

The large scale impact of offshore windfarm structures on pelagic primary production in the southern North Sea

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Abstract The increasing demand for renewable energy is projected to result in a 40-fold increase in offshore wind electricity in the European Union by 2030. Despite a great number of local impact studies for selected marine populations, the regional ecosystem impacts of offshore windfarm structures are not yet well investigated nor understood. Our study investigates whether the accumulation of epifauna, dominated by the filter feeder *Mytilus edulis*, on turbine structures affects pelagic primary production and ecosystem functioning in the southern North Sea. We estimate the anthropogenically increased potential distribution based on the current projections of turbine locations and understanding of *M. edulis* settlement patterns. This distribution is integrated through the Modular Coupling System for Shelves and Coasts to state-of-the-art hydrodynamic and ecosystem models. Our simulations reveal non-negligible changes in regional annual primary production of up to a few percent, and larger changes (up to $\pm 10\%$) of the phytoplankton stock, and thus water clarity, during the bloom period. Our setup and modular coupling are effective tools for system scale studies of other environmental changes arising from large-scale offshore wind-farming such as ocean physics and distribution of pelagic top predators.

Keywords Offshore wind farm · primary production · North Sea · MOSSCO · modular coupling · biofouling

1 Introduction

Recognition of the role of the burning of fossil fuels in anthropogenic climate change has led to increased

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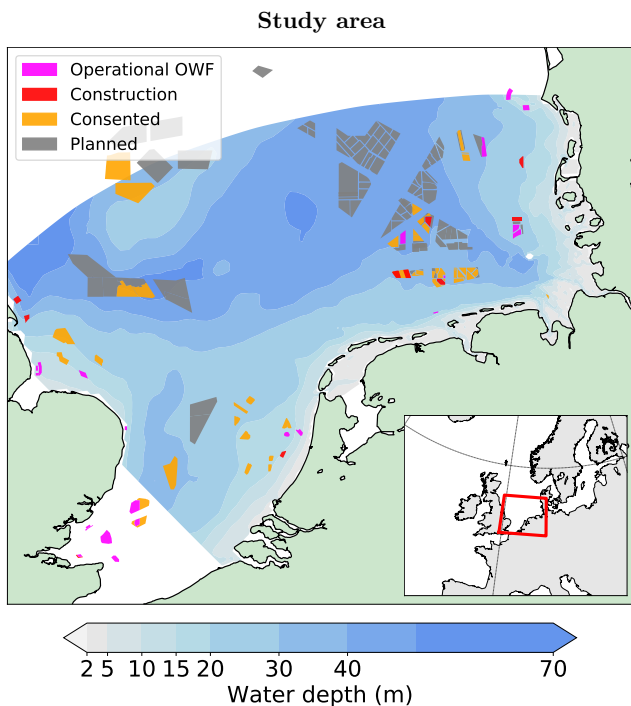


Fig. 1 Overview of the geography of the Southern North Sea and the distribution of offshore wind farms (OWF). Color indicates the planning status of each OWF as of September 2015 where parks in operation and under construction are shown in magenta and red color, and foreseen constructions with consented or planned status in orange and gray color.

investment in renewable energy such as wind farming (Edenhofer et al, 2011). Especially offshore wind energy has proliferated over the past decade and is projected to be integral in the transition to renewable energy systems; in the Europe Union (EU), offshore wind farms (OWFs) are predicted to increase 13-fold between 2015 and 2020, and 40-fold by 2030, in order to meet 4.2% of EU total electricity consumption (Global Wind Energy Council, 2015).

Currently, 63% of OWFs in EU waters are concentrated in the southern North Sea (SNS), with the remainder located in the Atlantic Ocean and Baltic Sea. The SNS is expected to remain a hotspot for EU OWF development, where $\approx 85\%$ of OWFs are currently under construction and $\approx 75\%$ of OWFs are consented (Ho et al, 2016) Offshore wind turbines are solid structures, typically larger than their onshore counterparts, built of steel or concrete, with monopiles accounting for 80%. OWFs are being built further offshore and into deeper waters, with the average water depth increasing three-fold and the average distance from shore five-fold between 1991 and 2010 (Kaldellis and Kapsali, 2013). The large additional build-up of OWF until 2030 is evident from the spatial distribution of operational, under

construction, consented and planned OWFs in the SNS (Fig. 1)

The increasing number of OWFs alter the functioning of the surrounding pelagic ecosystem by restructuring the biological communities at and around the submerged foundations and pile structures (Joschko et al, 2008; Krone et al, 2013). Specifically, they increase the biomass and distribution of filter feeders (Krone, 2012; Lindeboom et al, 2011), because OWFs provide the hard substrate needed for colonisation by a variety of epifaunal species. This colonisation is also referred to as biofouling; among the colonisers, the blue mussel *Mytilus edulis* (hereinafter referred to as blue mussel) is the dominant species near the water surface (Table 1) (Freire and Gonzalez-Gurriaran, 1995; Riis and Dolmer, 2003; Wilhelmsson and Malm, 2008; Joschko et al, 2008; Krone et al, 2013). For example, piles of the OWF research platform FINO 1 (Forschungsplattformen in Nord- und Ostsee) are covered by an average of 4300 kg of blue mussels, with a turnover rate of more than half per year (Krone et al, 2013).

Biofouling not only generates habitat for a new epistuctural community, but it has further consequences for the benthic community underneath and for the surrounding pelagic zone (Krone, 2012; Maar et al, 2009). Filter feeders, especially blue mussel, have been shown to significantly reduce the ambient concentration of phytoplankton and of micro- and mesozooplankton (Dolmer, 2000; Maar et al, 2007), which to some extent likely applies to epistuctural blue mussels as well (Maar et al, 2009). By changing phytoplankton biomass, epistuctural filtration can be expected to affect primary productivity and thus the very basis of the marine food web and biogeochemical cycling locally above mussel beds and around the offshore wind turbine.

Our study aims to assess the sensitivity of pelagic primary production to changed abundance and distribution of blue mussels on OWFs for an entire regional-scale ecosystem. It is the first study to investigate the accumulated effects on primary production at the systems scale, beyond the local impacts of individual offshore wind turbines. Prerequisites for such an assessment are (i) the reconstruction of blue mussel abundance both for their natural, epibenthic habitat and for the new epistuctural niches; (ii) the functional coupling of the lateral and vertical distribution of reconstructed mussels to phytoplankton prey fields in a realistic hydrodynamic and biogeochemical representation of the SNS.

For the integrated modelling of benthic and epistuctural filtration, water physics and pelagic biogeochemistry, we use the recently introduced modular framework by Lemmen et al that contains a novel ecosystem

Table 1 Offshore wind farms in the Southern North Sea where *Mytilus edulis* are the dominant species.

Country	Location	Reference
Germany	FINO 1 research platform	Krone et al 2013
Belgium	C-Power OWF	Kerckhof et al 2012
Netherlands	Egmond aan Zee OWF	Bouma and Lengkeek 2012; Lindeboom et al 2011
Denmark	Horns Rev OWF	Leonhard et al 2006
Sweden	West coast of Sweden	Langhamer et al 2009

model recently applied to and verified for the SNS by Kerimoglu et al (2017). Multi-annual simulations run with and without epistuctural mussels allow a first estimate of the sensitivity of pelagic primary productivity to the projected OWFs in this regional sea.

2 Materials and Methods

2.1 Study location

The southern North Sea (SNS) is located between 51° N and 56° N and bordered by the United Kingdom, Belgium, the Netherlands, Germany and Denmark (Fig. 1). The water is fairly shallow with an average depth of 30 m and comprises an extended area of intertidal flats and several major estuaries (Eisma and Kalf, 1987). The seabed is predominately composed of sand and, in the deeper and more coastal parts, mud (Walday and Kroglund, 2002). The SNS experiences strong seasonal variability, with winter storms often generating large surface waves and suspending greater amounts of sediments. Currents in the North Sea are generated by tides and wind forcing, with the latter especially important during storm events (Howarth, 2001).

2.2 Reconstruction of epibenthic *Mytilus edulis*

Open spatial data on the abundance and distribution of *Mytilus edulis* were obtained from the Joint Nature Conservation Committee (JNCC), the Ocean Biogeographic Information System (OBIS), the Archive for Marine Species and Habitats Data (DASSH), the Global Biodiversity Information Facility (GBIF) and the Belgian Marine Data Centre (BMDB). Most of the data (43%) was from JNCC, 26% and 23% from BMDC and GBIF (containing presence only data), and 9% from OBIS; only few data points came from DASSH < 1%. Removing duplicate locations, in total 4074 count observations and 37 214 presence only data were used for the reconstruction.

To extrapolate and interpolate the count and occurrence data to the entire domain of the SNS, we used empirical relationships between blue mussel abundance,

sediment grain size and depth; we added to this a low abundance random distribution for deep water and a constant high abundance for mussel beds. The blue mussel prefers larger sediment grain sizes and hard substrate (OSPAR Commission, 2010), thus an increase in abundance density (n) with increasing sediment grain size, ranging from an abundance of 1 m^{-2} in muddy areas (median grain size $d_{50} < 0.06 \text{ mm}$) to 40 m^{-2} in areas of coarse gravel. The abundance–sediment grain size relationship is modulated by a 10 m natural depth limitation (Reise and Schubert, 1987; Suchanek, 1978). Outside the depth limitation, blue mussels still occur, however at a much reduced density ; , a random density between 0 m^{-2} and 5 m^{-2} is assigned based on field sampling data (Reise and Schubert, 1987). Mussel beds were incorporated as point data using the OSPAR Biodiversity Committee habitat classification, where a constant density of 3911 m^{-2} is assumed (Nielsen and Maar, 2007).

As blue mussels are tolerant to large variations in temperature (0–29 °C) and salinity (Seed and Suchanek, 1992), such factors were not considered in the reconstruction. Taking the average adult blue mussel individual biomass as 600 mg dry weight (DW) (Bayne and Worrall, 1980), which equals 64.5 mg ash free dry weight (AFDW Ricciardi and Bourget, 1998), the abundance and distribution of blue mussel in the SNS was spatially reconstructed using the median sediment grain size map that is publicly available from the NOAH habitat atlas (www.noah-project.de/habitatatlus/).

Presence only data is not a preferred estimator for species distribution modelling, especially when there is a sampling bias. Many of the GBIF-reported blue mussel observations are opportunistic finds reported by citizen scientist divers, with a bias towards more accessible near-coast areas. This bias may be overcome by environmental constraints that can serve as proximate absence (Phillips et al, 2009), such as water depth for the blue mussel. We note that the epibenthic reconstruction of blue mussel abundance presented here is preliminary; as it serves as a baseline only, the uncertainty in this epibenthic reconstruction does not harm the results obtained for the epistuctural ecosystem sensitivity (see below).

Table 2 *Mytilus edulis* abundance with depth (Krone et al, 2013).

Depth (m)	Distribution (%)	Abundance (m ⁻²)
0.0 – 2.5	95	3258.08
2.5 – 7.5	3	58.58
7.5 – 15	2	19.29
15.0 – 30.0	0	1.63

2.3 Epistuctural blue mussel

The biomass and species diversity of epifaunal communities at OWFs are much higher than would be found on natural hard substrate (Wilson and Elliott, 2009), with species composition varying with both depth and time, as recorded at both FINO 1 (Krone et al, 2013; Joschko et al, 2008), and the Kentish Flats OWF (Bessel, 2008). The blue mussel is the dominant macrofauna species at shallower depths, while at greater depths Anthozoa and *Jassa spp.* are more prolific. Other major taxa such as green algae, *Asterias rubens* (Asteroidea), Bryozoa, Porifera and *Tubularia spp.* are also present. The blue mussel is the most abundant and ecologically important species at OWF epifaunal communities in the North Sea (Table 1 and Borthagaray and Carranza 2007), contributing up to 90% of epifaunal biomass in some locations; it is therefore also the main driver of ecological change around offshore structures (Krone et al, 2013; Maar et al, 2009).

The additional blue mussel settlement as a result of OWFs is considered by incorporating the vertical distribution observed by Krone et al (2013) at the FINO 1 OWF. The blue mussel abundance (n) at an offshore wind turbine is a function of its radius (r) and its base depth (z), with the radius assumed to be 3 m at all OWFs (4C Offshore, 2015). The influence of blue mussels on water properties is assumed to be equal around the entire circumference, without consideration of current direction. Multiplying the abundance density by the circumference gives the vertical distribution of blue mussel with depth at offshore wind turbines (Table 2). The abundance density over depth at each offshore wind turbine was calculated by converting the wet weight reported by Krone et al (2013) to DW using a factor of 6.6% and assuming 600 mg DW ind⁻¹ (Ricciardi and Bourget, 1998; Bayne and Worrall, 1980).

2.4 Spatial subgrid distribution

The spatial distribution of current and projected OWFs in the southern North Sea (Fig. 1) was overlaid on a curvilinear grid later used for the numerical model.

Epibenthic areal abundance of blue mussel was considered to be (vertically) equally distributed within the lowermost representable physical layer in the grid of the hydrodynamic model. Epistuctural areal abundance was vertically distributed in all simulation layers representing the upper 2.5 m of the water column in the hydrodynamic model.

Estimating abundance density at OWFs from the abundance at individual turbines requires consideration of the turbine density at OWFs. Offshore wind turbines are often spaced between five and eight times the rotor diameter (E.ON Climate & Renewables, 2011), which tend to range from 80 to 100 m (International Renewable Energy Agency, 2012). Assuming a rotor diameter of 100 m and a spacing of five times this distance, this means that each offshore wind turbine requires 500 m spacing or 0.25 km² area, giving an average wind turbine density of 4 km⁻².

2.5 Coupled model system

Extrapolation from the compiled OWF locations to the entire SNS area and the description of blue mussel influence on the pelagic ecosystem requires a spatially explicit, coupled model approach, for which we employ the recently developed open source software infrastructure Modular System for Shelves and Coasts (MOSSCO, www.mossco.de, Lemmen et al 2017). MOSSCO facilitates the exchangeable coupling of models and data sets and enables the integration of modules describing physical, chemical, geological, ecological and biogeochemical processes. MOSSCO applications for the 3D coastal ocean focus on processes at the benthic–pelagic interface and, among others, explain spatio-temporal patterns in coastal nutrient concentration (Hofmeister et al, 2017; Kerimoglu et al, 2017), primary production (Kerimoglu et al, 2017), macrobenthic biomass and community dynamics (Wang and Wirtz, subm. J. Geophysical Research) and suspended sediment concentration as affected by macrobenthic activities (Nasermoadeli et al et al., subm. Estuarine, Coastal, and Shelf Science).

MOSSCO features generic output and input components that can be used to integrate, e.g., river nutrient fluxes, open ocean boundary conditions and faunal abundance. As a physical driver within MOSSCO, we employed the coastal ocean model GETM (General Estuarine Transport Model, Burchard et al 2002; Klingbeil and Burchard 2013) to calculate sea level, currents, temperature and salinity distributions, and to transport the biogeochemical and ecological quantities. GETM obtains state-of-the-art turbulence closure from the General Ocean Turbulence Model (GOTM, Umlauf

and Burchard, 2005)), and has been shown to have high skill in various studies for the North Sea and SNS (e.g. Gräwe et al, 2016; Purkiani et al, 2016).

Pelagic ecology was described by the Model for Adaptive Ecosystems in Coastal Seas (MAECS, Kerimoglu et al 2017) implemented as a FABM module; MAECS simulates pelagic nutrient, phytoplankton, zooplankton and detritus dynamics and accounts for the acclimation of intracellular composition in phytoplankton (Wirtz and Kerimoglu, 2016). A full description and an extensive performance assessment of the model for a decadal hindcast of the SNS has been provided by Kerimoglu et al (2017); our coupled setup differs, however, as it resolves filtration (see below) but neglects biogeochemical processes in the benthos and assumes a spatially uniform top-down mortality of zooplankton.

2.5.1 Filtration model

Mytilus edulis actively passes water over a specialized filtering structure (the gill), thereby removing a significant proportion of both organic (i.e., mainly phytoplankton) and inorganic particles with high efficiency (Widdows et al, 1979); the volume of passed water over the gill area per unit of time and individual body volume is referred to as the clearance rate (CR). CR has been observed to increase with rising current velocity (Cranford and Hill, 1999), while at very low ambient phytoplankton concentration about 0.5 mg m^{-3} Chlorophyll a, however, CR ceases for energetic reasons (Riisgård et al, 2003). The amount of particles removed from the cleared water, termed the filtration rate (FR), depends, among others, on the concentration and organic quality of particles; a physiological regulation of filtration rate is, however, debated and has been studied for high ambient food concentrations only. At the concentrations typically found in the SNS, full exploitation of the ambient concentration can be expected (Clausen and Riisgård, 1996; Asmus and Asmus, 1991).

Our model implementation of blue mussel FR is formulated in terms of phytoplankton carbon amount concentration ($[C]$) for an individual of 300 mg DW.

$$\text{FR}_{\text{TPM},300} = 0.05 \cdot [C]^{0.983}, \quad (1)$$

referring to the empirical relationship based on TPM (Bayne et al, 1993) and using the following assumptions for the conversion of their coefficients and carbon units: we (i) take the experimentally-determined organic matter fraction of 56%, (ii) apply molar mass conversion in Redfield stoichiometry to express the DW to amount carbon ratio as 32.43 mg per mmol C; rate scaling to individual mass 600 mg was performed with the experimentally confirmed exponent 0.67 (Bayne et al, 1993).

Table 3 Scenarios contrasted in this study

Scenario	Description
REF	Presence of epibenthic mussels and mussel beds; this represents the references state against which the addition of artificial hard substrate by OWFs is compared.
OWF	As REF, but with additional presence of epistuctural mussels in pelagic surface layers.

As a lower threshold for filtration, a phytoplankton carbon concentration of $[C]_{\text{min}} = 0.7 \text{ mmol m}^{-3}$ was chosen, consistent with Riisgård et al (2003). Filtration of phytoplankton biomass by blue mussels removes (in stoichiometric proportion) particulate carbon, nitrogen, and phosphorus from the pelagic phytoplankton compartment, and with it reduces also dependent phytoplankton properties like chlorophyll. digested) detritus material.

The filtration model is technically realised as an Earth System Modeling (ESMF, Hill et al, 2004) component and coupled with MOSSCO (Lemmen et al, 2017) to the Framework for Aquatic Biogeochemistry (FABM, Bruggeman and Bolding, 2014) with the MAECS biogeochemical model.

2.5.2 Model setup

The SNS was represented on a curvilinear grid with cell size between 2 and 64 km^2 , with the highest resolution in the German Bight; vertically, the water column was represented by 20 terrain-following σ -layers (Kerimoglu et al, 2017). The model setup accounts for the discharge of freshwater, phosphorous and nitrogen from major rivers into the southern North Sea, including the Elbe, Weser, Ems, Rhine, Meuse, Scheldt and Humber (see Kerimoglu et al, 2017). Tidal sea surface elevation was forced at the open ocean boundary; open ocean boundary conditions for nutrients in dissolved and particulate forms were obtained from a North Atlantic shelf simulation with ECOHAM (Ecosystem Model Hamburg, (Große et al, 2016)) and provided as a 10 year climatology Kerimoglu et al (2017). Phytoplankton and zooplankton were assumed to be at zero-gradient at the boundaries. The meteorological forcing was obtained from the long-term Climate Limited area Model reconstruction available in the CoastDat database (Geyer, 2014).

Simulations were consecutively run for the duration of one calendar year for the years 2000 to 2007. As we are evaluating a sensitivity for a projected year 2030 scenario, the choice of this period is arbitrary and reflects availability of station and satellite data for model evaluation. The spin-up period for the first year was

one year (repeat of the same year), which was needed to redistribute the pelagic pools of nutrients in winter; a longer spin-up was not required because slow diagenetic processes were not considered in this experiment. Two different scenarios were compared, (1) presence of only epibenthic mussels (scenario “REF”), and (2) additional presence of epistructural blue mussel at OWFs, focussed within the upper pelagic layers (scenario “OWF”) (Table 3).

The filtration model was configured with phytoplankton carbon as the main species to filter, with co-filtration of phytoplankton nitrogen, phosphorous, chlorophyll and rubisco. The ecological model MAECS was configured similar to the parameterisation presented by Kerimoglu et al (2017). The model diagnostic rates of relative carbon uptake were multiplied by phytoplankton carbon concentration and subsequently integrated for the entire year to obtain the annual net primary production. The 3D time step of the hydrodynamic model was 6 minutes. Data exchange between the different components of the model system was performed every 30 minutes. The bottom roughness length was constant at $z_0 = 0.002$ m, wave forcing was disabled. A Jerlov Type III water class was used for the radiation scheme.

2.6 Data for model evaluation

No observational data is available for primary productivity at the scale of the SNS. Rather than the rate of production, the stock of phytoplankton is readily observed with *in situ* methods or by remote sensing. We evaluate chlorophyll-a as simulated by the model against station observations of chlorophyll fluorescence along three transects and against synoptic satellite observations of ocean color.

Time series of near-surface chlorophyll a concentration were obtained from the Dutch authority Rijkswaterstaat through the OpenEarth portal (Rijkswaterstaat, 2017). From all available station data, we selected three transects that cross the coastal nutrient gradient from nearshore Noordwijk, Terschelling and Rotterdamplate to up to 235 km offshore (Fig. 3). Satellite observations were obtained from the European Space Agency Ocean Color Climate Change Initiative (ESA-CCI version 3.1), a multi-platform combined product of chlorophyll concentration.

3 Results

The reconstructed abundance of blue mussel in the SNS suggests $1.7 \cdot 10^{11}$ individuals within the 10 m water depth coastal zone excluding the mussel beds and $0.9 \cdot$

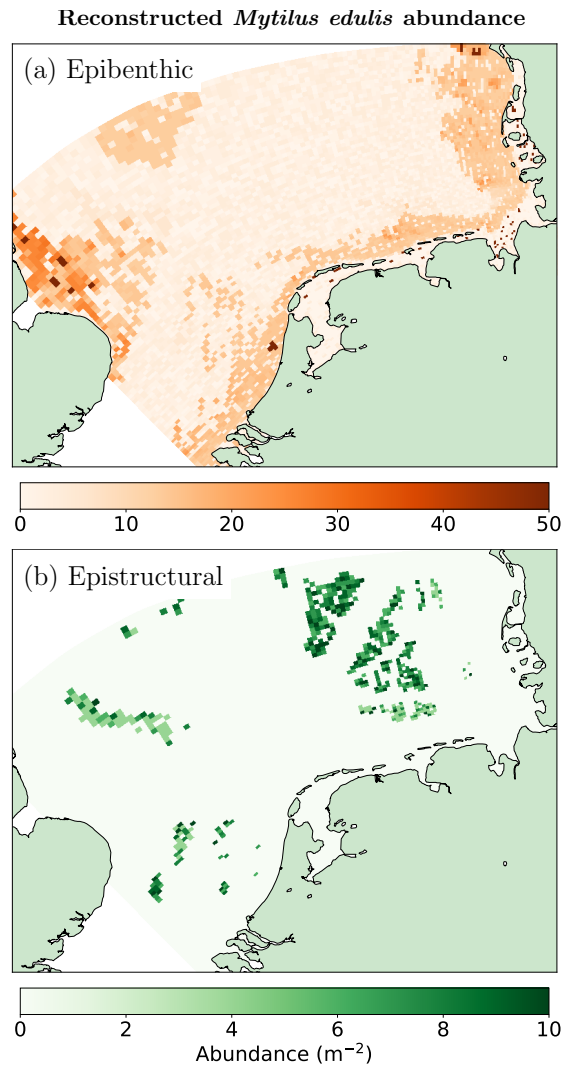


Fig. 2 Reconstructed abundance of *Mytilus edulis* at the (a) sea floor, estimated from presence and count data and sediment habitat mapping, and (b) on wind turbine piles, estimated from scaling individual pile monitoring observations.

10^{11} individuals beyond the 10 m water depth zone excluding the wind turbines. Although the density of mussels peaks in shallow coastal waters (Fig. 2a), also the offshore seafloor with water depth larger than 10 m hosts a significant portion of the total estimate. The reconstructed accumulated biomass of blue mussel in the SNS amounts to in total $1.7 \cdot 10^7$ kg (AFDW) excluding the mussel beds and wind turbines. Estimated biomass of the mussel beds in the Wadden Sea and along the British coast in addition contributes another $0.9 \cdot 10^7$ kg, which is $\approx 32\%$ of the total estimated budget in the SNS. The above estimates represent the natural stock of blue mussel in the SNS. For the potential “artificial” stock at offshore wind turbines, the reconstructed abundance (Fig. 2b) in the entire SNS amounts to $1.8 \cdot 10^6$ kg biomass, which is equal to 6.5% of the total mussel

Chlorophyll model–data comparison

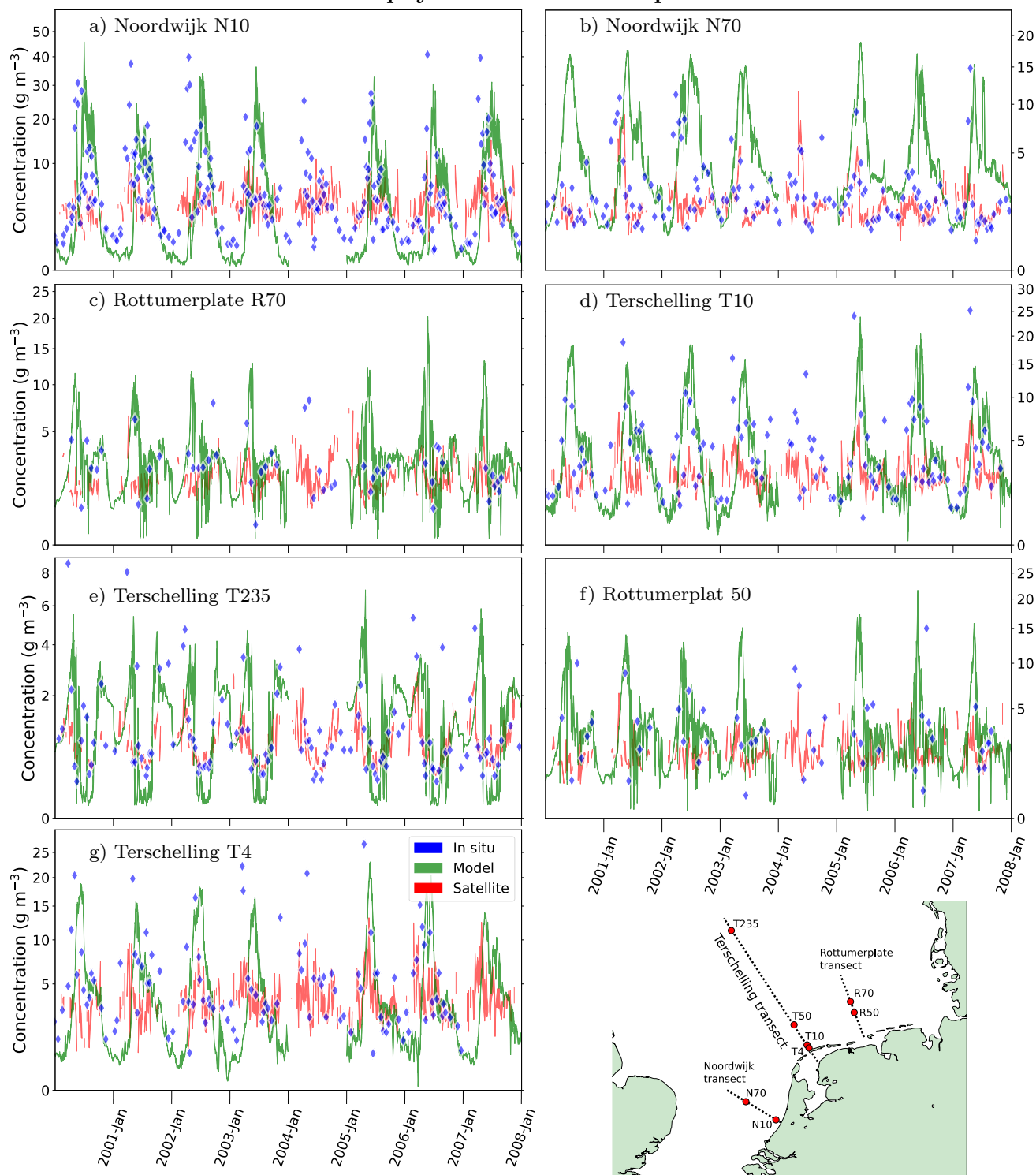


Fig. 3 Comparison between in situ measurements (blue diamonds), satellite observations (red line) and simulations (green line) of surface chlorophyll for three coastal transects “Noordwijk”, “Terschelling” and “Rottumerplate”, where numbers denote distance from coast (e.g., R10 = 10 km off Rottumerplate). The satellite gridded observation and the simulation from scenario REF were sampled in a 5000 m radius around the respective station location. Data from Rijkswaterstaat (Waterbase) and European Space Agency (CCI v3.1 product).

biomass in the SNS. This result indicates that, once all the planned wind farms are in operation, they will provide habitat for mussels that are equal to 20% of the current stock from natural mussel beds along the coast.

Simulated surface chlorophyll for the years 2000–2007 exhibits a typical annual phytoplankton cycle with a large spring bloom and a smaller summer bloom; at the bloom peak, the chlorophyll concentration reaches 20–50 mg m⁻³ at coastal and falls below 10 mg m⁻³ at far offshore locations (Fig. 3). The reference simulation reproduces *in situ* time series of near-surface chlorophyll concentration along the three transects from Noordwijk, Terschelling and Rottumerplate. The peak spring bloom chlorophyll concentrations are well matched across the entire coastal gradient, the range of chlorophyll concentrations is also well represented. The comparison against satellite observations shows that both model and *in situ* observations have a wider temporal variability, while the mean chlorophyll concentration is again well represented.

The simulated climatology of vertically integrated net primary production (NPP, expressed as carbon production) in the SNS averaged over the years 2000–2007 broadly separates the model domain into three regions (Fig. 4): (1) the coastal area including the Wadden Sea, of low vertically integrated carbon production (around < 50 g m⁻² a⁻¹, very shallow and turbid water), (2) the near-coast transition zone with a high production of up to ≈ 180 g m⁻² a⁻¹, and (3) the offshore SNS, again with medium production rate around 80 g m⁻² a⁻¹. A similar spatial pattern is evident for all simulation years, but the magnitude of production is highest in 2001 and 2003 and lowest in 2005 and 2006. Maximum production in this simulation occurs in an elongated coast-following area 20 km north and east of the West-Frisian island chain, in the central Southern Bight, and off the East coast of England in the year 2003.

In the simulations, NPP does not differ greatly between the reference scenario (REF) and the OWF scenario in any year. There is up to 4.5% (or 3 g m⁻² a⁻¹) less primary production locally in the OWF than in the REF scenario (Fig. 5a,b, shown for the year 2002). The maximum loss occurs within the OWF areas and a less substantial loss of $\approx 2\%$ (or 1–2 g m⁻² a⁻¹) is observed in the vicinity of the OWFs. The difference in annual average phytoplankton stock is of the same order of a few percent. Within the seasonal cycle, production and loss due to filtration are greatest during the bloom periods, thus between mid-April to late May and around late July, when the additional filtration by epistuctural blue mussel lowers NPP by up to 1.7 mg m⁻² d⁻¹. The largest draw-down occurs where the abundance of mussels is highest and when food is plentiful, i.e. dur-

ing the phytoplankton bloom. During one of the days with highest production (May 26, 2003), we contrast the effect of epistuctural filtration on phytoplankton stock in the surface layer to that directly above the sea floor layer (Fig. 3). The filtration effect is largest in the surface layer within OWF areas, where phytoplankton carbon concentration is reduced by 10%. In the vicinity of wind parks, a small reduction of a few percent is visible. Downstream of the prevailing circulation and extending up to several hundreds of km away from the platforms, phytoplankton carbon concentration is increased by 5–10%. This increase does not occur before the phytoplankton production peak. Epistuctural filtration loss is transmitted to the bottom layer by vertical advection and diffusion. The OWF signature is visible in and above the benthic–pelagic interface (Fig. 3b), although the effect is smaller in intensity and more diffuse than at the surface. In the near-bottom layer, the area of greatest phytoplankton carbon loss is located below areas of enhanced phytoplankton carbon in the surface layer; OWFs in the windward direction do not show any signature of epistuctural loss in their bottom or surface layer.

4 Discussion

The reconstruction of mussel abundance in the southern North Sea is based on analysis of field data (in total 4074 count observations and 37 214 presence only data, which reveals a positive correlation ($r = 0.78$) between abundance and sediment grain size. The 10 m water depth line is introduced to provide a pseudo-absence criterion. To test a sensitivity of the reconstruction result to the water depth limitation, we also calculated the abundance using 25 m water depth contour line ($\approx 95\%$ of observed presence occurs within this water depth) as an alternative constraint, which leads to an increase in abundance by $\approx 0.4 \cdot 10^{11}$ compared to that using the 10 m. This amounts to $\approx 9\%$ of the total budget estimated using the 10 m water depth constraint, and thus does not affect our estimation to a large degree. The area covered by mussel beds in the Wadden Sea oscillated annually between $6.2 \cdot 10^7$ and $3 \cdot 10^7$ m² since 1998 (Neehls et al, 2009). Since our estimation of the stock in the Wadden Sea is based on a maximum value ($6.2 \cdot 10^7$ m²), the annual oscillation of mussel beds would affect the total estimated budget in the SNS by 10% at most: our reconstruction and the annual fluctuation should be within 30% of the total estimated budget, taking into account oscillations of the mussel beds and the impact of extreme wind-waves on offshore wind turbines, which might occasionally clear all mussels from a wind turbine (Krone et al, 2013).

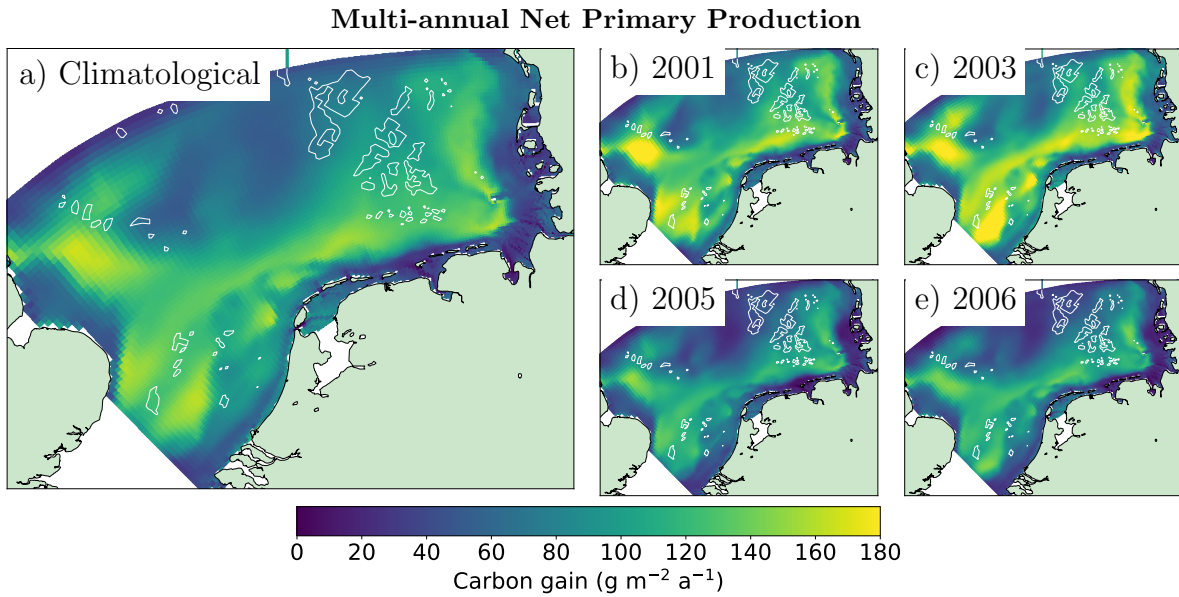


Fig. 4 Simulated annual total net primary production from simulations covering the years 2000 to 2007 (panel a). Selected years of high production (panels b, c) and low production (panels d, e) shown on right. Contours denote areas with OWF epistructural blue mussels.

Net primary production calculated by our coupled model shows low production in the Wadden Sea area (Fig. 4). Simulated chlorophyll concentrations in this area are also lower than those estimated by the satellite imagery (e.g., Kerimoglu et al, 2017; Ford et al, 2017), while in the open SNS, our model modestly overestimates Chl-a and probably also NPP. Interestingly, NPP simulated by van Leeuwen et al 2013 with the same hydrodynamic (GETM) but with a different ecosystem model (ERSEM, Baretta et al 1995) is much higher (on average $318 \pm 29 \text{ g m}^{-2} \text{ a}^{-1}$) than NPP simulated here for their region termed “SNS”, referring to a small area of the Southern Bight of the North Sea. Their results are, however, averaged over the much higher trophic state period 1985–2005, such that lower production should be expected for the period 2000–2007.

Already Emeis et al 2015 report values around $200\text{--}270 \text{ g m}^{-2} \text{ a}^{-1}$, for an area corresponding to our coastal high production region in the year 2002, based on the Ecosystem Model Hamburg (ECOHAM, Pätsch and Kühn 2008). van Leeuwen et al (2013)’s comparison with *in situ* observation derived NPP estimates by Weston 2005, however, also showed that their model under- or overestimates observations by a factor of two depending on the area type (stratified, frontal bank), and overestimated surface mixed layer production by up to a factor of five (van Leeuwen et al, 2013, Table 1). Given these considerations the simulated production in the coastal and open SNS (up to $180 \text{ g m}^{-2} \text{ a}^{-1}$) is plausi-

ble, and its skill needs to be assessed against observational data in forthcoming studies.

In contrast to productivity, biomass related variables are readily observable from a variety of platforms: the agreement between the *in situ* measured, the remote sensing observed, and the simulated chlorophyll concentrations (Fig. 3) suggests that phytoplankton dynamics is well reproduced, which builds confidence in the representation of primary productivity by the model. Moderate discrepancies in the cross-coastal distribution of NPP and Chl-a are in part due to the simplified description of water attenuation by high concentrations of suspended particles close to the coast (Kerimoglu et al, 2017) and the top-down mortality of zooplankton. Our parameterisation neglects the accumulation of carnivorous predators such as juvenile fish and larvae of many invertebrate and vertebrate species in shallower coastal waters, resulting in too high herbivorous grazing and, thus, too low phytoplankton concentrations nearshore or too high phytoplankton concentrations in offshore waters, respectively. However, given that the concentrations are in the range where mussel filtration exhibits a rather linear functional response, the moderate mismatch should not affect relative effects.

4.1 Spatial and temporal trends

During a bloom, phytoplankton will usually first appear at the surface and then sink down through the water column (Cloern, 1996), producing a delay between sur-

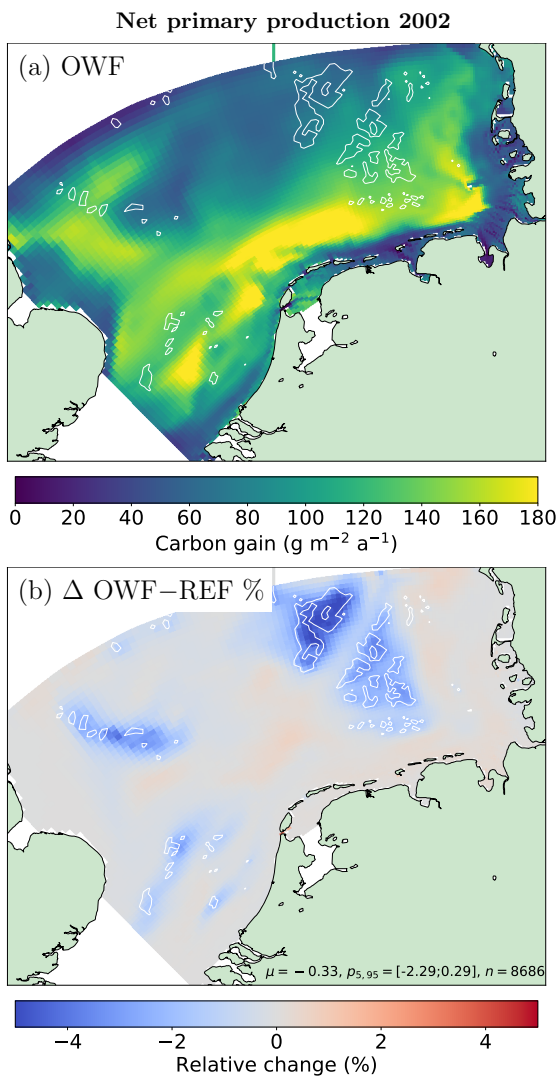


Fig. 5 Simulated annual net primary production for the year 2002 (panel a, scenario OWF), and the relative difference between the scenarios (OWF- REF, relative to REF, panel b).

face phytoplankton concentrations and those at depths. Similarly, the phytoplankton loss from epistuctural filtration is first and clearly visible at the surface, where blue mussels are concentrated, before being transmitted down the water column. In addition, the drift of the modified phytoplankton concentration causes a far field effect of filtration. The snapshot taken on May 26, 2003 (Fig. 3) shows that the ecological effect of epistuctural filtration is not a local one, but a regional one, with a decrease of phytoplankton carbon up to 20 km and an increase several hundred km downstream of the wind farms. It can be argued that the magnitude of around a few percent per year in regional draw-down is well within the uncertainty range of state-of-the-art ecosystem models. Nevertheless, this effect exceeds previous estimates of fully negligible impacts distant to

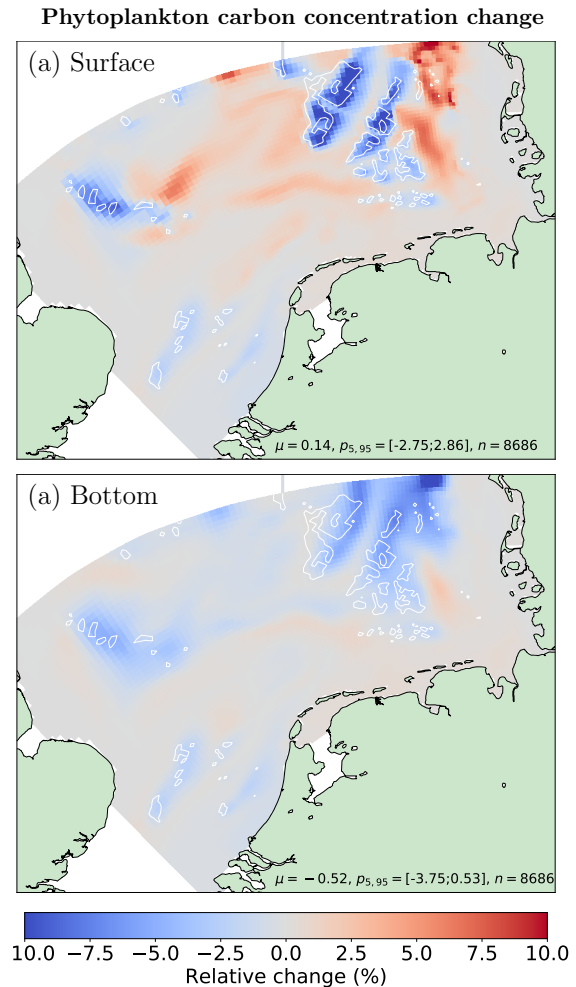


Fig. 6 Relative difference of phytoplankton stock (phytoplankton carbon concentration) between scenarios REF and OWF for the surface (a) and the bottom (b) layers on May 26, 2003 during the production peak.

the OWFs and points to a notable impact of projected epistuctural suspension feeders on the ecosystem functions of a regional shelf sea. Even though the decrease in primary production is relatively small, it extends over a large area and intensifies in close proximity to OWFs, reaching a maximum reduction in annual net primary production of 4%. Despite the dilution of meso-scale mussel density due to the low area density of offshore wind turbines, massive biofouling accumulates to an effect size which is only one order of magnitude lower than the 60% reduction within shellfish aquacultures (Waite, 1989)

Moreover, the snapshot also shows that the vertical structure of the filtration effect can be very different depending on the location of the OWF. OWFs in the high productivity Southern Bight of the North Sea have no clear surface signature and the (small) loss is equally

visible in the surface and bottom layers (Fig. 3). The western OWFs off the British Coast exhibit a downward trail of enhance carbon stock extending in filaments across the entire central SNS only in the surface layer; For the eastern wind farms, the effect is locally a strong decrease of phytoplankton through the entire water column, and an increase leeward of the farms in the surface layer. With the current setup, a far-field effect of these eastern OWFs cannot be investigated as the Northfrisian coastal current transports the phytoplankton out of the model domain.

4.2 Altered ecological functioning

Primary production represents the major energy source for ecosystems globally (Imhoff et al, 2004). Our model results indicate that the construction of OWFs reduces available primary production, especially at the local scale, as a result of a higher abundance of filter feeders (Prins et al, 1997). Filtration activity transforms the carbon, nutrient and energy flows at OWFs from which the benthic food-web benefits, with faeces, pseudofaeces and dead mussels enriching the benthic organic pool, as observed in many shellfish aquaculture facilities worldwide (e.g. Cranford et al, 2007).

Our results suggest that the increased abundance of blue mussel at OWFs only moderately affects ecosystem functioning; they emphasize the blue mussel's role as an ecosystem engineer (Borthagaray and Carranza, 2007), not just locally but on a scale of greater than 100 km. Pelagic primary production is just one of many facets of ecosystem functioning, which have been hypothesized to be altered by OWFs:

1. Networks of OWFs are beneficial for the conservation of threatened species by acting as *de facto* marine protected areas (Inger et al, 2009). Access to most areas designated as OWFs is limited, primarily for safety reasons, which limits anthropogenic pressures such as fishing, including bottom trawling, potentially leading to an increased level of biodiversity at OWFs as compared to unprotected areas (Kaiser et al, 2006; Tillin et al, 2006; Inger et al, 2009).

2. Mussels such as the blue mussel play a significant role in modifying the natural substrate and increasing species richness (Borthagaray and Carranza, 2007). The blue mussel bioengineers its surrounding environment through shell litter fall (White and Pickett, 1985), water filtration and clarification (Newell, 2004), concentration of nutrients (van Broekhoven et al, 2014), ultimately increasing the species diversity and landscape heterogeneity as a result of structural and functional effects (Norling and Kautsky, 2007). Shells, both dead

or living, increase the degree of habitat complexity, encouraging a higher level of species richness (White and Pickett, 1985). Bivalve and gastropod shells are persistent and abundant physical structures which provide substrata for attachment and refuge from predation as well as physical or physiological stress (Gutiérrez et al, 2003).

3. Mediated through the associated epibenthic community, OWF constructions can act as stepping stones for the dispersal of exotic species (Glasby et al, 2007). The artificial habitat is open for colonization by new species assemblages (Wilson and Elliott, 2009), which could not quickly establish in soft-bottom sea regions. One example of this is *Telmatogeton japonicus*, the marine splash midge, which is native to Australasian waters. Known to be transported on the hulls of ships, it has been observed at OWFs in Denmark and along the Swedish Baltic coast (Wilhelmsson and Malm, 2008). The projected density of offshore constructions will likely facilitate immigration by non-native species (Bulleri and Airoldi, 2005), such as the leathery sea squirt (*Styela clava*), slipper limpet (*Crepidula fornicate*), pacific oyster (*Crassostrea gigas*) and Japanese skeleton shrimp (*Caprella mutica*) (Buschbaum and Gutow, 2005; Diederich et al, 2005; Lützen, 1999; Thieltges et al, 2003). Through these changes in biodiversity, OWFs could shape the marine ecosystem beyond their physical boundaries.

4. blue mussels are a highly diverse prey source capable of supporting higher trophic levels, especially vagile demersal megafauna (e.g. fish like *Trisopterus luscus* and crabs like *Cancer pagurus*) (Langhamer et al, 2009; Reubens et al, 2011). Their abundance and distribution at OWFs is driven by changes in attraction, production and redistribution (Bohnsack, 1989). An increase in the population of vagile demersal megafauna further impact the local community, leading to increased species diversity (Wilhelmsson and Malm, 2008). Larger megafauna may also benefit from increased food availability (Brasseur et al, 2012), with seals extending their distribution towards an OWF after construction in Denmark (Tougaard et al, 2006).

Many of the ecosystem feedbacks and hence changes to ecosystem services are yet unknown and need to be studied both *in situ* and in future system-wide synoptic studies. Mostly for supporting the planning process, a high number of often not published studies were conducted, almost always considering individual offshore wind turbines and focused on selected potential effects such as on birds, megafauna, or hydrodynamics (Bailey et al, 2014, e.g.).

4.3 Limitations and outlook

This study is the first large scale assessment of epistuctural blue mussel filtration at OWFs. The level of quantification achieved in our study clearly shows that at least with respect to primary production there is a non-negligible regional ecosystem effect originating from epistuctural blue mussel filtration. Modular model systems are needed to integrate effects and feedbacks across trophic levels and up to the regional scale, as proposed and to a large but not complete degree realised here.

There are still large uncertainties related to simulating complex ecosystem interactions. The reconstruction of filter feeder epistuctural abundance is yet a simple up-scaling of data sampled from single piles; and the benthic reconstruction suffers from the sampling bias introduced by opportunistic observations. These data issues will likely ameliorate in the future with monitoring programs and systematic surveys. The filtration model is very simple and does not include, for example, age structured population dynamics or nutrient recycling: this study shows how essential it is to improve filtration models, which so far are often neglected in shelf ecosystem models. For studies addressing the forthcoming decades, a more accurate quantification of the epistuctural filtration effect seems to be required. Physical effects of wind farm on atmospheric boundary layer circulation and ocean current and vertical mixing (e.g. McCombs et al, 2014; Carpenter et al, 2016) have not been considered by our coupled model: there is still a scale problem that needs to be addressed in physical modelling to bridge the wind pile (order of 10 m) to ecosystem (order of 100 km) scales; recent developments in nested or unstructured models seem promising here. Last but not least, the uncertainties of the simulation result are difficult to quantify: estimates of production in the literature have large uncertainties themselves. There are no regional studies to which the filtration rates can be compared. Our findings of a 4% annual and up to 10% local effect in both production and phytoplankton stock can justify further research into the large-scale impact of OWFs. Remote sensing observations might provide the first regional direct observations of OWF effects as the resolution of the sensors now allows the identification of single wind turbines. The more OWFs are completed and inhabited by mussels, the more likely a filtration effect can be observed directly.

5 Conclusions

Construction of offshore wind farms (OWFs) in the southern North Sea is predicted to continue into the future, highlighting the importance of understanding the potential nature and magnitude of the environmental impact of the epifaunal biomass known to accumulate on their subsurface structures. Epifaunal communities at OWFs in the southern North Sea are dominated by the blue mussel, a filter feeder capable of inducing extensive ecological change through filtration, amongst other processes. The construction of all currently planned, consented and under construction OWFs, in addition to those already in operation, is likely to increase the overall abundance of blue mussels in the southern North Sea by more than 10%. In addition to providing an additional food source and a new habitat, blue mussels also remove phytoplankton from the water column through filtration, which impacts ecosystem functioning.

Reconstructing and analysing the impact of epifaunal biomass at OWFs on pelagic primary production at a larger spatial scale, in this case the southern North Sea, provides valuable insights into ecosystem functioning which are not visible at the scale of a single offshore wind turbine or OWF. The impact of OWFs on annual primary production is predominately local, at short time scales there is a larger regional effect on biomass and productivity that extends up to several 100s of km beyond the bounds of the OWF area.

Code and data availability

Development code and documentation are hosted on Sourceforge (<https://sf.net/p/mosso/code>) The release version 1.0.1 is permanently archived and accessible under the digital object identifier <https://doi.org/10.5281/zenodo.43892>. All external software used is available as open source and can be obtained together with MOSSCO. The simulations were performed in parallel on 192 cores on the Jureca high performance computer at Forschungszentrum Jülich, Germany (Krause and Thörnig, 2016).

Satellite data are freely available from the Ocean Colour Climate Change Initiative dataset, Version 3.1, European Space Agency, at <http://www.esa-oceancolour-cci.org/>. Meteorological forcing data are available on request from CoastDat at www.coastdat.de (Geyer, 2014). Chlorophyll and other water quality parameters are freely available at <http://www.waterbase.nl> (Rijkswaterstaat, 2017).

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