other areas with many wind farms in close proximity, such as the Dogger Bank show fairly minor effects, in comparison to the German Bight. The wind farms off the coast of Scotland also form a relatively dense clusters, but the impacts on primary production and phytoplankton biomass are less than in the southern part of the North Sea. This is likely a consequence of the fact this area is deeper and in most places the seabed contains little fine sediment. In the German Bight the density effect of wind farms is particularly strong because impacts on stratification and turbidity interact between wind farms.

6.4 Valuation of effects and policy relevance

It remains very difficult to assess whether certain increases or decreases in e.g. primary production or in phytoplankton biomass are significant in terms of carrying capacity for higher trophic levels or not. However, in the Eastern North Sea Wozep impact area we see an average increase of 3% in primary production over an area of 61167 km^2. This is an area larger than the Dutch EEZ. It amounts to 583 tons of carbon per day that is produced more in this area. If we would define this area differently and only calculate impacts on the southwestern part, impacts on primary production would be a nearly 10% increase, over an area of 34000km^2.

We only analysed annual average impacts on primary production in the Wozep impact areas, to illustrate the effect of how sensitive such analyses are to the choice of size and exact delineation of the areas. The seasonal analysis, based on the OSPAR Assessment areas indicates that in certain seasons (e.g. spring) impacts may be much more pronounced. For the development of an evaluation framework, the temporal impacts certainly need to be taken up.

In the German Bight area (as defined in the new Wozep impact areas) the decrease is -0.015g C/m^2/day (nearly 4%), over an area of 16718 km^2. It is not unlikely that these numbers are large enough to have effects on regional populations of grazers and fish. Exactly how and how much, will strongly depend on how strongly certain species depend on a region and also in which time of year they use the region. Annual averages may be irrelevant for species that only use a region in spring or in late summer.

Capuzzo et al. (2018) analysed patterns of primary production over the period 1988-2013 based on time series of chlorophyll and under water light measurements. They could not directly link the derived decline in primary production to changes in nutrient levels, light availability or temperature increases, due to the lack of direct measurements of primary production in relation to environmental variables. With the development of offshore wind farms and their associated monitoring and research programmes and the recent development in technologies such as FRRF (Kromkamp et al. 2008), as well as new remote sensing technology to measure primary production (Louchart et al. 2022) that make routine field measurements of primary production much more feasible, we can hopefully gain such insights in the near future.

Even for substantial changes in primary production, it is very difficult to predict consequences for individual species, e.g. those with a protection status under Natura2000. However, changes in primary production in different regions of the North Sea over the past 25 years have been linked to reductions in particularly small copepods and in recruitment of several fish species (Capuzzo et al. 2018, Holland et al. 2023). Offshore wind is not the only human activity in the North Sea that can have significant impacts on primary production. Recent work on the potential impact of low-trophic aquaculture (particularly seaweed), has highlighted how quickly upscaling of such activities can lead to significant nutrient and phytoplankton depletion over large areas (Vilmin and Van Duren 2021).

Human use and exploitation of the marine environment is expected to diversify and increase over the coming decades, with the energy transition, the food transition and the nature transition. Having an appropriate framework in place, intrinsically linked to the MSDF, to assess what impacts on primary production and phytoplankton biomass are acceptable, and what is not, in cumulation with other human uses of the marine environment and semi-autonomous impacts such as climate change, will be an important instrument to responsibly manage our seas.

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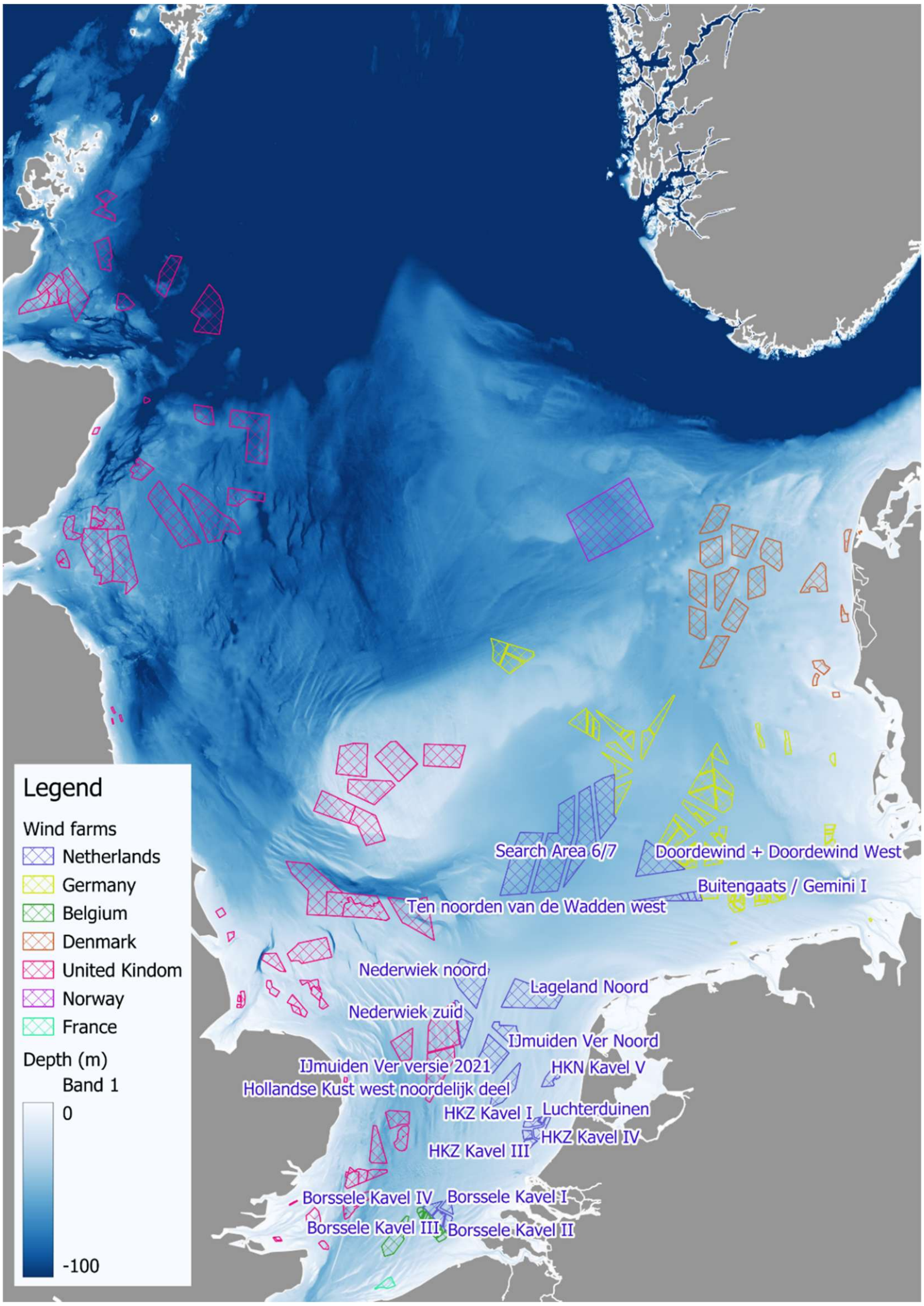
A Names of wind farms and search areas

The map below shows the current names of the wind farms and search areas in the Netherlands and the location of wind areas in neighbouring countries. Note that the names of designated areas and search areas are the names by which they were known early 2024, when this scenario study was carried out. These are subject to change.



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B Detailed results average effects in Wind farms

B.1 Primary production

The table below details the average rates of primary production in the various Dutch Wind farms areas and the changes due to the presence of wind farms in absolute and relative terms.

Name	Reference primary production	Primary production change (absolute)	Primary production change (Relative)
	gC/m2/day	gC/m2/day	%
Borssele Kavel I	0.238	-0.014	-5.8
Borssele Kavel II	0.208	-0.080	-38.3
Borssele Kavel III	0.280	-0.046	-16.3
Borssele Kavel IV	0.319	-0.051	-16.0
Borssele Kavel V	0.112	-0.041	-37.2
Doordewind + Doordewind West	0.372	-0.120	-32.3
Gemini I / Buitengaats	0.453	-0.255	-56.2
Gemini II / Zeeenergie	0.433	-0.189	-43.7
HKN	0.527	-0.064	-12.2
HKZ Kavel I	0.586	-0.038	-6.5
HKZ Kavel II	0.619	-0.088	-14.2
HKZ Kavel III	0.560	-0.082	-14.7
HKZ Kavel IV	0.500	-0.045	-9.0
Hollandse Kust West north	0.403	-0.004	-1.0
Hollandse Kust West south	0.453	0.002	0.5
IJmuiden Ver	0.455	0.004	0.9
IJmuiden Ver Noord	0.412	-0.007	-1.8
Lageland Noord	0.350	-0.013	-3.7
Luchterduinen	0.528	-0.070	-13.3
Nederwiek noord	0.266	-0.013	-4.8
Nederwiek zuid	0.411	-0.004	-1.0
Search Area 6/7	0.257	0.024	9.3
Ten noorden van de Wadden oost	0.464	-0.247	-53.2
Ten noorden van de Wadden west	0.382	-0.019	-5.1

B.2 Phytoplankton biomass

The table below details the average concentrations of phytoplankton biomass in the various Dutch Wind farms areas and the changes due to the presence of wind farms in absolute and relative terms.

Name	Phytoplankton biomass reference	Phytoplankton biomass change absolute	Phytoplankton biomass change relative
	mg/m2	mg/m2	%
Borssele Kavel I	0.048	-0.0037	-7.6
Borssele Kavel II	0.050	-0.0090	-18.0
Borssele Kavel III	0.050	-0.0070	-14.0
Borssele Kavel IV	0.048	-0.0039	-8.1
Borssele Kavel V	0.048	-0.0053	-11.2
Doordewind + Doordewind West	0.044	-0.0049	-11.0
Gemini I / Buitengaats	0.073	-0.0150	-20.7
Gemini II / Zeeenergie	0.066	-0.0073	-11.0
HKN	0.108	-0.0027	-2.5
HKZ Kavel I	0.119	-0.0016	-1.3
HKZ Kavel II	0.119	0.0019	1.6
HKZ Kavel III	0.112	0.0060	5.4
HKZ Kavel IV	0.111	0.0015	1.4
Hollandse Kust West north	0.076	-0.0008	-1.0
Hollandse Kust West south	0.076	-0.0023	-3.0
IJmuiden Ver	0.070	0.0010	1.4
IJmuiden Ver Noord	0.076	-0.0007	-0.9
Lageland Noord	0.070	-0.0007	-0.9
Luchterduinen	0.114	0.0003	0.3
Nederwiek noord	0.043	-0.0009	-2.0
Nederwiek zuid	0.054	0.0011	2.0
Search Area 6/7	0.027	0.0028	10.4
Ten noorden van de Wadden oost	0.070	-0.0123	-17.8
Ten noorden van de Wadden west	0.057	-0.0017	-3.0

B.3 Chlorophyll Concentration

The table below details the average concentrations of chlorophyll biomass in the various Dutch Wind farms areas and the changes due to the presence of wind farms in absolute and relative terms of chlorophyll concentration.

Name	Chlorophyll concentration reference	Chlorophyll concentration change absolute	Chlorophyll concentration change relative
	µg / l	µg / l	%
Borssele Kavel I	1.831	-0.090	-4.9
Borssele Kavel II	1.876	-0.319	-17.0
Borssele Kavel III	1.888	-0.240	-12.7
Borssele Kavel IV	1.674	-0.045	-2.7
Borssele Kavel V	1.847	-0.183	-9.9
Doordewind + Doordewind West	1.041	0.194	18.6
Gemini I / Buitengaats	2.089	-0.006	-0.3
Gemini II / Zeeenergie	1.812	0.108	5.9
HKN	3.218	0.001	0.0
HKZ Kavel I	3.607	0.022	0.6
HKZ Kavel II	3.613	0.164	4.5
HKZ Kavel III	3.571	0.244	6.8
HKZ Kavel IV	3.695	0.081	2.2
Hollandse Kust West north	1.874	-0.012	-0.7
Hollandse Kust West south	2.045	-0.102	-5.0
IJmuiden Ver	1.962	0.039	2.0
IJmuiden Ver Noord	1.682	0.145	8.6
Lageland Noord	2.053	-0.026	-1.3
Luchterduinen	3.653	0.033	0.9
Nederwiek noord	1.181	-0.028	-2.4
Nederwiek zuid	1.559	0.038	2.5
Search Area 6/7	0.508	0.104	20.4
Ten noorden van de Wadden oost	1.944	0.050	2.6
Ten noorden van de Wadden west	1.540	0.085	5.5

C Detailed results of average effects in the OSPAR assessment regions

C.1 Primary Production

The table below details the average rates of primary production in the OSPAR assessment areas and the changes due to the presence of wind farms in absolute and relative terms.

Name	Reference primary production	Primary production change (absolute	Primary production change (Relativ
	gC/m2/day	gC/m2/day	%
Northern North Sea	0.3701	-0.0019	-0.52
Eastern North Sea	0.3410	0.0040	1.18
Dogger Bank	0.2919	-0.0001	-0.02
German Bight (deep)	0.4765	0.0107	2.25
Elbe plume	0.3166	-0.0071	-2.24
Ems plume	0.2352	-0.0009	-0.39
Rhine plume	0.4325	0.0012	0.28
Meuse plume	0.4764	0.0021	0.44
Scheldt plume 1	0.3515	0.0009	0.24
Scheldt plume 2	0.3785	-0.0051	-1.34
Humber plume	0.3151	-0.0050	-1.58
Thames plume	0.3023	-0.0071	-2.34
Southern North Sea	0.3013	-0.0038	-1.27
East Coast (permanently mixed) N	0.4086	-0.0060	-1.46
East Coast (permanently mixed) S	0.3393	0.0014	0.42
Scottish Sea	0.4505	-0.0058	-1.28
Channel well mixed tidal influenced	0.2117	-0.0090	-4.26
Coastal UK channel	0.3602	-0.0053	-1.46
Coastal UK 1	0.4014	-0.0027	-0.68
Outer Coastal DEDK	0.4176	0.0088	2.12
Norwegian Trench	0.7265	-0.0076	-1.05
Skagerak	0.6306	0.0054	0.86
Intermittently Stratified 2	0.4638	-0.0077	-1.66

C.2 Phytoplankton biomass

The table below details the average concentrations of phytoplankton biomass in the OSPAR assessment areas and the changes due to the presence of wind farms in absolute and relative terms.

Nr	Name	Phytoplankton biomass reference	Phytoplankton biomass change absolute	Phytoplankton biomass change relative
		mg/m2	mg/m2	%
1	Northern North Sea	0.0253	-0.0001	-0.22
2	Eastern North Sea	0.0416	0.0004	0.95
3	Dogger Bank	0.0508	-0.0002	-0.30
4	German Bight (deep)	0.0687	-0.0013	-1.91
5	Elbe plume	0.1049	0.0007	0.68
6	Ems plume	0.0820	0.0019	2.29
7	Rhine plume	0.1267	0.0010	0.82
8	Meuse plume	0.1306	0.0000	0.04
9	Scheldt plume 1	0.1392	0.0016	1.12
9	Scheldt plume 2	0.1568	0.0003	0.18
10	Humber plume	0.1078	-0.0001	-0.12
11	Thames plume	0.0934	0.0004	0.47
12	Southern North Sea	0.0557	-0.0003	-0.62
13	East Coast (permanently mixed) N	0.0400	-0.0001	-0.37
13	East Coast (permanently mixed) S	0.0568	0.0002	0.30
14	Scottish Sea	0.0349	-0.0002	-0.48
15	Channel well mixed tidal influenced	0.0239	0.0001	0.42
16	Coastal UK channel	0.0669	0.0002	0.31
17	Coastal UK 1	0.0389	-0.0001	-0.27
18	Outer Coastal DEDK	0.0885	0.0011	1.22
19	Norwegian Trench	0.0125	0.0001	0.56
20	Skagerak	0.0463	0.0002	0.44
21	Intermittently Stratified 2	0.0318	-0.0004	-1.13

C.3 Chlorophyll concentration

The table below details the average concentrations of chlorophyll biomass in the OSPAR assessment areas and the changes due to the presence of wind farms in absolute and relative terms of chlorophyll concentration.

Nr	Name	Chlorophyll concentration reference	Chlorophyll concentration change absolute	Chlorophyll concentration change relative
		µg / l	µg / l	%
3	Dogger Bank	1.0002	-0.0075	-0.75
19	Norwegian Trench	0.3417	0.0014	0.40
12	Southern North Sea	1.6450	0.0090	0.55
4	German Bight (deep)	1.7686	-0.0029	-0.17
16	Coastal UK channel	1.6584	0.0043	0.26
15	Channel well mixed tidal influenced	0.8388	0.0047	0.56
9	Scheldt plume 1	4.1715	0.0567	1.36
5	Elbe plume	3.2405	0.0249	0.77
9	Scheldt plume 2	5.5661	0.0595	1.07
8	Meuse plume	4.9372	0.0289	0.58
7	Rhine plume	3.9732	0.0339	0.85
6	Ems plume	2.9228	0.0679	2.32
11	Thames plume	2.2365	0.0116	0.52
10	Humber plume	3.2179	0.0110	0.34
13	East Coast (permanently mixed) N	1.1718	-0.0021	-0.18
13	East Coast (permanently mixed) S	1.4273	0.0152	1.06
21	Intermittently Stratified 2	0.9047	-0.0032	-0.36
18	Outer Coastal DEDK	2.3951	0.0474	1.98
2	Eastern North Sea	0.9735	0.0517	5.31
17	Coastal UK 1	1.1396	-0.0040	-0.35
1	Northern North Sea	0.6004	-0.0015	-0.25
20	Skagerak	1.1261	0.0051	0.46
14	Scottish Sea	1.0731	-0.0062	-0.58

D Detailed results average effects in the new Wozep Impact areas

D.1 Primary Production

The table below details the average rates of primary production in new Wozep impact areas and the changes due to the presence of wind farms in absolute and relative terms.

Name	Reference primary production	Primary production change (absolute)	Primary production change (Relative)
	gC/m2/day	gC/m2/day	%
Medium stratification	0.373	0.0025	0.67
Eastern North Sea	0.362	0.0095	2.63
Northern North Sea	0.367	-0.0033	-0.91
Outer Coastal Wadden	0.383	0.0038	0.98
German Bight central	0.397	-0.0147	-3.69
Intermittently Stratified	0.448	-0.0038	-0.85
Dogger Bank	0.292	-0.0001	-0.02
Rhine plume	0.474	-0.0003	-0.06
Ems plume	0.235	-0.0009	-0.39
Elbe plume	0.304	-0.0024	-0.78
Southern North Sea	0.294	-0.0005	-0.19
East Coast (permanently mixed) N	0.409	-0.0060	-1.46
East Coast (permanently mixed) S	0.339	0.0014	0.41
Scottish Sea	0.450	-0.0058	-1.28
Norwegian Trench			

D.2 Phytoplankton biomass

The table below details the average concentrations of phytoplankton biomass in the new Wozep impact areas and the changes due to the presence of wind farms in absolute and relative terms.

Name	Phytoplankton biomass reference	Phytoplankton biomass change absolute	Phytoplankton biomass change relative
	mg/m2	mg/m2	%
Medium stratification	0.0244	0.00020	0.84
Eastern North Sea	0.0473	0.00069	1.46
Northern North Sea	0.0252	-0.00015	-0.58
Outer Coastal Wadden	0.0895	0.00120	1.34
German Bight central	0.0656	-0.00182	-2.78
Intermittently Stratified	0.0313	-0.00010	-0.33
Dogger Bank	0.0508	-0.00015	-0.30
Rhine plume	0.1219	0.00046	0.38
Ems plume	0.0820	0.00188	2.29
Elbe plume	0.1062	0.00135	1.28
Southern North Sea	0.0594	0.00005	0.08
East Coast (permanently mixed) N	0.0400	-0.00015	-0.37
East Coast (permanently mixed) S	0.0568	0.00017	0.30
Scottish Sea	0.0349	-0.00017	-0.48
Norwegian Trench			

D.3 Chlorophyll concentration

The table below details the average concentrations of chlorophyll biomass in the new Wozep impact areas and the changes due to the presence of wind farms in absolute and relative terms of chlorophyll concentration.

Name	Chlorophyll concentration reference	Chlorophyll concentration change absolute	Chlorophyll concentration change relative
	µg / l	µg / l	%
Medium stratification	0.5749	0.0083	1.4
Eastern North Sea	1.1122	0.0233	2.1
Northern North Sea	0.5930	-0.0050	-0.8
Outer Coastal Wadden	2.4260	0.0523	2.2
German Bight central	1.9220	0.0541	2.8
Intermittently Stratified	0.8721	0.0035	0.4
Dogger Bank	1.0002	-0.0075	-0.7
Rhine plume	3.8143	0.0341	0.9
Ems plume	2.9228	0.0679	2.3
Elbe plume	3.2563	0.0348	1.1
Southern North Sea	1.6640	0.0106	0.6
East Coast (permanently mixed) N	1.1718	-0.0021	-0.2
East Coast (permanently mixed) S	1.4274	0.0152	1.1
Scottish Sea	1.0731	-0.0062	-0.6
Norwegian Trench	0.3417	0.0014	0.4

E Underlying stratification maps OSPAR

The OSPAR methods for delineation of assessment units for the Greater North Sea is based on the indicator *Chlorophyll a* (OSPAR 2022). The ‘common procedure’ identifies cross-border areas with similar ecological and physical functioning, including depth, salinity, stratification regime chemical and biological factors and anthropogenic pressures. Figure E.1 shows the physical conditions.

Stratification was determined based on the modelled monthly averaged density difference between the top and bottom layer in the model. A grid cell was classified as stratified when the density difference was larger than 0.75 kg m^{-3}.

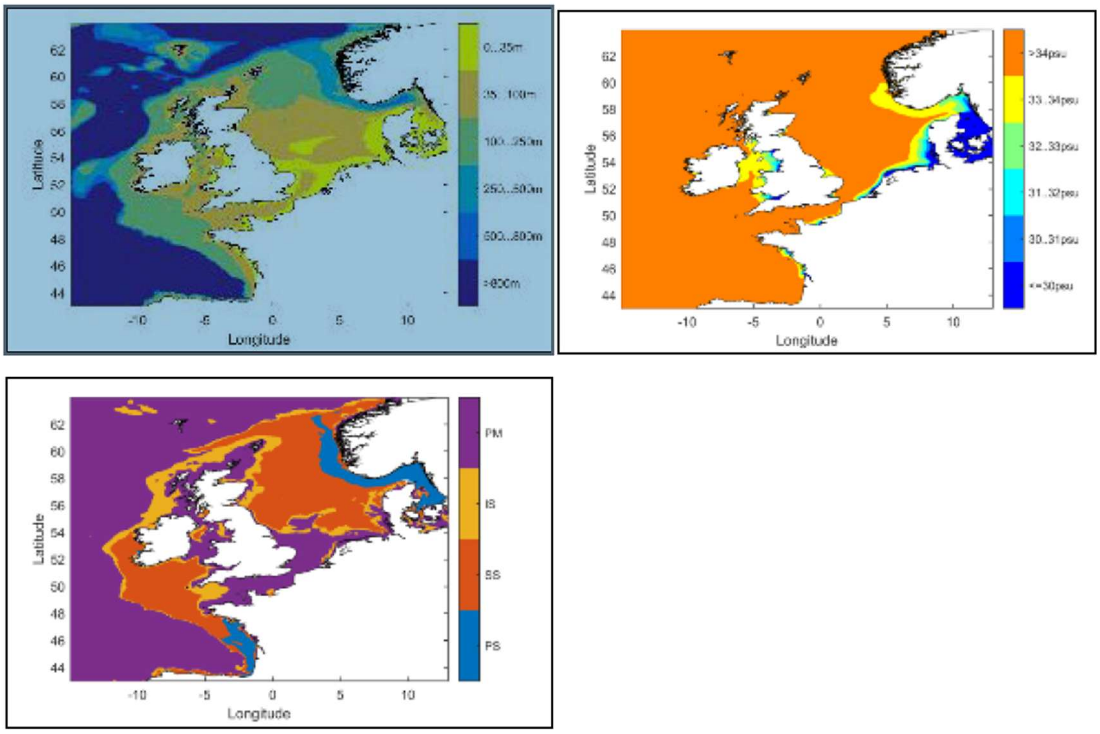

Figure E.1 Physical conditions used to determine the delineation of the OSPAR assessment areas. Top left (a): Depth contours; top right (b): Salinity contours of the modelled salinity in the top layer; bottom (c): Stratification classes: Permanently stratified (PS), seasonally stratified (SS), and intermittently stratified (IS) or permanently mixed (PM)

F Direct comparison old and new delineation Wozep impact areas

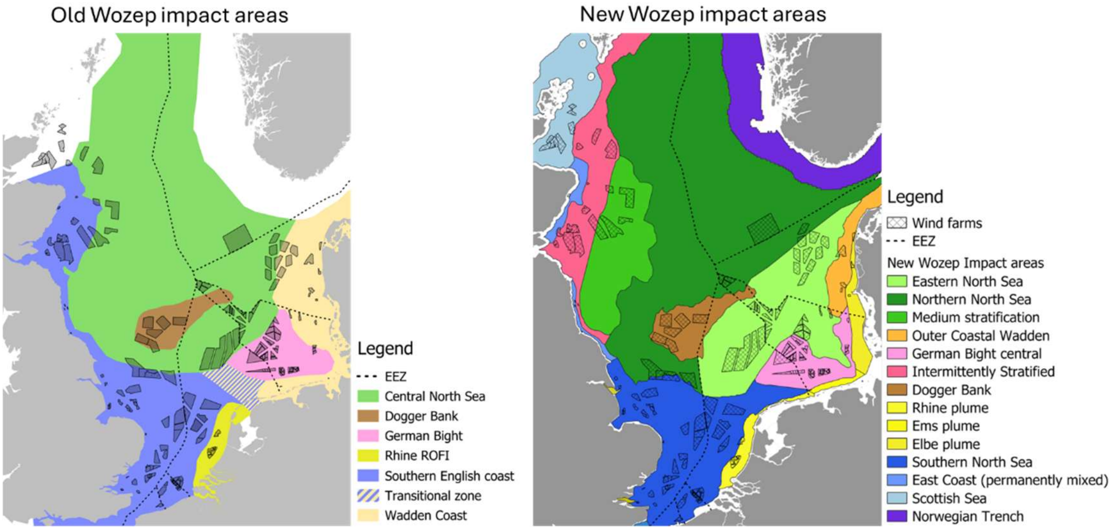

Figure F.1 Side by side comparison of former and current Wozep impact areas

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