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The effect of offshore wind farms on the variation of the phytoplankton population

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A R T I C L E I N F O

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A B S T R A C T

Ocean and coastal areas have the opportunity to harness renewable energy with a rapidly growing rate of investment. Among the categories of marine energy, offshore wind energy produces an enormous amount of electricity for over 15 countries. The devices used for harvesting renewable energy can directly or indirectly affect habitat change, climate change, material-energy cycling, and the development of new communities. Studying their impacts can help fill the knowledge gap related to topics such as global carbon management and the reduction of ecological risks. This study aims to investigate changes in phytoplankton population after offshore wind farm (OWF) construction events at intervals of 2, 4, 7, 11, 18, 30, 50, and 80 days. The wind farms selected for this study are located in the North Sea, which is the most active area for OWF activity. The necessary information for this study was gathered from the Copernicus Marine Environment Monitoring Service (CMEMS) and the 4 C Offshore database. Python package in Jupyter Notebook and SPSS (version 25) were used to identify significant changes with a 95% confidence interval, along with their effect size. The results of the study are reported in four sets based on the eutrophication status of the studied OWFs. The events that have a diminishing effect on the phytoplankton population include foundation installation, array cable installation, and fully commissioning. Turbine installation was the only event where primary producers experienced growth afterward. The occurrence and duration of phytoplankton population changes during different eutrophication zones vary. The findings of this study can be beneficial for governments and various organizations when making decisions about the fishing industry, coastal management, ecosystem-based management, and ecological studies.

1. Introduction

The fact of climate change and the limited source of fossil fuels direct governments toward renewable energy sources (Argin et al., 2019; Dhunny et al., 2020; Emeksiz and Demirci, 2019; Kaldellis and Apostolou, 2017; Kim et al., 2018; Ou et al., 2018; Wang et al., 2019). Ocean and coastal areas provide an opportunity to supply renewable energy (Martínez et al., 2021; Ward et al., 2010). The ocean renewable energy industry can have both positive and negative effects on the marine environment. Therefore, by mitigating the undesirable environmental effects, ocean renewable energy sources help decrease adverse effects (Haraldsson et al., 2020; Martínez et al., 2021; Mendoza et al., 2019; Simmonds and Brown, 2010). Environmental and ecological impacts can occur due to the changes in hydrodynamic behavior caused by marine energy devices (Broadhurst and Orme, 2014). Not much is known about the induced changes of coastal energy-generating infrastructures on beach characteristics, water quality, and species. This lack of knowledge creates a high degree of uncertainty that affects the actions of regulatory agencies, opinions and concerns of stakeholder groups, commitment of energy project developers and investors, and ultimately, the solvency of the industry (Ward et al., 2010). There is a gap in the investigation of the impacts of marine energy harvesting tools on different trophic levels of the food webs during the different phases of these marine energy devices (Gillis et al., 2017; Halpern et al., 2015; Ward et al., 2010). The lack of information needs to be addressed to ensure that these devices do not threat environmental protection through indirect cascade effects within the dynamic and complex marine context (Martínez et al., 2021; Simmonds and Brown, 2010). Thus, understanding the relationship between organisms living on project sites and the activities of non-petroleum offshore energy production is crucial (McClure et al., 2010). Moreover, it is urgent to monitor the effects of ocean renewable energy gathering systems on coastal ecology for global carbon management (Gill, 2005).

Small changes can have an enormous impact on the environment

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(Subramanian, 2012). Physical or chemical changes are related to the biological changes in ecosystems (de Los Santos et al., 2009; Gillis et al., 2014; Wolanski and Elliott, 2016). Mooring operations and deployed operational structures can have environmental impacts, alter habitats, and adversely affect the marine environment, along with climate change, simultaneously (Boehlert and Gill, 2010; Gillis et al., 2014; Martínez et al., 2021). The induced physical changes in benthic zones due to various human-made structures can lead to the development of new communities and alter habitat characteristics, which may also impact the habitat of certain organisms (Boehlert and Gill, 2010; Broadhurst and Orme, 2014; Coates, 2014; Degraer et al., 2019, 2018; Nabe-Nielsen et al., 2018; Petersen and Malm, 2006; Wilding, 2014).

Economic conditions and technological advancements in the wind energy industry are making offshore wind farms (OWFs) increasingly competitive as a clean energy source in the coming decades (Sun et al., 2012). Wind energy, as the primary clean alternative to non-renewable energies, is the most sustainable form of renewable energy, with the lowest greenhouse gas emissions. However, the growing rate of investment in wind energy can have negative impacts on human life and wildlife (de Andrade Meireles et al., 2013; Kumar, 2020; Mendoza et al., 2019; Petersen and Malm, 2006; Saidur et al., 2011; Subramanian, 2012; Sun et al., 2012). The OWF industry, which utilizes high-velocity offshore winds to serve numerous coastal cities, has experienced rapid growth compared to other forms of energy generation (Baidya Roy, 2011; Belu et al., 2017; Haraldsson et al., 2020; Martínez et al., 2021; Mendoza et al., 2019; Reimers et al., 2014).

It is crucial to investigate OWFs to identify potential hidden effects on vulnerable areas. This research is necessary not only to protect the marine environment and ecosystems from negative impacts but also to fill knowledge gaps before construction begins, which can aid decision-making for all marine energy generation devices (Dai et al., 2015; de Andrade Meireles et al., 2013; Esteban et al., 2011; Haraldsson et al., 2020; Lima et al., 2013; Martínez et al., 2021; Mendoza et al., 2019; Mooney et al., 2020; Vanhellemont and Ruddick, 2014; Wang et al., 2019). Due to the dynamic complexity of the ocean and the biodiversity in various habitats, the temporal, spatial, direct, and indirect environmental effects of OWFs are largely unknown. Investigating these effects is of utmost importance in decision-making and policy regulation for governments. Furthermore, mitigating the environmental impacts of these policies is of paramount importance (Martínez et al., 2021).

Depending on local characteristics, the construction and operation of OWFs can have an impact on the ecosystem, both above and below water, by altering trophic levels and biodiversity (Burkhard et al., 2011; Mangi, 2013; Petersen and Malm, 2006). Underwater equipment such as buoys, cables, hard fixed structures, and anchors can affect communities (Boehlert and Gill, 2010). While OWF construction may destroy approximately 1% of the impacted area, it can also create new species by generating new habitats (Petersen and Malm, 2006). Operational OWFs can impact the marine environment and organisms through the generation of magnetic and electromagnetic fields, noise, vibrations at different frequencies, and changes in pressure due to induced noise (Mooney et al., 2020; Petersen and Malm, 2006). OWFs can function as artificial reefs at different scales (depending on size and distance from natural reefs), enhancing seawater filtration rates, biological structures, and influencing the biodiversity, hydrodynamic conditions, composition, and density of species colonizing hard substrates throughout their life stages (Gillanders and Kingsford, 1996; Krone et al., 2013; McClure et al., 2010; Petersen and Malm, 2006). Offshore human-made structures, including OWFs, can alter local food webs and pose a threat to local biodiversity by impacting nutrient cycling and food availability for vertebrates and invertebrates (Krone et al., 2013; Petersen and Malm, 2006). On the other hand, OWFs can also contribute to the emergence of new species through reef species generation, the migration of certain organisms (such as fish species), and the growth of new fish species, which may lead to potential challenges (Bohnsack, 1989; Davis et al., 2000; Petersen and Malm, 2006; Streich et al., 2017).

1.1. Significance of the study

Changes in light energy capture, entropy, carbon production, nutrient intensity and cycling, food web dynamics, current velocity, and biotic diversity induced by OWFs during the construction and operation phases can affect marine habitats and species, including primary producers such as plankton, as well as all other trophic levels of the ecosystem (Burkhard et al., 2011; Mangi, 2013; Silva et al., 2021). Moreover, changes in nutrient cycling resulting from OWFs can have an impact on land areas, exemplified by the reciprocal interaction between primary producers and seabirds (Graham et al., 2018). Ecosystem-based management requires an investigation of how ecosystem elements response to human-induced changes like OWFs, which may persist for about 50 years (Boehlert and Gill, 2010; Mooney et al., 2020). Understanding the effects of OWFs on ecosystem elements is crucial to assess their impacts on the marine ecosystem and address the ambiguity of this topic (Mangi, 2013). Additionally, coastal management can benefit from adopting ecosystem-based measures (Silva et al., 2021), including the management of phytoplankton populations. Recognizing primary productivity and phytoplankton's role as a key component of the marine ecosystem, which helps regulate climate change by consuming CO_2, can greatly contribute to effective ecosystem management (Mooney et al., 2020; Tweddle et al., 2018).

Marine energy structures, along with the communication among different ecosystems, can have both positive and negative effects on marine ecology and various organisms, such as phytoplankton and zooplankton, through direct or indirect changes in the physical and biological properties of neighboring waters, the food web, and primary production during different phases of their life (Boehlert, 2007; Broadhurst and Orme, 2014; Gill, 2005; Gillis et al., 2014; Lima et al., 2013; Martínez et al., 2021; Want et al., 2017; Yin et al., 2004; Zeitzschel, 1978). While the impact of OWF activities on phytoplankton is minimal (Boehlert and Gill, 2010); Raoux et al. (2018) report some ambiguities about the effect of OWFs on plankton (both phytoplankton and zooplankton), claiming that OWFs, in combination with global warming, can decrease plankton biomass. The increased utilization of wind energy has a promising impact on mitigating the negative consequences of climate change (Pryor and Barthelmie, 2010). However, it is important to investigate wind parks due to their potential environmental effects on the food web and biodiversity, such as altering the concentration of incoming sunlight and damaging benthic wildlife (Dai et al., 2017; Thaker et al., 2018). Among studies on the environmental effects of marine energy production, OWFs account for 4.5% of the research, and the number of studies focused on the installation period is less than 4 (Mendoza et al., 2019). The wind farm industry is experiencing rapid development and expansion, especially in UK waters. Therefore, investigating the impacts of OWFs is essential for improving the socio-environmental acceptance of this industry (de Andrade Meireles et al., 2013; Shawn Smallwood, 2017; Simmonds and Brown, 2010; Sun et al., 2012). The purpose of this paper is to investigate the significant changes in the population of primary producers following the construction events of OWFs, focusing on the North Sea as a region of interest. This study can contribute to optimizing the application of OWF technology for clean energy production.

1.2. Primary producers and OWFs

Phytoplankton, which are responsible for almost half of global net primary production (NPP) through photosynthesis, are mostly found in the euphotic zone (Field et al., 1998; Martínez et al., 2021; Turekian et al., 2009; Urry et al., 2017; Zeitzschel, 1978). They play a significant role in biogeochemistry, climate change, carbon regulation, nitrogen cycle, and most of the production of organic carbon in the ocean by transferring atmospheric carbon into the deep ocean (Reynolds, 2006; Sunda, 2012; Turekian et al., 2009; Urry et al., 2017). According to Figure 6 in the study of Martínez et al. (2021), which incorporates findings from 19 refereed articles, plankton can be influenced by various factors, including water quality, entrainment, hydro sedimentation, and energy extraction. The process of photosynthesis, growth, resource utilization (light and nutrients), temperature regulation, and predator avoidance contribute to the success of phytoplankton in producing dissolved organic matter (Aktan et al., 2009; Daly and Smith, 1993; Litchman, 2007). Consequently, any potential changes in phytoplankton can lead to alterations in the cycling and transformation of energy and matter across different biological levels of the marine ecosystem. Changes in light, nutrients, and temperature can influence phytoplankton biomass and their stoichiometric ratio, thereby impacting higher trophic levels in a complex manner (Dickman et al., 2006; Thompson, 2005; Wilhelm and Adrian, 2007). For instance, a decrease in phytoplankton biomass (or primary producers) can affect the fish community (Ybema et al., 2009). Human-made structures have the potential to impact the benthic zone and the ecosystem by altering water circulation and currents (Boehlert and Gill, 2010), which in turn can influence the distribution of phytoplankton (Turekian et al., 2009). OWFs contribute to changes in water turbulence and habitat due to the alteration of wind kinetic energy patterns (blockage effect) (Turekian et al., 2009). Consequently, OWFs can affect the intensity and direction of waves, which subsequently impact water circulation, leading to anomalies for primary producers (Kalvig et al., 2014; Van Nes et al., 2007).

Light is a fundamental factor and a limiting parameter for the growth rate of phytoplankton (Turekian et al., 2009). It plays a crucial role in the photosynthetic activity of photoautotrophic organisms and net primary production (Pratt et al., 2014). According to Turekian et al. (2009), phytoplankton can adapt to low light conditions, such as those found in turbid waters, by adjusting the amount of chloropyll-a (chl-a) per cell. OWFs can impact the environment during both the construction and operation phases, primarily through the introduction of suspended solids. However, the effect diminishes as one moves away from the emission center into larger zones (Burkhard et al., 2011). The presence of suspended materials restricts the availability of light and can regulate phytoplankton production (Cloern, 1987). An increase in suspended particles leads to a decrease in NPP (Pratt et al., 2014). Turbidity exhibits a linear relationship with suspended materials and a non-linear relationship with organic particles and the physical properties of particles (Bright et al., 2020). When combined with water mixing, turbidity has an even greater impact on phytoplankton production compared to its individual effects (Grobbelaar, 2009). Light, inorganic nutrients, and major nutrient elements such as phosphorous, nitrogen, and silicon (Sunda, 2012), along with metal nutrients, particularly iron, are crucial for regulating phytoplankton populations and organic matter production (Tilman et al., 1982). The transport of nutrients into the euphotic zone is influenced by factors such as wind (including upwelling winds), waves, temperature, the initial nutrient concentration, and patterns of material mixing within the water layers (Alonso et al., 2015; Correa-Ramirez et al., 2020; Zeitzschel, 1978). Temperature can potentially limit the growth rate of phytoplankton (Daly and Smith, 1993). It indirectly influences photosynthesis and phytoplankton activity (Venkataraman, 1969) by modulating their respiration covertly (Zeitzschel, 1978). While an increase in temperature may initially benefit phytoplankton to some extent, beyond a certain point, it can have negative effects on phytoplankton (Turekian et al., 2009). Large-scale OWFs can reduce wind speed, leading to a minor increase in water temperature in areas such as lakes due to reduced surface vaporization (Abbasi and Abbasi, 2000). The rapid movement of warm air around wind farm turbines can result in a temperature increase of approximately 0.72°C in the immediate vicinity, particularly during nighttime (Agency, 1996; de Andrade Meireles et al., 2013). Water mixing plays a significant role in high seasonal phytoplankton production (Daly and Smith, 1993), and it can be influenced by factors such as river runoff, land drainage, eddies and turbulence, convective circulation, wave mixing, tidal circulation, coastal upwelling, internal wave mixing, and island circulation (Zeitzschel, 1978). Temperature decreases at the water surface can facilitate water circulation, which brings nutrients to the euphotic zone (Zeitzschel, 1978).

2. Method

The effects of marine energy harvesting devices depend on the area specification (Martínez et al., 2021; Petersen and Malm, 2006) and the function of the device (Martínez et al., 2021). Wind energy is developing in regions such as China, the United States, and the European Union (Boehlert and Gill, 2010; Mooney et al., 2020; Petersen and Malm, 2006; Simmonds and Brown, 2010; Subramanian, 2012). There were 900 wind farms (WFs) just in Europe alone until 2018 (Nabe-Nielsen et al., 2018), as stated by Petersen and Malm (2006). Monitoring of OWF activities before and after construction can be beneficial in reducing wildlife and ecological risks (Walter et al., 2021). During the establishment of marine energy devices, both short-term and long-term impacts should be considered for the different phases of the devices on both plant and non-plant elements of the ecosystem (Martínez et al., 2021). Short-term biodiversity change is highly dependent on the local context (Mangi, 2013). According to Mooney et al. (2020), OWF development can be divided into four phases: site survey, construction, operation, and decommissioning. The construction and decommissioning phases can physically disturb the local environment, while the operational phase can have indirect impacts on species (Gill, 2005).

2.1. Candidate areas

According to Table 1, it is obvious that Europe accounted for over 70% of the installed OWF capacity by the end of 2020. Consequently, the North Sea is a densely populated area in terms of OWF activity. This marginal sea is connected to the ocean through the English Channel in the south and the Norwegian Sea in the north (Xu et al., 2020). In this study, we aim to investigate the short-term response of phytoplankton populations to the induced pressure from OWF construction activities in selected fully commissioned OWF locations in the North Sea.

Comprehensive view the OWFs in the North Sea can be seen in Fig. 1. Among the fully developed OWFs depicted in Fig. 1, which are colored in green, some of them have been selected for this study. The selected areas in this study will each contain only one OWF and will be situated away from other OWFs to minimize the potential impact of different activities on each other. In cases where multiple OWFs exist in a single location, their activities should not overlap temporally to prevent the neutralization or amplification of possible effects. Moreover, the selected locations should not be intersected by vessel traffic routes. Additionally, data accessibility for the chosen areas is an important point.

The selected OWF areas should exhibit homogeneity in various

Table 1
Total OWF installations (in Megawatt (MW)) until the end of 2018, 2019 and 2020 by country and continent (Lee and Zhao, 2021a; Walter et al., 2021).

MW	2018	2019	2020
Total	**22,997**	**29,136**	**35,293**
Europe	**18,280**	**21,903**	**24,837**
United Kingdom	7963	9723	10,206
Germany	6382	7493	7728
Belgium	1186	1556	2262
Denmark	1329	1703	1703
Netherlands	1118	1118	2611
Other Europe	302	310	327
Asia-Pacific	**4687**	**7204**	**10,414**
China	4443	6838	9996
South Korea	73	73	136
Other Asia	171	292	282
Americas	**30**	**30**	**42**
USA	30	30	42

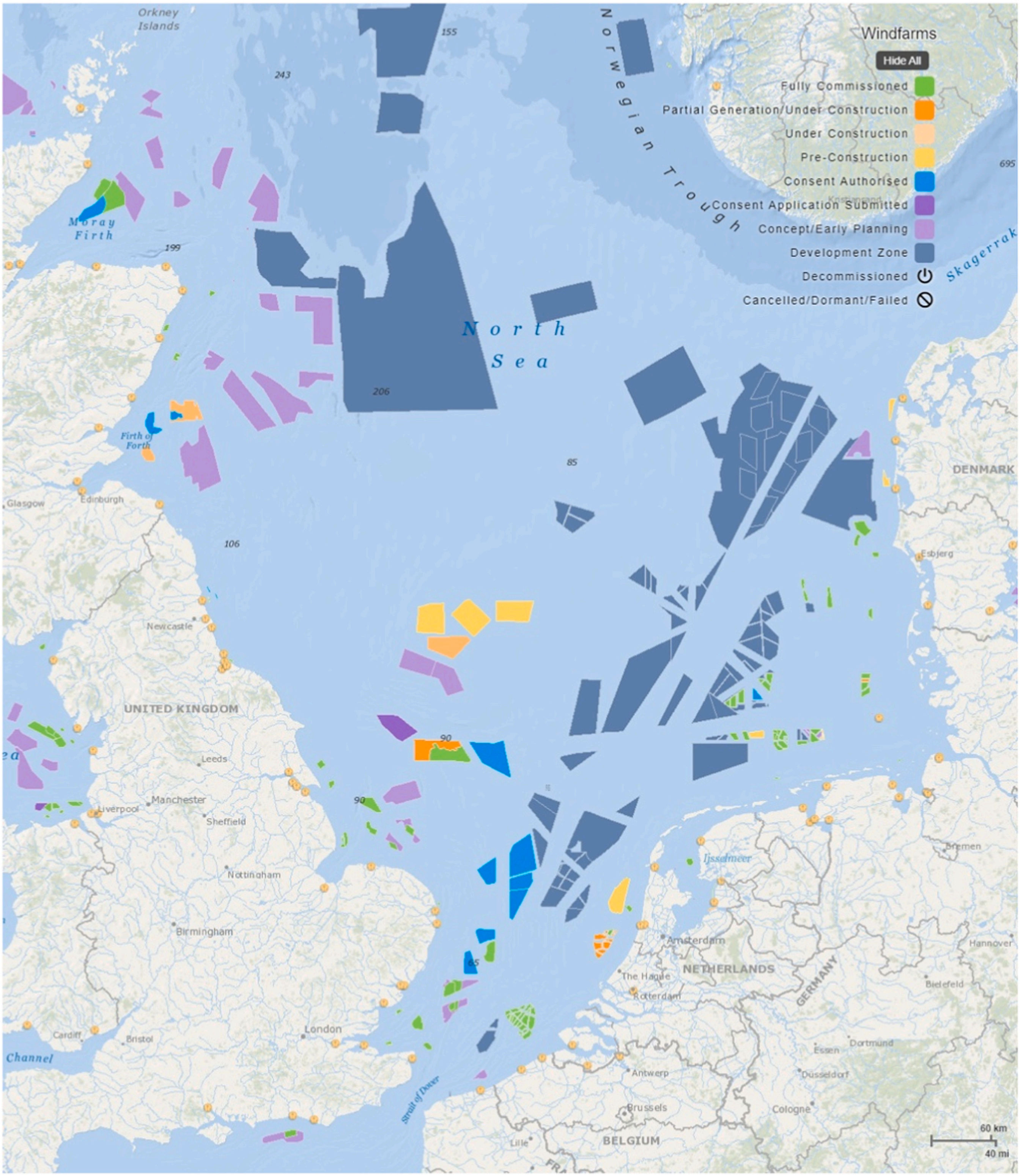

Fig. 1. Broad view of OWFs in the North Sea (https://map.4coffshore.com/offshorewind/).

oceanic parameters that can influence phytoplankton distribution and the ecosystem to ensure reliable study results. A total of 27 parameters (listed in Table 2) are considered locally to determine the selection of study locations, taking into account both human activity and oceanographic characteristics. The corresponding maps for the parameters in Table 2 can be found in the Fig. 2 and the appendix section. Among these 27 parameters and their associated figures, five parameters carry more weight than the others. These five parameters are chlorophyll-a mass concentration (Fig. 2a), net primary production of biomass (Fig. 2b), eutrophication (Fig. 2c), fishing intensity (Fig. 2d), and human vessel trafficking (Fig. 2e). The maps for parameters marked with asterisk (* or **) in Table 2 were visualized using the Python package in Jupyter notebook after averaging the data from 1993 to 2020. Monthly data for parameters marked with a single asterisk (available at depth of 0.494 m

Table 2

Parameters used to select OWF locations (*, **: Data acquired from CMEMS database and visualized by Python package in Jupyter notebook after averaging from 1993 to 2020).

Dumping and placement of wastes or other material	Density ocean mixed layer thickness*	Chlorophyll-a mass concentration**
Marine protected areas	Eastward seawater velocity*	Surface partial pressure of CO_2**
Eutrophication status	Northward seawater velocity*	Nitrate mole concentration**
Bottom fishing intensity (surface and subsurface)	Seawater salinity*	Dissolved iron mole concentration**
Human vessel activities	Sea surface height above geoid*	Net Primary Production (NPP)**
Ports	Sea floor potential temperature*	Dissolved molecular Oxygen**
North Sea inlet rivers	Sea surface temperature*	Seawater pH**
Oil and gas		Seawater Phosphate (PO_4)**
Bathymetry		Phytoplankton concentration**
Streams and their intensity		Seawater Silicate concentration**

with a spatial resolution of 0.083°x0.083°) were obtained from https://resources.marine.copernicus.eu/product-detail/GLOBAL_MULTIYEAR_PHY_001_030/INFORMATION. Monthly data for parameters marked with two asterisks (available at a depth of 0.5058 m with a spatial resolution of 0.25°x0.25°) were obtained from https://resources.marine.copernicus.eu/product-detail/GLOBAL_MULTIYEAR_BGC_001_029/INFORMATION.

Fig. 3 illustrates the chosen locations of the OWFs for this study. These locations are denoted by black rectangles numbered from 1 to 19 in Fig. 3 and will be referred to as NS-01 through NS-19, as listed in Table 3, which also includes their corresponding longitudes and latitudes. These 19 locations represent sites that exhibit the highest conformity with the local parameters listed in Table 2. The average values of the selected 27 parameters in the region of interest are presented in Table 4. Among these parameters, eutrophication is the only one varies across the selected areas. As a result, the OWF locations will be

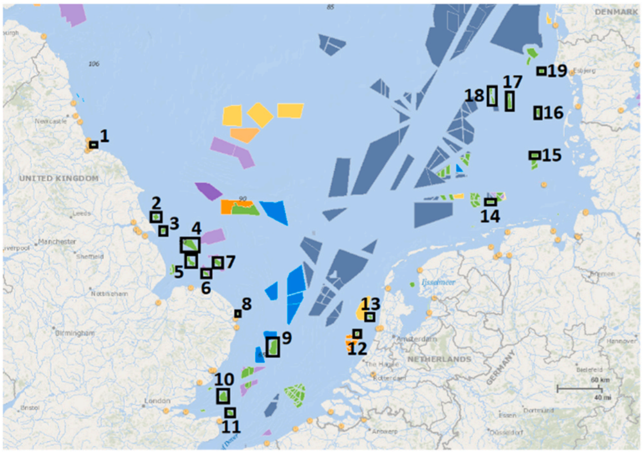

Fig. 3. Candidate OWF locations to investigate (https://map.4coffshore.com/offshorewind/).

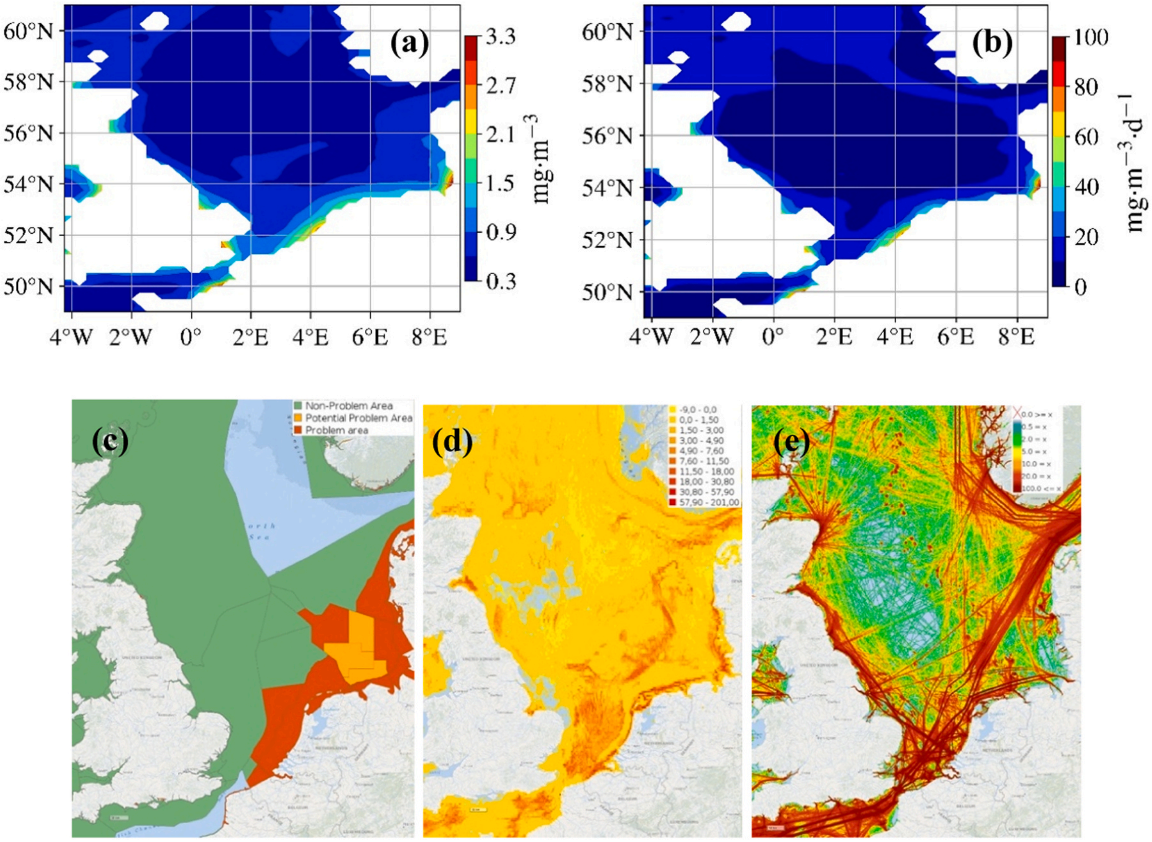

Fig. 2. Important factors in selection of OWF locations through the North Sea: (a) average chlorophyll-a mass concentration, (b) average net primary production, (c) the eutrophication status (https://odims.ospar.org/en/maps/ia2017-eutrophicatio_-of-biscay-20062014_wwz9t/), (d) fishing intensity (https://odims.ospar.org/en/maps/map-bottom-fishing-i_-surface-subsurface_khexe/), and (e) human activities vessel density (https://odims.ospar.org/en/maps/emodnet-human-activi_ng-fishing-2019-map_e522y/).

Table 3
OWF candidates (https://map.4coffshore.com/offshorewind/) and their corresponding longitudes and latitudes.

Name	Included OWFs	Longitude	Latitude
NS-01	Teesside	-1.11969	54.63994
		-1.06270	54.65742
NS-02	Westermost Rough	0.08445	53.76963
		0.21492	53.84424
NS-03	Humber Gateway	0.24788	53.60128
		0.33302	53.67456
NS-04	Triton Knoll	0.68696	53.40791
		0.99183	53.54359
NS-05	Rce Bank	0.75013	53.22085
		0.92866	53.33745
NS-06	Sheringham Shoal	1.07639	53.09695
		1.21922	53.17522
NS-07	Dudgeon	1.31672	53.21142
		1.44993	53.31738
NS-08	Scroby Sands	1.76878	52.62537
		1.80860	52.66313
NS-09	East Anglia ONE	2.40736	52.14620
		2.57078	52.33122
NS-10	London Array	1.40093	51.57125
		1.57259	51.70250
NS-11	Thanet	1.56747	51.40186
		1.68695	51.46180
NS-12	Eneco Luchterduinen	4.12531	52.37472
		4.20908	52.43504
NS-13	Egmond aan Zee	4.34465	52.57409
		4.46275	52.63580
NS-14	Nordsee ONE	6.74158	53.95572
		6.90088	54.00000
NS-15	Amrumbank West	7.63697	54.50318
		7.77155	54.53985
NS-16	Butendiek	7.73364	54.96194
		7.80642	55.06194
NS-17	Dan Tysk	7.16235	55.06315
		7.25161	55.23971
NS-18	Sandbank	6.79568	55.11423
		6.91241	55.29917
NS-19	Horns Rev I	7.79260	55.46534
		7.88599	55.50736

categorized into three different eutrophication statuses for further investigation, as indicated in Fig. 2c.

2.2. Data gathering and analyzing

In this study, we require two categories of data for the candidate areas. The first category pertains to OWF data, while the second category focuses on measurements related to phytoplankton. OWF data can be obtained from the 4 C Offshore database (https://map.4coffshore.com/offshorewind/). Phytoplankton-related data will be collected from the database of CMEMS (Copernicus Marine Environment Monitoring Service). Chl-a serves as a reliable indicator of phytoplankton abundance, regardless of size (Turekian et al., 2009). The data acquired for this study consists of daily, fine-processed level 4 (L4) chl-a means, with a resolution of 0.25°x0.25° at a depth of 0.5058 m. The daily data package with these characteristics from CMEMS is available from January 1993 until the end of 2020 (https://resources.marine.copernicus.eu/product-detail/GLOBAL_MULTIYEAR_BGC_001_029/INFORMATION).

Table 4
Average values of different parameters through the selected OWF locations.

Parameter	Value
Bottom fishing intensity	-9 – 300
Bathymetry	21 – 40 m
Chl-a mass concentration	0.6 – 2.4 $mg.m^{-3}$
Ocean mixed layer thickness	0 – 30 m
Surface CO_2 partial pressure	34.5 – 39 Pa
Nitrate mole concentration	0 – 4 $mmol.m^{-3}$
Dissolved Iron concentration	0.0016 –0.004 $mmol.m^{-3}$
Net Primary Production	10 – 50 $mg.\ m^{-3}.d^{-1}$
Eastward seawater velocity	-0.06 – 0.06 $m.s^{-1}$
Northward seawater velocity	-0.08 – 0.08 $m.s^{-1}$
Dissolved molecular Oxygen	273 – 285 $mmol.m^{-3}$
Seawater ph	8.055 – 8.07
Seawater Phosphate (PO_4)	0 – 0.3 $mmol.m^{-3}$
Phytoplankton concentration	2 – 5 $mmol.m^{-3}$
Seawater salinity	31.5 – 34.5 psu
Sea-surface above geoid	-0.4 – – 0.24 m
Sea floor temperature	9 – 13.5°C
Water silicate concentration	2.5 – 5 $mmol.m^{-3}$
Sea surface temperature	10.8 – 12.4°C

The analysis of the L4 CMEMS data enables the investigation of the potential impact of induced pressure on the phytoplankton population. Subsequently, the statistical analysis of the L4 CMEMS data will be conducted to identify any potential effects on changes in phytoplankton abundance following different OWF construction activities. These effects will be examined across four categories based on the eutrophication status of the selected OWF locations. The first category examines the possible effects without considering the eutrophication status. The second, third, and fourth categories investigate the potential effects within non-problematic (NP), potential problematic (PP), and problematic (P) areas, respectively.

Despite lockdown measures in sectors such as transportation and supply chain (Eroğlu, 2020; Lee and Zhao, 2021a), the offshore wind industry was not significantly impacted by the COVID-19 pandemic (Lee and Zhao, 2021a). Many countries provided incentives for the energy sector, recognizing it as a fundamental need, allowing the industry to continue operations in 2020 without significant delays (Walter et al., 2021). During the second half of 2020, the market successfully overcame potential negative effects caused by COVID-19 (Lee and Zhao, 2021b). In fact, 2020 became the second-best year globally in terms of financing for the industry (Lee and Zhao, 2021a). However, the full extent of the pandemic's impact on the offshore wind industry remains unclear (Walter et al., 2021). Given the relatively insignificant effect of COVID-19, data required for this study was obtained for each of the 19 candidate locations (NS-01 through NS-19) from 1993 to the end of 2020.

For most of the OWF construction events, the 4 C Offshore database provides the respective start and finish dates. Therefore, the beginning and ending dates of different events will be considered to analyze short-term effects. In this study, events with a frequency of less than five will be excluded. Specifically, only events occurring between the start of offshore construction and the fully commissioning dates will be considered, while activities outside of this interval will be disregarded. The average amount of chl-a will be statistically compared before and after offshore construction activities using SPSS (Statistical Package for Social Sciences). In the SPSS analysis, the Shapiro-Wilk test will be employed to assess the normality of the data, with a significance level of $p \leq 0.05$. If the data is normally distributed, a paired samples t-test will be utilized. Otherwise, the Wilcoxon Signed Ranks nonparametric test will be employed. The statistical tests will be conducted with a 95% confidence level to explore potential impacts during eight different time intervals after the announcement date (as provided by the 4 C offshore database) for the start and completion of each construction event. These time intervals will commence from the announcement date and last for 2, 4, 7, 11, 18, 30, 50, and 80 days thereafter. For instance, in the case of a 7-day interval, if offshore construction for an OWF started in 2009 and turbine installation activity was completed on July 13, 2011, the average chl-a will be evaluated for each 365-day period of the year by averaging the chl-a values from the start of 1993 until the end of 2007 (using the Python package in Jupyter notebook) for that specific OWF. The average chl-a amount for July 13, 2011 through July 20, 2011, as well as for July 13 through July 20 for 15 years (1993–2007), will be calculated for the farm. Then, the average chl-a for other OWFs will be calculated for their respective turbine installations occurring within a seven-day window. Finally, the obtained p-value (from either the paired samples t-test or the Wilcoxon Signed Ranks non-parametric test) and Cohen's d parameter (with standard deviation as the standardizer) will indicate whether turbine installation has an effect on chl-a after one week or not, provided that the number of finishing turbine installation announcements for all 19 areas is not less than five.

3. Results

The results of the analyzed data from CMEMS, in accordance with the event announcements in the 4 C Offshore database and considering the eutrophication status, will be presented in this section. This study will investigate all construction events of NS-01 through NS-19 that occur with a frequency of more than four times (Table 5). The sample size, indicating the number of occurrences for each event (start and completion), in relation to the eutrophication status, can be found in Table 6. The results for each event will be classified into four categories based on the eutrophication status of the areas where the OWF candidates have been established.

Based on the sample size of the events in Table 6, they were analyzed without taking into account the eutrophication status of the OWF locations. After performing computations using Python and SPSS, Table 7 presents the results of the statistical analysis in terms of p-values. For p-values ≤ 0.05, the calculated Cohen's d value can be found in Table 8.

For the events with a sample size of ≥ 5 (as indicated in Table 6) in OWFs located in non-problematic eutrophication areas, Table 9 displays the magnitudes of the p-values. Table 10 presents the relative Cohen's d values for events with p-values ≤ 0.05 from Table 9.

The statistical analysis p-values for the construction events (with a sample size ≥ 5 in Table 6) of OWFs established through the potential problematic parts can be found in Table 11. The Cohen's d value of the events with a p-value of ≤ 0.05 can be seen in Table 12.

The statistical analysis p-values for construction events of candidate locations (with a sample size ≥ 5 in Table 6) that have problematic eutrophication status are presented in Table 13. The corresponding Cohen's d values for p-values ≤ 0.05 in Table 13 can be found in Table 14.

4. Discussion

Tables 7–14 provide important information regarding the significance of changes in phytoplankton (or chl-a) abundance and its strength following the events listed Table 5. The p-values and Cohen's d values play a crucial role in this determination. A p-value of ≤ 0.05 indicates a significant change in the phytoplankton population, while a larger Cohen's d value signifies a greater effectiveness or effect size. When considering Cohen's d values, it is worth noting that according to Cumming and Calin-Jageman (2017), values of $d = 0.2$, $d = 0.4$, and $d = 0.6$ are typically regarded as indicating small, medium, and large effect sizes, respectively. During the statistical analysis, the post-event parameters were subtracted from pre-event parameters when necessary. Therefore, a negative sign in the Cohen's d value implies an increment in phytoplankton magnitude.

According to Table 7, the phytoplankton population undergoes changes following the initiation of Foundation Installation (FI) and the

Table 5
OWF construction events to investigate.

Meteorology Mast Installation (MMI)
Array Cable Installation (ACI)
Export Cable Installation (ECI)
Foundation Installation (FI)
Turbine Installation (TI)
Offshore Substation (OS)
Construction - Seabed Preparation (CSP)
Generating Power (GP)
Fully Commissioning (FC)

Table 6
Start and completion number of events trough all Table 3 and according to eutrophication (S = Start, F = Finish, *: will dismiss because it is less than 5, •: Either starting or finishing is valid for the event).

Event	All OWFs		Non Problematic		Potential Problematic		Problematic	
	S	F	S	F	S	F	S	F
MMI	1*	7	1*	4*	0*	0*	0*	3*
ACI	11	23	9	12	1*	7	1*	4*
ECI	15	17	13	12	1*	1*	1*	4*
FI	16	68	12	39	1*	14	3*	15
TI	13	84	11	49	1*	18	1*	17
OS	7	10	5	6	0*	3*	2*	1*
CSP•	7		5		1*		1*	
FC•	18		10		3*		5	
GP•	37		23		8		6	

Table 7
p-value of events within NS01 – NS19 without eutrophication (S = Start, F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
MMI	F	0.61	0.50	0.40	0.40	0.13	0.06	0.40	0.87
ACI	S	0.06	0.15	0.31	0.31	0.29	0.17	0.16	0.30
	F	0.24	0.22	0.25	0.24	0.19	0.23	0.52	0.90
ECI	S	0.61	0.65	0.55	0.51	0.34	0.39	0.53	0.65
	F	0.94	0.84	0.72	0.69	0.79	0.59	0.29	0.79
FI	S	0.35	0.22	0.09	0.03	0.16	0.35	0.53	0.80
	F	0.41	0.35	0.32	0.21	0.22	0.25	0.11	0.08
TI	S	0.38	0.35	0.46	0.65	0.86	0.92	0.86	0.55
	F	0.02	0.04	0.05	0.04	0.08	0.06	0.06	0.01
OS	S	0.94	0.98	0.98	0.84	0.92	0.85	0.93	0.46
	F	0.09	0.11	0.11	0.17	0.24	0.72	0.72	0.88
CSP		0.40	0.31	0.40	0.24	0.61	0.40	0.87	0.40
FC		0.09	0.16	0.40	0.37	0.31	0.21	0.10	0.62
GP		0.62	0.97	0.50	0.31	0.23	0.40	0.80	0.48

Table 8
Cohen's d number for p-value ≤ 0.05 of Table 7 in the case of events within NS01 – NS19 without eutrophication (S = Start, F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
FI	S	–	–	–	0.59	–	–	–	–
TI	F	-0.27	-0.23	-0.22	-0.22	–	–	–	-0.27

Table 9
p-value of events within OWFs located in non-problematic eutrophication part of the North Sea (S = Start, F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
ACI	S	0.09	0.09	0.44	0.51	0.27	0.44	0.44	0.86
	F	0.69	0.69	0.81	0.75	0.81	0.94	0.64	0.03
ECI	S	0.36	0.29	0.25	0.23	0.12	0.20	0.25	0.38
	F	1.00	0.94	0.69	0.69	0.88	0.94	0.94	0.64
FI	S	0.94	0.86	0.44	0.18	0.56	0.68	0.82	0.75
	F	0.05	0.03	0.04	0.03	0.03	0.03	0.01	0.01
TI	S	0.66	0.59	0.86	1.00	0.66	0.66	0.53	0.29
	F	0.21	0.29	0.13	0.13	0.18	0.05	0.04	0.01
OS	S	0.69	0.69	0.69	0.89	0.89	0.65	0.69	0.35
	F	0.07	0.07	0.12	0.12	0.12	0.46	0.35	0.35
CSP		0.35	0.22	0.22	0.08	0.50	0.50	0.89	0.50
FC		0.01	0.05	0.24	0.20	0.33	0.17	0.09	0.65
GP		0.67	0.86	0.65	0.37	0.14	0.22	0.95	0.82

Table 10
Cohen’s d number for p-value ≤0.05 of Table 9 events for OWFs located in non-problematic eutrophication zone (F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
ACI	F	–	–	–	–	–	–	–	0.63
FI	F	0.33	0.35	0.34	0.36	0.37	0.37	0.44	0.43
TI	F	–	–	–	–	–	-0.28	-0.29	-0.41
FC		0.79	0.63	–	–	–	–	–	–

Table 11
p-value of events within OWFs located in potential problematic eutrophication part of the North Sea (F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
ACI	F	0.24	0.13	0.13	0.09	0.13	0.03	0.02	0.01
FI	F	0.02	0.01	0.01	0.01	0.03	0.02	0.04	0.06
TI	F	0.92	0.78	0.73	0.83	0.78	0.78	0.81	0.31
GP		0.48	0.78	0.78	0.89	0.89	0.40	0.89	0.78

Table 12
Cohen’s d number for p-value ≤0.05 of Table 11 events of OWFs located in potential problematic eutrophication zone (F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
ACI	F	–	–	–	–	–	0.83	0.89	1.62
FI	F	0.63	0.66	0.71	0.68	0.60	0.63	0.55	–

Table 13
p-value of events within OWFs located in problematic eutrophication part of the North Sea (F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
FI	F	0.15	0.08	0.06	0.01	0.02	0.02	0.04	0.17
TI	F	0.33	0.29	0.08	0.10	0.41	0.83	0.62	0.38
FC		0.69	0.89	0.89	0.69	0.08	0.35	0.14	0.69
GP		0.35	0.35	0.35	0.60	0.75	0.35	0.46	0.17

Table 14
Cohen’s d number for p-value ≤ 0.05 of Table 13 events of OWFs located in problematic eutrophication zone (F = Finish).

Event		Days after event							
		2	4	7	11	18	30	50	80
FI	F	–	–	–	0.65	0.62	0.59	0.53	–

completion of turbine installation (TI), regardless of the eutrophication status of the locations. Specifically, 11 days after starting FI event, there is a decrease in phytoplankton abundance with a large effect size (Table 8). At 2, 4, 7, 11, and 80 days after completing TI, there is an increase in phytoplankton abundance with a small effect size (Table 8). Table 9 demonstrates that the phytoplankton population can be influenced by various events, such as fully commissioning (FC), finishing array cable installation (ACI), FI, and TI, occurring at different time intervals within non-problematic areas of the North Sea from an eutrophication perspective. The phytoplankton community shows a decrease 80 days after finishing ACI with a large effect size (Table 10). A mitigation in the phytoplankton population is observed at 2, 4, 7, 11, 18, 30, 50, and 80 days after completing FI, with an effect size ranging from medium to almost medium (Table 10). Additionally, Table 10 indicates that the phytoplankton abundance increases not only 30 and 50 days after completing TI, with an effect size between small and medium, but also 80 days after completion, with a medium effect size. Following OWF commissioning, there is a significant decrease in phytoplankton abundance with a large effect size at 2 and 4 days (Table 10).

The *p*-values in Table 11 demonstrate the effect on the phytoplankton abundance within potential problematic eutrophication zones after completing ACI and FI events. The phytoplankton community exhibits a significant decrease with a very large effect size at 30, 50, and 80 days after finishing ACI (Table 12). A notable reduction in the phytoplankton population can be observed 2, 4, 7, 11, 18, 30, and 50 days after completing FI, with an almost large effect size (Table 12).

In the case of eutrophic regions in the North Sea, the quantity of phytoplankton undergoes changes after the completion of FI (Table 13). The magnitude of phytoplankton decreases significantly 11, 18, 30, and 50 days after the completion of FI, as indicated by the large effect size (Table 14). This study reveals an induced effect on the abundance of phytoplankton following different OWF construction events in the region of North Sea, taking into account the eutrophication status of the OWF locations. Table 15 provides a brief overview of the days after the events when the phytoplankton population is affected. In the table, upward and downward arrows denote increases and decreases, respectively. The superscript numbers of the arrows indicate the strength of the effect sizes of the events, ranging from 1 (small) to 4 (large).

It seems from Table 15 that the pattern of the increase or decrease remains the same, independent of the passing days. The duration of 80 days seems too long to come to a conclusion related to the effect of OWFs on the phytoplankton population due to the other physical factors that are effective on the primary production like the seawater temperature in connection with the sunlight radiation. However, it is deduced from Table 15 that the trends of increase or decrease mostly come out within 7 or 11 days. Thus, long-time period of observations presented in Table 15 should be considered as an overview, keeping in mind that there are other physical and biogeochemical factors for the evaluation of the phytoplankton population variation. This study demonstrates the potential effects of OWFs on the phytoplankton population following various time intervals from the construction events of fully commissioned OWFs, while considering the eutrophication status of the locations. These effects could be attributed to the events themselves or to a combination of other activities that coincided during those time intervals. For instance, we observed a significant reduction induction in the number of phytoplankton two days after the fully commissioning of an OWF in non-problematic eutrophication areas of the North Sea, with a large effect size. It is not clear whether the observed effect (decrease in the phytoplankton abundance in this example) was directly caused by the OWF fully commissioning or not. However, what is evident is that the large size effect occurs after the event. In other words, while the cause of the effect remains ambiguous, the timing of the effect is known

Table 15
Induced effect on phytoplankton population following different events with related eutrophication status of locations (S = Start, F = Finish, NP = non problematic, PP = potential problematic, P = problematic, 1: small effect size, 2: between medium and small effect size, 3: medium effect size, and 4: large effect size).

	Event		Days after event							
			2	4	7	11	18	30	50	80
–	FI	S				$\downarrow^{4}$				
	TI	F	$\uparrow^{1}$	$\uparrow^{1}$	$\uparrow^{1}$	$\uparrow^{1}$				$\uparrow^{1}$
NP	ACI	F								$\downarrow^{4}$
	FI	F	$\downarrow^{3}$	$\downarrow^{3}$	$\downarrow^{3}$	$\downarrow^{3}$	$\downarrow^{3}$	$\downarrow^{3}$	$\downarrow^{3}$	$\downarrow^{3}$
	TI	F						$\uparrow^{2}$	$\uparrow^{2}$	$\uparrow^{3}$
	FC		$\downarrow^{4}$	$\downarrow^{4}$						
PP	ACI	F						$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$
	FI	F	$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	
P	FI	F				$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	$\downarrow^{4}$	

(for instance, 2 days after fully commissioning in non-problematic zones).

5. Conclusion

The changes in the phytoplankton population (or chl-a concentration) have the potential to influence biogeochemistry, carbon regulation, and material-energy cycling across different biological levels within the investigated locations and time intervals. However, the extent of this effect may diminish with increasing distance from the OWF sites. Therefore, it should be kept in mind that the results are valid in the vicinity of OWFs and may not be directly applicable to the entire North Sea region. When considering the findings of this study, it becomes evident that alterations in phytoplankton population are associated with changes in the flows of energy, materials, and organisms. These flow changes may occur not only within the phytoplankton ecosystem but also between neighboring ecosystems, involving multiple connections among their respective organisms. These connections can be either direct or indirect. Thus, in order to narrow the effect of the marine environment dynamics, this study focused on the variation of the phytoplankton population in the vicinity of 19 selected OWFs depending on various parameters as given in Table 2. As a result, it is observed that among 9 of the OWF construction events given in Table 5, the events of the foundation, turbine and array cable installation with fully commissioning are found effective on the variation of the phytoplankton population in the vicinity of the selected OWFs. It is apparently seen in Table 15 that when the positive or negative variation has initiated, it proceeds with the same trend. It is also observed that the event of foundation installation is always negatively effective on the phytoplankton population, independently of the eutrophic status of the OWFs surrounding environment. Considering the long duration of the observed period and the other physical and biogeochemical parameters affecting the population dynamics, the event of array cable installation can de dismissed from the general evaluation, even it has a large size effect, due to the time of its first effect which is seen after 1 month of the observation period. In addition to the general evaluation, it should be mentioned that the size effect of the turbine installation remains between small and medium for different status of eutrophication, with an increase in the phytoplankton population, on the contrary to the other events. And, the fully commissioning has a large size effect in the non-problematic eutrophication status beginning from the early days of the event. Moreover, it is perceived in this study that it is not possible to distinguish the exact source of variation in phytoplankton population. The ambiguity regarding the actual cause of the induced variation in the phytoplankton abundance remains, while the timing of variation is clearly evident (for example, two days after OWF FC in NP zones). Therefore, in order to address these uncertainties, further investigation, including field sampling and analysis, is required. However, the results of this study have practical implications for governmental decision-making, ecosystem-based management, coastal management, the fishing industry, and ecological studies. They can provide valuable insights into understanding and managing the effects of OWFs on marine ecosystem and inform various sectors related to coastal and marine resource management.

CRediT authorship contribution statement

Meysam Balaneshin Kordan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Sevil Deniz Yakan:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

Meysam Balaneshin Kordan completed his MSc thesis entitled “The effect of offshore wind farm activities on the phytoplankton population” successfully in 2021, under the supervision of Sevil Deniz Yakan. This study was accomplished within the scope of his thesis.

Appendix

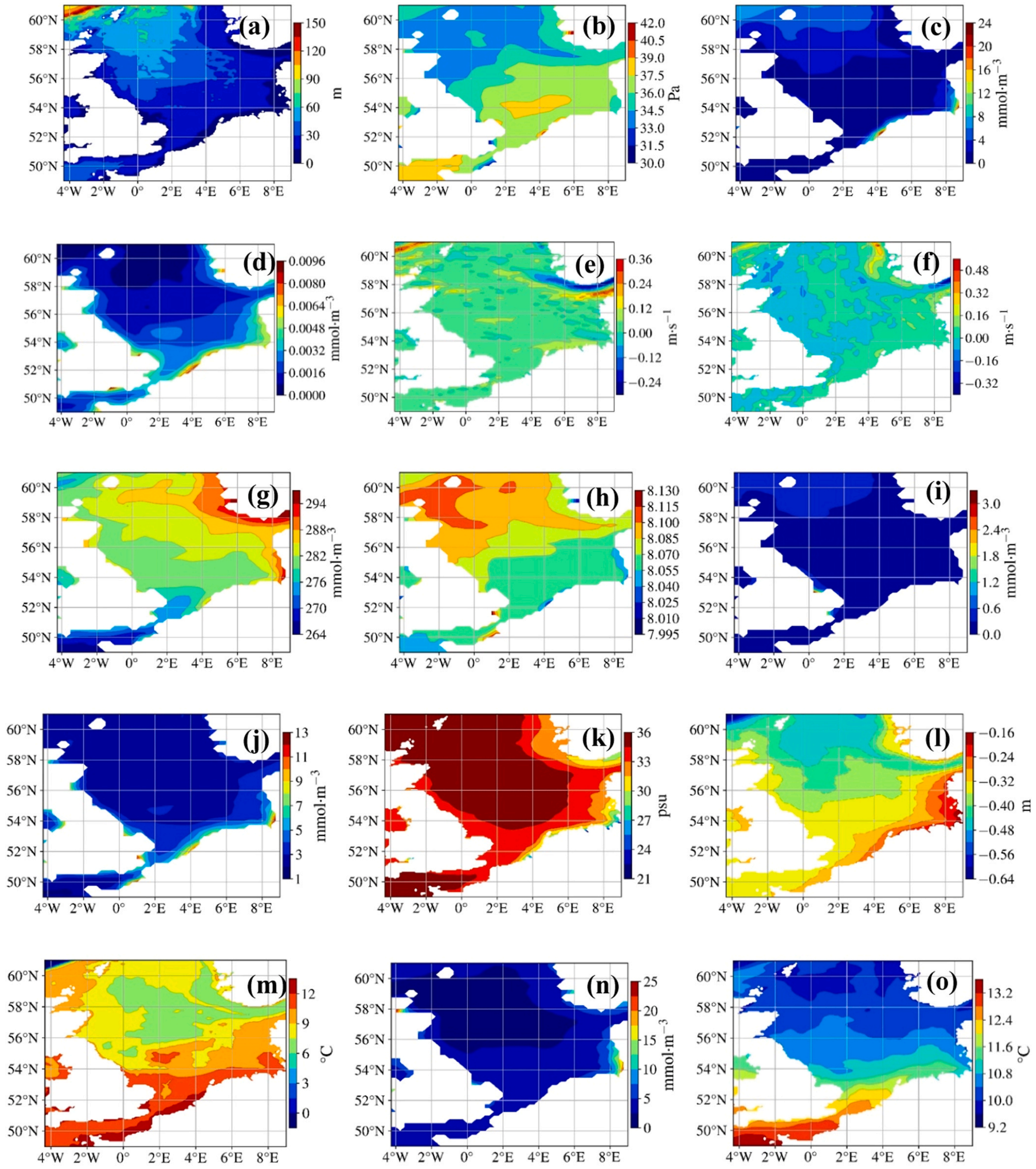

Fig. A.1. Factors used in the selection of OWF locations through the North Sea: (a) Density ocean mixed layer thickness, (b) surface partial pressure of CO_2, (c) nitrate mole concentration, (d) dissolved Iron mole concentration, (e) eastward seawater velocity, (f) northward seawater velocity, (g) dissolved molecular oxygen, (h) seawater pH, (i) seawater phosphate (PO_4), (j) phytoplankton concentration, (k) seawater salinity, (l) sea surface height above geoid, (m) sea floor potential temperature, (n) seawater silicate concentration, (o) sea surface temperature.

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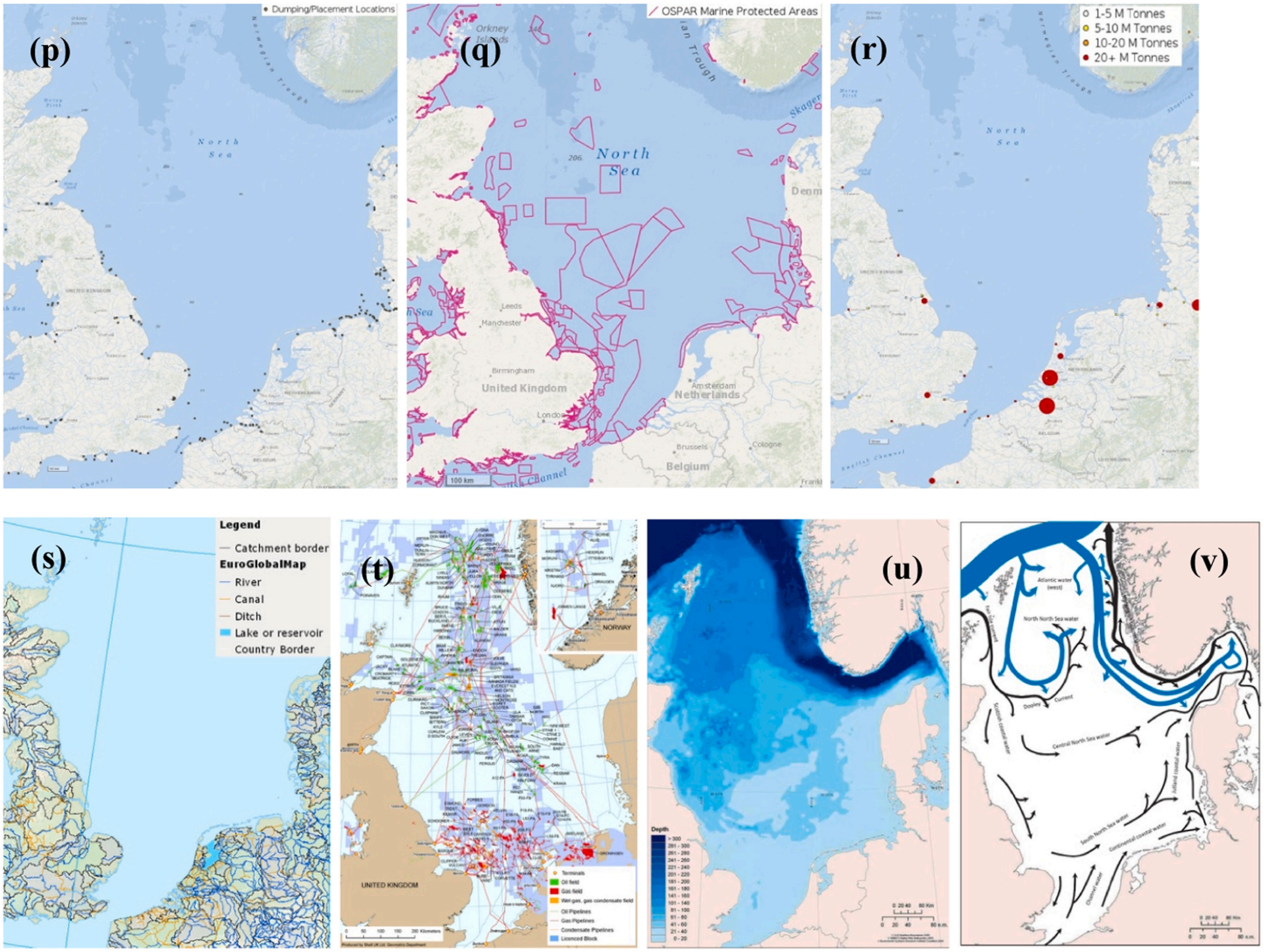

Fig. A.2. Factors used in the selection of OWF locations through the North Sea: (p) dumping and placement of wastes or other material (https://odims.ospar.org/en/maps/map-dumping-and-plac_-matter-at-sea-2014_snlw5/), (q) marine protected areas (https://odims.ospar.org/en/maps/map-marine-protected-areas/), (r) ports (https://odims.ospar.org/en/maps/eurostat-main-cargo-_reight-handled-2018_qpkkl/), (s) inlet rivers (https://www.eea.europa.eu/data-and-maps/figures/european-river-catchments-poster), (t) oil and gas (Young, 2009), (u) bathymetry (Paramor et al., 2009), and (v) streams and their intensity (Paramor et al., 2009).
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