Quantifying the cOntribUTion of Fouling fauna to the Local carbon budget of an Offshore Wind farm

SUMMARY

1. Context and Rationale

Offshore wind farms (OWFs) are rapidly expanding across European waters as part of the transition towards low-carbon energy systems. As OWF capacity grows, these structures increasingly shape marine ecosystems at both local and regional scales. Turbine foundations introduce extensive hard substrate into soft-sediment environments, and are rapidly colonised by dense fouling communities dominated by suspension-feeding organisms. These communities filter large volumes of seawater for food and release significant quantities of faecal pellets. This process alters particle fluxes, sediment composition, and biogeochemical cycling around the turbines. Although earlier studies documented elevated organic matter and changes in faunal composition near wind turbines, the precise magnitude, mechanisms, and ecological significance of these effects remained insufficiently quantified. The OUTFLOW project was therefore initiated to provide an integrated assessment of how fouling organisms influence carbon cycling at multiple spatial scales within and around OWFs in the Belgian Part of the North Sea (BPNS).

2. Project Objectives

The project aimed to quantify the contribution of fouling fauna to the local and regional carbon budget of offshore wind farms. To achieve this, OUTFLOW set five key objectives. First, the project sought to develop and apply methodologies capable of distinguishing and quantifying the relative contributions of different sources of organic matter to the marine environment. Second, it aimed to determine whether faecal pellets produced by fouling communities become incorporated into benthic food webs. Third, it intended to describe the biogeochemical mineralisation processes occurring in the sediments surrounding wind turbines, particularly within the permeable sediment regime that typifies the BPNS. Fourth, the project worked to characterise the carbon footprint of an individual turbine and quantify the amount of carbon stored and recycled within its immediate surroundings. Finally, OUTFLOW aimed to upscale local observations to wind farm and regional scales using advanced hydrodynamic and biogeochemical modelling tools.

3. Methodological Approach

To address these objectives, OUTFLOW employed an interdisciplinary approach combining field observations, laboratory analyses, food-web modelling, and multi-scale hydrodynamic and biogeochemical simulations. Field campaigns involved high-resolution sediment sampling around turbine foundations, using transects from 7 to 75 metres from the scour protection layer, and included the collection of porewater nutrients, granulometry, organic carbon, pigments, and samples for stable isotope analyses. Water-column sampling campaigns provided detailed information on suspended particulate matter, chlorophyll-a, and environmental conditions across different current regimes in the cross-bordering offshore wind farm zone at the border of Belgian and Dutch part of the North Sea. Laboratory analyses included the use of stable isotope and compound-specific amino acid fingerprinting to identify the contributions of faecal pellet-derived organic matter to water-column

organic matter pools. Food-web structure and carbon flows were reconstructed using a Linear Inverse Modelling framework, allowing comparisons between natural coarse-sediment, fine-sediment, and OWF communities. Hydrodynamic and biogeochemical modelling, based on the COHERENS model, used nested grids with spatial resolutions down to 10 metres to simulate the dispersal and deposition of faecal pellets and plankton-derived detritus, and regional 500-metre resolution simulations to analyse OWF-induced effects on primary production, particle fluxes, and benthic carbon.

4. Key Scientific Findings

4.1 Effects of Offshore Wind Farms on Food Web Structure

The OWF food web exhibited the highest species richness among the studied habitats, but it also had the lowest total faunal biomass. The reduced biomass was largely attributable to the absence of the large deposit-feeding sea urchin *Echinocardium cordatum*, a dominant biomass contributor in reference sediments. Although the OWF food web contained many more trophic links than the coarse or fine sediment systems, these links were generally weak. Food-web connectance and recycling indices were lower in the OWF than in the reference webs, suggesting a system that is less mature and potentially less stable. Hard-substrate species, despite covering only a very small fraction of the total area, played a disproportionately large role in carbon uptake. They contributed roughly one quarter of the uptake of water-column carbon within the OWF food web, creating a distinct trophic pathway linking pelagic production to benthic deposition via fouling species.

4.2 Faecal Pellet Production and Deposition

Fouling organisms such as the blue mussel *Mytilus edulis*, the amphipod *Jassa hermani*, and the plumose anemone *Metridium senile* produced substantial quantities of faecal pellets, with *Mytilus edulis* being the most important contributor. These pellets were rapidly exported to the seafloor, where they contributed to measurable organic enrichment near turbine foundations. However, FP deposition was strongly influenced by tidal currents, wake dynamics, and spatial variability in flows, resulting in complex patterns of accumulation. Although faecal pellets represented a novel and traceable source of carbon to the sediment, their contribution remained small relative to that of natural phytodetritus.. Nevertheless, FP deposition constitutes a functionally important pathway because it delivers organic matter efficiently and rapidly to the seafloor.

4.3 Sediment Biogeochemistry and Mineralisation Dynamics

Sediments within the OWF area remained predominantly permeable, which facilitated rapid advective transport of porewater and limited the potential for long-term carbon burial. Although local increases in sedimentary total organic carbon reached nearly nine percent relative to background values, this carbon was not sequestered permanently. Mineralisation occur efficiently due to high-energy seabed conditions and permeable sediment structure. Mineralisation modelling demonstrated that the composition of deposited organic matter—particularly the proportion of FP versus plankton-derived material—strongly influenced degradation rates. Overall, the presence of turbines enhanced short-term carbon deposition, but it did not result in substantial long-term storage.

4.4 Water-Column Processes

Water-column observations showed that suspended particulate matter and chlorophyll concentrations were shaped primarily by regional hydrodynamics, including the influence of the Scheldt plume and tidal advection. Although some enhancement of particle mixing and resuspension occurred within the OWF zone, OWF-induced effects were relatively minor compared with background environmental variability. The alternating northward and southward flows produced strong spatial and temporal gradients that explained much of the observed variability. This finding underscores that OWF impacts on water-column properties are small relative to natural drivers at the regional scale.

4.5 Regional Upscaling and Ecosystem-Level Impacts

Model upscaling revealed that OWF impacts, while clearly observable at local scales, were modest when spread across larger spatial domains. Simulations showed that phytoplankton biomass was reduced within a radius of approximately seven kilometres around the OWF due to filtration by fouling fauna. However, a ring of slightly elevated phytoplankton biomass emerged farther from the turbines, driven by nutrient release associated with excretion by the fouling community. Faecal pellet deposition was confined largely to the OWF footprint but extended up to ten kilometres along the major tidal axis. Changes in benthic carbon stocks were smaller than changes in deposition fluxes, because rapid mineralisation prevented substantial long-term accumulation. In summary, although OWFs significantly modify carbon pathways and benthic functioning in their immediate vicinity, their influence on regional ecosystem processes is relatively small.

5. Conclusions

The OUTFLOW project provides the first integrated, field-validated, and model-supported assessment of how fouling fauna alter carbon dynamics in and around offshore wind farms in the Belgian Part of the North Sea. The project demonstrates that fouling communities create novel trophic pathways that channel water-column production to the seafloor, leading to localised increases in benthic organic matter and measurable changes in food-web structure. However, the permeable nature of the sediments and the dynamic hydrodynamic environment strongly limit long-term carbon storage. While OWFs induce clear ecological and biogeochemical effects at the scale of individual turbines and wind farms, the broader regional effects remain modest. The findings highlight the importance of considering both physical sediment properties and hydrodynamic processes when assessing the potential of OWFs to influence carbon cycling or contribute to carbon storage.

6. Recommendations

The project recommends expanding field sampling around turbine foundations to include longer gradients, multiple axes relative to tidal flow, and different foundation types. Further work is needed to refine hydrodynamic models by incorporating local eddies, detailed wake dynamics, and interactions among turbines. Biomass gain or loss at individual turbines should be explicitly considered in upscaling analyses. Finally, continuous water-column monitoring using automated systems would provide essential year-round data to complement short-term sampling campaigns.

KEY WORDS: offshore wind farm, carbon cycling, food web, North Sea, upscaling