OLAMUR

Offshore Low-trophic Aquaculture in Multi-Use Scenario Realisation

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Executive Summary
The current task expanded the web-based operational decision support system (ODSS) from the Baltic Sea region to include the North Sea. The ODSS contains updated maps of human activity, environmental conditions, biomass yields, and nutrient and carbon capture potential for aquaculture species across both the Baltic and North Sea regions. Human use data was sourced from EMODnet, environmental conditions were calculated from Copernicus marine reanalysis products, and spatial models for aquaculture species were developed either within the OLAMUR project or sourced from scientific literature or previous projects. The tool includes spatial models for cultivating blue mussels (*Mytilus* spp.) and seaweeds like *Saccharina latissima*, *Fucus vesiculosus*, and *Ulva* sp. It provides optimal site-specific configurations for mussel farms, allowing scalability without significant nutrient or food limitations on macroalgal and mussel biomass yields. By integrating data on human use, environmental conditions, and production models, the web tool serves as a foundation for basin-scale multi-use planning. This provides managers and aqua-farmers with planning solutions to identify suitable locations for multi-use of low-trophic aquaculture and offshore wind parks. The report also illustrates the potential applications of the portal through case studies focused on multi-use and integrated multi-trophic aquaculture.

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1. Achieving sustainable coexistence in marine spaces through multiuse planning

Marine spaces are vital for various human uses, including transportation, energy production, fishing, tourism, and conservation. Each use relies on the seas for different benefits, such as providing food, enabling global trade, offering recreational areas, and sustaining biodiversity. However, as the demand for sea resources grows, so does the pressure on these marine environments (Halpern et al., 2015). This leads to spatial conflicts between different uses, such as fisheries overlapping with shipping routes or energy installations impacting marine biodiversity. To sustainably meet the growing demand, an integrated approach to marine spatial planning is essential. This approach should accommodate multiple uses within a single area, a concept known as "multiuse."

The multiuse concept in marine space encourages coexistence, where compatible activities can operate together within a shared marine area. This approach reduces spatial conflicts and maximizes the utility of limited marine resources, creating efficiencies that are essential for sustainable development. By strategically combining activities, marine spatial planning can provide social, economic, and environmental benefits without overburdening any single area. The multiuse approach also allows for the conservation of marine ecosystems by reducing the need for new infrastructure and minimizing human impact across multiple sites.

A promising solution for sustainable marine use involves relocating and concentrating human activities in designated offshore areas where expansion is less constrained by competing interests, such as recreational use or resource extraction. By consolidating activities in specific offshore zones, infrastructure, economic, and environmental benefits can be achieved through a multi-use approach, while other marine areas remain less impacted or are designated as strictly protected zones (MPAs) (Holmer et al., 2010; Buck et al., 2018).

The number of marine wind farms generating renewable energy as a sustainable alternative to fossil fuels is steadily increasing worldwide. However, there is opposition to expanding wind farms near scenic coastlines due to aesthetic concerns and the impact on the natural landscape. Relocating wind farms further offshore could help address these concerns while capitalizing on stronger and more consistent winds to boost energy production, albeit with increased construction and operational costs (Buck et al., 2004, 2018; Bugnot et al., 2021).

Combining offshore wind farms (OWF) with low-trophic aquaculture (LTA) has emerged as an effective multi-use strategy, collectively offering benefits such as emission-free energy production, artificial reefs that enhance marine biodiversity, nutrient-rich seafood, and restorative ecosystem services. Low-trophic aquaculture, i.e. farming species at lower food chain levels such as seaweed, shellfish, and other filter feeders, is highly sustainable due to its low resource requirements and positive environmental impact, making LTA a valuable addition to multi-use areas that balances economic and ecological goals and supports biodiversity (Buck and Langan, 2017; Buck et al., 2018; Gephart et al., 2021; Golden et al., 2021; Krause et al., 2022).

LTA provides key ecosystem services, including food production with a low carbon footprint and reduced resource use compared to terrestrial farming. Through photosynthesis and nutrient uptake, seaweed biomass incorporates carbon dioxide and dissolved nutrients from the water column. Similarly, mussels store carbon in their shells via bio-calcification and incorporate organic carbon and nutrients in their tissue through filtration. Harvesting these organisms effectively removes nitrogen and phosphorus from marine environments, improving water quality in nutrient-rich (eutrophic) areas while also facilitating nutrient and carbon recycling from sea to land, thereby contributing to a circular bioeconomy (Lindahl et al., 2005; Gephart et al., 2021; Krause et al., 2022; Duarte et al., 2022).

Several projects in northern Europe have explored the feasibility of co-locating offshore LTA with OWF in areas typically restricted due to operational safety and high infrastructure costs. Studies have shown that combining OWF with aquaculture of blue mussels (*Mytilus* spp.) and sugar kelp (*Saccharina latissima*) has strong potential in the saline waters of the North Sea (van den Burg et al., 2016, 2020). However, in the brackish Baltic Sea, low salinity limits the growth of many aquaculture species. In nutrient-rich, low-salinity regions, LTA can serve primarily for nutrient removal (mitigation culture) rather than direct food production. Mussel mitigation culture in these areas involves higher densities of smaller, variably sized mussels, distinct from those cultivated commercially for human consumption (Nielsen et al., 2016; Petersen et al., 2019; Timmermann et al., 2019; Kotta et al., 2020). When conducted sustainably, this practice can provide multiple ecosystem services, such as nutrient removal and the restoration of adjacent valuable benthic habitats.

Effective multiuse marine planning requires detailed spatial data across all sectors, e.g. transportation, energy, fishing, tourism, and conservation, each with unique spatial needs, economic impacts, and their combined environmental effects. Planners need high-resolution data and sector-specific insights to understand activity locations, interactions, and cumulative environmental impacts, enabling sustainable coexistence.

This analysis is complex: each sector has unique stakeholders, economic interests, and regulations, while marine ecosystems are interconnected and dynamic. Effective multiuse planning requires integrating these factors into detailed spatial analyses. Oversimplification risks missing critical details, leading to harmful environmental impacts or sector conflicts. Thus, spatial plans must consider both fine-scale environmental and socio-economic impacts for realistic, sustainable outcomes.

Obtaining the necessary data for such planning is unfeasible without the use of synoptic modeling to generate dense 4D datasets. This typically involves operational hydrodynamic models that incorporate advanced data assimilation schemes, using observation systems such as satellites, drones, buoys, and integrated sensor networks. These systems provide valuable validation data on sea conditions, ecosystem health, and human activities. Combined with sophisticated models of nature assets, environmental processes, and cumulative impacts, these observations offer valuable insights into the interactions between various activities and the marine environment. Integrated models also allow planners to simulate and evaluate multiuse scenarios, assessing the impacts of different configurations before implementation.

Given the volume and complexity of the data involved, it is essential to develop efficient ways to communicate this information to stakeholders and decision-makers. Web-based decision support tools can be invaluable here, providing a centralized, interactive platform where users can access, analyse and visualize the data. These tools can make complex information accessible and understandable, facilitating better-informed decisions. By integrating maps, sectoral overlays, and scenario simulations, a web-based decision support tool allows stakeholders to explore potential outcomes, assess risks, and collaborate more effectively, paving the way for a more streamlined and transparent multiuse planning process.

Figure 1. Conceptual diagram illustrating the planning of sustainable energy and food production in offshore areas using advanced web-based decision support tools (AI-generated image).

2. Data-driven decision support for sustainable multi-use: ODSS as a tool for low-trophic aquaculture and cross-border collaboration

Decision Support Tools (DSTs) are essential for integrated marine spatial planning, providing interactive platforms for centralized data management, analysis, interpretation and visualization of spatial data across different sectors. Web-based DSTs use intuitive interfaces to make complex spatial data accessible to non-technical stakeholders, with tools like map overlays and interactive models. Their collaborative nature improves communication and consensus, aligning planning goals across sectors and supporting long-term strategic planning by visualizing potential impacts of marine use configurations.

The Operational Decision Support System (ODSS; https://gis.sea.ee/odss) is a geoportal developed as part of the Baltic Blue Growth project to support the advancement of low-trophic aquaculture in the Baltic Sea region (https://submariner-network.eu/baltic-blue-growth/). Currently, it serves as a valuable resource for mussel and seaweed farmers, spatial planners, and other stakeholders, offering data-driven insights to identify optimal locations for low-trophic farming in the Baltic Sea. The ODSS has been used to identify the most suitable locations for low-trophic aquaculture during the Estonian Maritime Spatial Planning process. Additionally, the tool has been employed to quantify the intensity of associated ecosystem services during the preparation of Estonia's aquaculture development plans. It has also supported industry partners in identifying optimal test farming sites, particularly valuable since no mussel farms existed in the northeastern Baltic Sea when the tool was introduced. At the Baltic Sea scale, the ODSS has provided insights into the potential for low-trophic aquaculture to mitigate eutrophication in the region (Kotta et al., 2020, 2022).

The ODSS combines spatial data on environmental conditions, current and planned human activities, and modeled production maps for seaweed and mussels, enabling users to assess the potential of different marine areas for cultivation. The portal offers tools for overlap analysis of environmental and human activity data, helping to identify conflicts and synergies among various marine resource users. In addition to yield predictions, it supports decision-making with ecosystem service indicators related to low-trophic aquaculture, such as carbon and nutrient extraction and biomass yield. This data-driven approach provides insights into mitigating critical challenges like eutrophication. The platform also enhances transboundary collaboration, bringing together stakeholders across the Baltic Sea to advance sustainable aquaculture practices.

3. Data overview in ODSS: Integrating human use data with environmental and LTA farming data for the Baltic and North Seas

Human use data in the ODSS tool were sourced from European Marine Observation and Data Network (EMODnet; EMODnet; https://emodnet.ec.europa.eu/geoviewer/). These datasets cover sectors such as shipping, fishing, energy infrastructure, tourism, and marine protected areas in the Baltic and North Seas. Detailed and harmonized spatial data includes shipping routes, vessel density, fishing grounds, aquaculture sites, offshore wind farms, oil and gas platforms, tourism areas, dredging and dumping sites, marine protected areas, military zones, and subsea cables and pipelines. By integrating data from multiple sources, EMODnet provides a detailed view of human presence and usage in these marine environments. This information supports decision-makers, researchers, and stakeholders in assessing and managing the sustainable use of marine resources, enabling informed decisions that balance economic development with environmental protection across European seas.

Environmental data in the ODSS portal were sourced from Copernicus (https://data.marine.copernicus.eu/products), integrating multi-year products specifically tailored for the Baltic and North Sea regions. For the Baltic Sea, the data were derived from the BALTICSEA_MULTIYEAR_PHY_003_011 and BALTICSEA_MULTIYEAR_BGC_003_012 products. The biogeochemical data, including key nutrients (phosphate, nitrate, and ammonium), chlorophyll-a concentrations, dissolved oxygen, and Secchi depth, were modeled using the Ecological Regional Ocean Model (ERGOM), specifically adapted for the Baltic Sea. For the North Sea region, data came from NWSHELF_MULTIYEAR_PHY_004_009 and NWSHELF_MULTIYEAR_BGC_004_011 products. These products use a coupled physical-biogeochemical model system that integrates the Nucleus for European Modelling of the Ocean (NEMO) model with biogeochemical modules to cover biogeochemical parameters. The long-term time series for these regions extends back to 1993, providing daily, monthly, and annual mean values essential for analyzing seasonal and interannual trends. The horizontal resolution of these products ranges from 2 km for Baltic Sea datasets to 7 km for North Sea datasets.

A harmonized geo-referenced database, compiling all available experimental and commercial **data on macroalgal and mussel cultivation** in the Baltic and North Sea regions, was used to train models predicting the growth of these species along key environmental gradients. The database comprises observations from existing farms and controlled experimental studies, incorporating original datasets from the INTERREG Baltic EcoMussel, Baltic Blue Growth, and GRASS projects, as well as national research initiatives from Estonia, Finland, Sweden, Denmark, and Germany, and eventually the OLAMUR project. The modeling of seaweed and mussel farming is beyond the scope of this deliverable but is addressed under Work Package 3. This report primarily highlights modeling activities conducted before the OLAMUR project and summarizes key findings from OLAMUR modeling completed prior to this report's submission. Detailed information on forcing data, model calibration, validation, and specific topics—such as mussel larval dispersal from natural mussel banks, modeled using coupled hydrodynamic agent-based models—will be provided in the Work Package 3 deliverables. The ODSS portal utilizes these modeling outputs to support user-driven assessments of the feasibility of low-trophic farming within various multi-use contexts.

4. Modeling growth, nutrient, and carbon capture of seaweed and mussels in the Baltic and North Sea regions

Seaweed growth modeling in the Baltic Sea region considers both abiotic and biotic factors, with abiotic constraints like light, nutrients, temperature, and salinity often playing a dominant role (Field et al., 1998; Hauxwell et al., 2003; Titlyanov and Titlyanova, 2010). Light availability, influenced by sea surface irradiance, water optics, and self-shading within algal communities, defines photosynthetic rates and growth limits in natural settings. However, in macroalgal farms where algae are suspended, self-shading constraints are reduced, allowing optimal access to light and nutrients (Kirk, 1994; Anthony et al., 2004).

Nutrient availability significantly impacts macroalgal production (Raven and Hurd, 2012). Some species can store nutrients to buffer against shortages (Lüning, 1990), though high nitrogen and phosphorus levels enhance growth. Excessive seaweed density or limited water exchange can limit nutrient replenishment and reduce yields in farm settings (Titlyanov and Titlyanova, 2010). Temperature is known to have a weaker influence on growth compared to light and nutrient availability (Wiencke and tom Dieck, 1990; Nejrup et al., 2013). Salinity, however, can be a major stressor, particularly in the Baltic Sea, where gradients affect species diversity and distribution, sometimes overriding other environmental factors (Bonsdorff and Pearson, 1999; Krause-Jensen et al., 2007).

For modeling purposes, key environmental variables were obtained from the Copernicus Marine Portal, as detailed in Subsection 3, "Data Overview," in the ODSS. Macroalgal growth was measured by dry weight rather than length, allowing negative growth estimates during resource limitations. Growth rates were normalized per day, and Boosted Regression Trees (BRT) were applied to model relationships between growth yields and environmental variables such as temperature, salinity, irradiance, wave height, and nutrient levels (Elith et al., 2008). These models projected the production potential for species like *Saccharina latissima*, *Ulva intestinalis*, and *Fucus vesiculosus* across the Baltic Sea over entire harvest cycles.

To evaluate nutrient uptake by farmed macroalgae, the study integrated hydrodynamic data with growth potential models, estimating nutrient removal effects spatially. Using daily mean current velocities, the study defined maximum distances between farms to minimize nutrient limitation impacts on growth, ensuring effective nutrient cycling and sustainable production (Kotta et al., 2022).

In addition to the statistical approach described above for the three aquaculture species, we also used an alternative *Saccharina latissima* growth model tailored to the western Baltic Sea region. This model offers a structured framework for simulating the biomass development and nutrient extraction potential of this seaweed in aquaculture environments. This model divides the biomass into structural, carbon storage, and nitrogen storage components, each serving different functions in the plant's growth and nutrient dynamics. Phosphorus concentration is considered low and is managed without a separate storage compartment. Salinity is a key factor influencing the growth of *Saccharina latissima* in the region, as sugar kelp growth is known to decrease to 50% of its optimum at a salinity of 16 psu. To support modeling efforts, an average salinity dataset, along with other relevant variables for the key growth period from October to May, was generated using the Copernicus Marine Data Products.

The model operates in daily time steps, with each step broken down into computing growth demands, assessing available supplies, and allocating resources accordingly. Key inputs for the growth include light (affecting photosynthesis), nutrient availability in the water, and the plant's ability to resorb nutrients from senescent tissue. This allows the model to simulate daily growth based on changing environmental factors and resource availability.

Carbon, nitrogen, and phosphorus are sourced through photosynthesis, nutrient uptake from the water, and recycling within the plant. Growth demands represent the resources required to support basic metabolism, tissue construction, and exudation. Carbon is the primary element required for photosynthesis, while nitrogen and phosphorus are critical for overall health and nutrient balance.

Resource allocation prioritizes maintenance respiration, which is essential for the plant’s survival. Structural growth follows, with carbon and nitrogen stores adjusted according to remaining supplies. If nutrients are insufficient, the plant’s structural biomass may decrease, affecting overall health. The carbon and nitrogen stores, acting as reserves, help buffer the plant against temporary nutrient shortages.

In calibrating the model, data from seaweed growth experiments were used to fine-tune parameters, especially the rates of nutrient and carbon acquisition. The calibrated model enables predictions of *S. latissima* biomass growth under varying environmental conditions, providing insights into carbon and nutrient extraction rates across different scenarios. This framework aids in optimizing farm layouts and enhancing nutrient cycling efficiency, which are essential for sustainable seaweed aquaculture in the Baltic and North Sea regions. For further details, refer to Bruhn et al. (2024).

Currently, similar dynamic models for *Ulva intestinalis* and *Fucus vesiculosus* are under development as part of the OLAMUR project. Once these models are completed, the existing spatial predictions based on statistical models will be replaced with predictions generated by the dynamic models.

Mussel growth modeling in the Baltic and North Sea regions employed an innovative approach through a regional Dynamic Energy Budget (DEB) model, tailored to include biocalcification processes (Vaher et al., 2024). This model evaluates the growth, nutrient cycling, and carbon capture potential of farmed blue mussels (*Mytilus edulis/trossulus*) under region-specific conditions. DEB theory offers a mechanistic framework, quantifying metabolic processes like energy, mass, and elemental budgets while maintaining the organism's chemical homeostasis (Kooijman, 2010). The model's primary function is to track nutrient fluxes and estimate carbon capture in shellfish farms, a process crucial for climate mitigation assessments in these ecologically diverse regions (Lavaud et al., 2020, 2021; Kotta et al., 2023).

A significant challenge in modeling mussel growth has been accurately representing carbon capture through shell growth, which traditional DEB models often tie to overall body mass. Research has shown that shell growth may be decoupled from somatic tissue growth (Campana, 1990; Lewis and Cerrato, 1997), and the adapted DEB model developed in the OLAMUR project addresses this by treating shell production independently. Using DEB product rules, the model dynamically quantifies shell formation, linking it to primary fluxes such as assimilation, growth, and dissipation (Kooijman, 2010; Pecquerie et al., 2012). This advanced modeling of shell growth expands the framework's utility beyond aquaculture, providing insights into biocalcification in other ecosystems like coral reefs and algal populations (Muller and Nisbet, 2014).

Operating on a daily time scale, the DEB model calculates nutrient and carbon fluxes within a single mussel as influenced by salinity, temperature, and chlorophyll a levels. This structure allows the model to dynamically reflect environmental changes on mussel physiology and nutrient cycling, offering a rigorous simulation of how factors like salinity gradients and seasonal shifts affect carbon capture. To scale up from individual mussel growth to a full farm, the model applies realistic mussel densities, capturing how high-density setups can reduce phytoplankton concentrations due to mussel filtration. By considering both phytoplankton availability and horizontal water flow, the model adjusts food supply levels to reflect potential food limitations within the farm (Holbach et al., 2020).

The model calculates daily phytoplankton uptake, using flow velocity data to gauge whether incoming food is sufficient or if depletion within the farm is likely. Adjusted phytoplankton density is then used in the DEB model to simulate phytoplankton ingestion rates and mussel growth under realistic conditions, providing an accurate representation of biomass growth at the farm level. This approach enables the model to predict the impact of mussel farming on local nutrient cycles, offering a valuable tool for optimizing farm setups and assessing the role of mussel aquaculture in nutrient management and carbon sequestration within the Baltic and North Sea regions.

Importantly, farming data are still being collected at the pilot sites, and validated data for advanced seaweed and mussel models are yet to be developed within the OLAMUR project. Once these new model outputs are available, they will be uploaded to the ODSS portal, providing stakeholders with up-to-date information for conducting various multi-use or IMTA-related analyses in the portal.

5. Development of the ODSS within the OLAMUR Project

The ODSS tool was developed to support various end-users in making informed decisions about algal and mussel farming. These decisions are based on the best available monitoring and modeling data, enhancing users' capacity to consider environmental, economic, and socio-economic aspects of long-term aquaculture (LTA) decision-making (Figure 2).

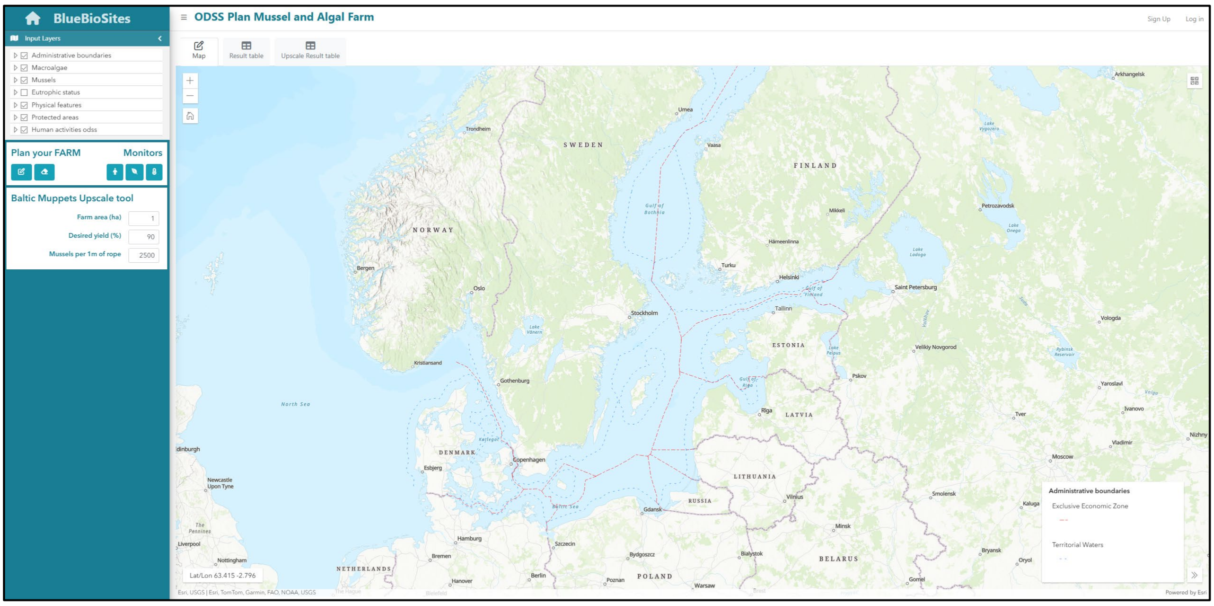

Figure 2. Landing page of the ODSS portal for decision support in algal and mussel farming.

The ODSS tool's information flow begins with the collection of near real-time observations from the Baltic and North Seas, retrieved from Copernicus. This data is stored in a PostgreSQL database and is automatically downloaded into the system. It is then combined with data from farms and processed through various models described above that simulate algal and mussel growth and production potential. The results are integrated and visualized through an ArcGIS server and made available via ODSS, where users can access data outputs. Additionally, a web map service is provided for geospatial visualization, while an MS SQL database is used for data storage and input uploads, supporting user decision-making across environmental, economic, and socio-economic dimensions (Figure 3).

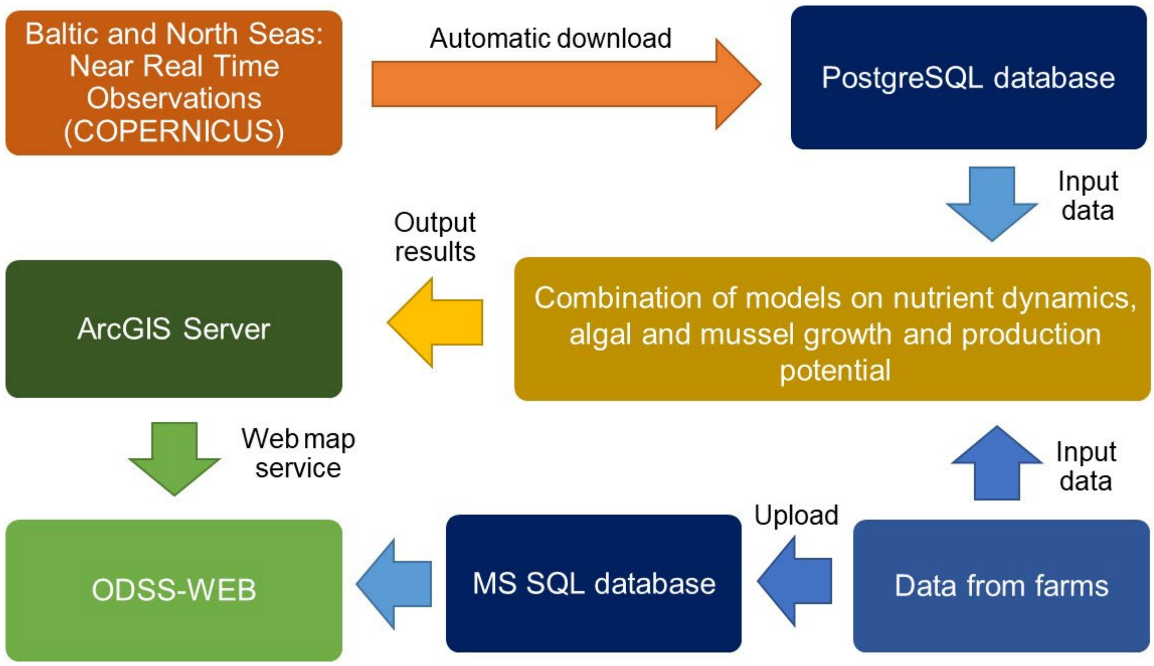

Figure 3. Schematic information flow of the ODSS tool.

In the OLAMUR project, task 2.3 expanded the Operational Decision Support System (ODSS), extending its coverage from the Baltic Sea to the North Sea. To ensure comparable and harmonized environmental data, long-term spatial statistics for key environmental variables were sourced from Copernicus marine services. Spatial models capable of predicting biomass yields, nutrient and carbon uptake for low-trophic aquaculture species in both the North and Baltic Sea regions, including blue mussels (*Mytilus* spp.) and seaweeds like *Saccharina latissima*, *Fucus vesiculosus*, and *Ulva* sp., were identified and refined.

These map layers were then integrated into the ODSS platform to support basin-scale multi-use planning for OWF, low-trophic aquaculture, and Integrated Multi-Trophic Aquaculture (IMTA) solutions. This functionality aids different actors in locating optimal sites for low-trophic aquaculture and provides site-specific farm configurations to enable upscaling without significantly impacting nutrient or food availability for shellfish yields. By combining data layers, the tool also identifies potential co-location sites for LTA, IMTA, and existing or planned OWFs.

The "Plan Your Farm" feature in ODSS enables users to select a specific area of interest and access detailed statistics on environmental factors, human activities, potential yields, and ecosystem services such as nutrient and carbon capture. This tool helps identify optimal cultivation sites that enhance ecosystem services while minimizing conflicts.

The same tool can be applied within designated human-use areas, such as wind parks, to evaluate the potential for low-trophic aquaculture solutions, such as seaweed or mussel farming, in each park. The analysis results can then guide the selection of wind park areas with the highest production potential or the best capacity for carbon and nutrient mitigation, depending on the specific objectives of the low-trophic aquaculture initiative.

To support the scaling up of mussel farming, a specialized ODSS tool integrates DEB-based mussel spatial growth models with 3D hydrodynamic modeling. This tool evaluates the maximum number of mussels that can be cultivated within a given area of interest without encountering food (chlorophyll-a) limitations. If food limitations prevent maximum growth, the model adjusts mussel growth rates accordingly to reflect the reduced availability of resources. Users begin by defining an area within the Baltic Sea and entering specific parameters, such as rope density and the desired yield as a percentage of the theoretical maximum. This adjustment accounts for scenarios where mussel farms are expected to experience food limitations due to high density, preventing them from achieving their maximum growth potential. For instance, a user may opt for denser substrates at a slightly reduced yield, such as 70%, or set the yield to 100% if they prefer maximum growth potential. Based on these inputs, the tool assesses food availability in the chosen area and recommends the optimal substrate density for sustainable mussel growth (Figure 4).

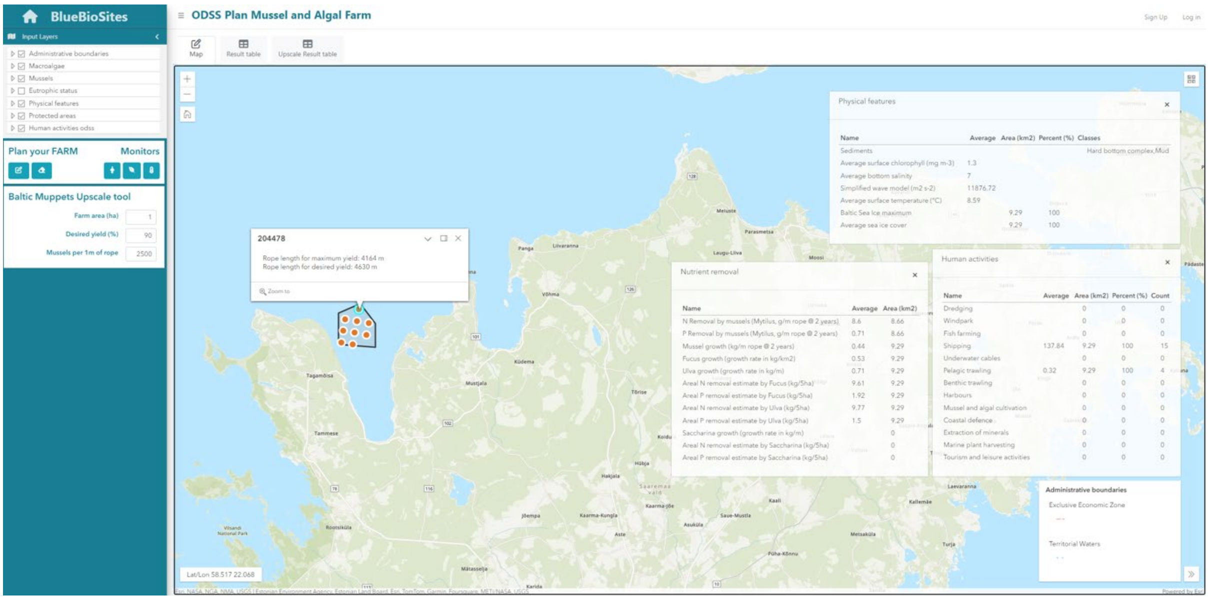

Figure 4. The current view of the ODSS portal provides a snapshot of analyses for identifying key statistics in an area of interest. This includes data on human activities, environmental variables, potential yield, and the delivery of ecosystem services from low trophic aquaculture species, as well as the scale-up potential for mussel farming.

The ODSS portal will incorporate the micro-siting multi-use tool developed under OLAMUR task 2.2. This tool is focused on high-resolution spatial planning for clusters of sea uses, specifically LTA integrated with wind farms. This tool will enable precise planning that balances constraints and objectives—such as minimizing costs, maximizing revenue, or reducing marine impact—across multiple uses. Key features include a customizable scoring table for objective weighting, compatibility with XML for multi-use configurations, and access to various data layers (e.g., bathymetry, currents) to inform productivity, costs, and impacts. The tool will initially support manual layout selection, with future development aiming for site optimization and user-friendly GUI integration. A prototype using placeholder parameters will enable testing within the ODSS, helping to refine data needs, functionality, and documentation for optimized offshore multi-use planning.

The OLAMUR project will keep collecting validation data from seaweed and mussel farms at the pilots and use these to further develop and update aquaculture models. As soon as the updated models become available, they will be integrated into the ODSS web tool for more precise and efficient analyses to be done.

Moreover, the OLAMUR project will compare biodiversity between natural boulder reefs in the area and artificial reef structures created by turbine foundations and scour protection. The analysis involves species identification by taxonomic experts using biological samples collected from the various reef structures, as well as video surveys conducted with remotely operated vehicles (ROVs). In addition, eDNA samples have been collected from the scraped material and the surrounding water column. Once the results and conclusions are finalized in early 2025, this information will also be integrated into the ODSS portal, enabling users to evaluate the potential for combining OWF with sustainable artificial reefs.

6. Using the ODSS tool to analyze basin-scale siting potential for multi-use low-trophic aquaculture in the North and Baltic Seas

Case study 1: Exploring the multi-use potential of offshore wind farms and low-trophic aquaculture

This case study explores the integration of offshore wind farms (OWF) with low-trophic aquaculture (LTA) at a regional scale, focusing on the North Sea-Baltic Sea transition zone (Figure 5), where national authorities plan to establish large-scale OWFs by 2030. The study examines areas suitable for co-locating OWFs with LTA, projecting potential biomass yields of blue mussels and sugar kelp that could serve as resources for food, feed, and materials. Additionally, it assesses the potential of LTA to capture and utilize carbon (C), nitrogen (N), and phosphorus (P), contributing to nutrient cycling and environmental health. Finally, the analyses are scaled up to a global context for similar LTA species (for further details, see also Maar et al., 2023).

Potential locations for OWF-LTA multi-use were assessed across the North Sea–Baltic Sea region using publicly available Copernicus data products. These products, based on numerical models and satellite observations, provided monthly aggregated spatial data of salinity, temperature, phytoplankton and horizontal flow velocity. For each product, we first calculated means and standard deviations for each month of the year and the time range from 2007 to 2017, while chlorophyll a concentrations were log-transformed beforehand. OWF locations were sourced from the 4C global offshore database (https://map.4coffshore.com/offshorewind/). In the North Sea–Baltic Sea transition zone, the projected offshore wind farm area is anticipated to grow threefold, reaching 325,000 ha, with 169,000 ha in the North Sea, 36,000 ha in the Danish Straits, and 120,000 ha in the Baltic Sea. Spatial models estimating harvest potential were applied for blue mussels (*Mytilus* spp.) and sugar kelp (*Saccharina latissima*).

The blue mussel harvest model was a function of temperature, chlorophyll a, and salinity. Model calculations of the critical flow velocity ratio (0.65 to 21), representing the minimum horizontal flow velocity required relative to the actual flow velocity to prevent severe food limitations, showed that there was sufficient food supply to avoid food limitation for the mussels at all sites. Mussel farms at salinity >16 psu were configured as commercial culture (human consumption), whereas the mussel farms at lower salinity were configured as nutrient mitigation culture. The total production potential of commercial mussel farms in the more saline North Sea and Danish Straits (>16 psu) showed an average area-specific harvest potential of 16-18 t-fresh weight (FW) ha^{-1} y^{-1} (Table 1, Figure 5). In the brackish Baltic Sea (8-16 psu), mussel farms produce smaller mussels unsuitable for human consumption. However, these farms can achieve higher harvest potentials, up to 33 t-FW ha^{-1} y^{-1}, as they are designed to maximize nutrient removal rather than growth for consumption.

The sugar kelp harvest model was a function of salinity only, since salinity is the dominating environmental factor determining the yield potential of kelp in brackish waters. It is assumed that sugar kelp is harvested before high summer temperatures may limit productivity. The sugar kelp model predicted a 3-4 times higher harvest potential of 16-18 t-FW ha^{-1} y^{-1} in the more saline North Sea and Danish Straits compared to the brackish Baltic Sea (Table 1, Figure 5). The model assumed that nutrient limitations for sugar kelp aquaculture within OWF regions are unlikely; however, this assumption should be subjected to sensitivity testing in the future. Our deployment of sugar kelp farms, covering just 10% of the wind farm area, and the strong water exchange typical of offshore areas, reduce this possibility. Overall, the potential LTA harvest was 17 t-FW ha^{-1} y^{-1} and 19 t-FW ha^{-1} y^{-1} at salinities >16 and <16, respectively, assuming a 50/50 areal distribution of mussels and sugar kelp.

However, according to the experience with wind farm operators and other multi-use projects, not all the area between wind turbines can be used for LTA. This is because accessible routes to the wind turbine must be maintained and safety zones around the wind farm area, and within the windfarm around cables, and the wind turbines. Additionally, this can be further combined with other multi-use scenarios (e.g., ecotourism, passive fishing, nature conservation) that also require space. Based on this, we have made a conservative calculation of the possible OWF-LTA areas, which is derived from the long-term results of other multi-use projects at both the national level (Germany) and international level (EU). When allocating 10% of OWF to LTA (i.e., a conservative regional scenario), the total LTA harvest potential reached 578 kt-FW y^{-1} with the yields being higher for blue mussels than sugar kelp (365 kt-FW y^{-1} mussels and 213 kt-FW y^{-1} seaweed; Figure 5). Total LTA harvest potential was highest in the North Sea with 290 kt-FW y^{-1}, followed by 226 kt-FW y^{-1} in Baltic Sea, and lowest with 62 kt-FW y^{-1} in the Danish Straits due to the smaller allocated area (Table 1, Figure 6).

Table 1. Potential yearly OWF-LTA harvest (kt-FW y^{-1}) in the North Sea - Baltic Sea transition zone. Projected total OWF areal size, the salinity (mean ± SD), and model results (mean ± SD) of area-specific harvest of blue mussels (commercial culture at salinity >16 psu, mitigation culture at salinity<16), sugar kelp and LTA (area distribution of 50/50 %), and total harvest of OWF-LTA for each area and all three areas. The blue mussel and sugar kelp harvest potentials are based on 10% of the total size of all OWF in the respective areas.

Area	OWF	Salinity	Blue mussel	Sugar kelp	OWF-LTA	Total OWF-LTA
North Sea	169	33.0 ± 0.8	16 ± 3	18 ± 0	17 ± 1	290
Danish Straits	36	21.0 ± 2.0	18 ± 2	16 ± 2	17 ± 1	62
West Baltic Sea	120	9.1 ± 1.6	33 ± 5	5 ± 1	19 ± 3	226
All areas	325		22 ± 14	13 ± 6	18 ± 3	578

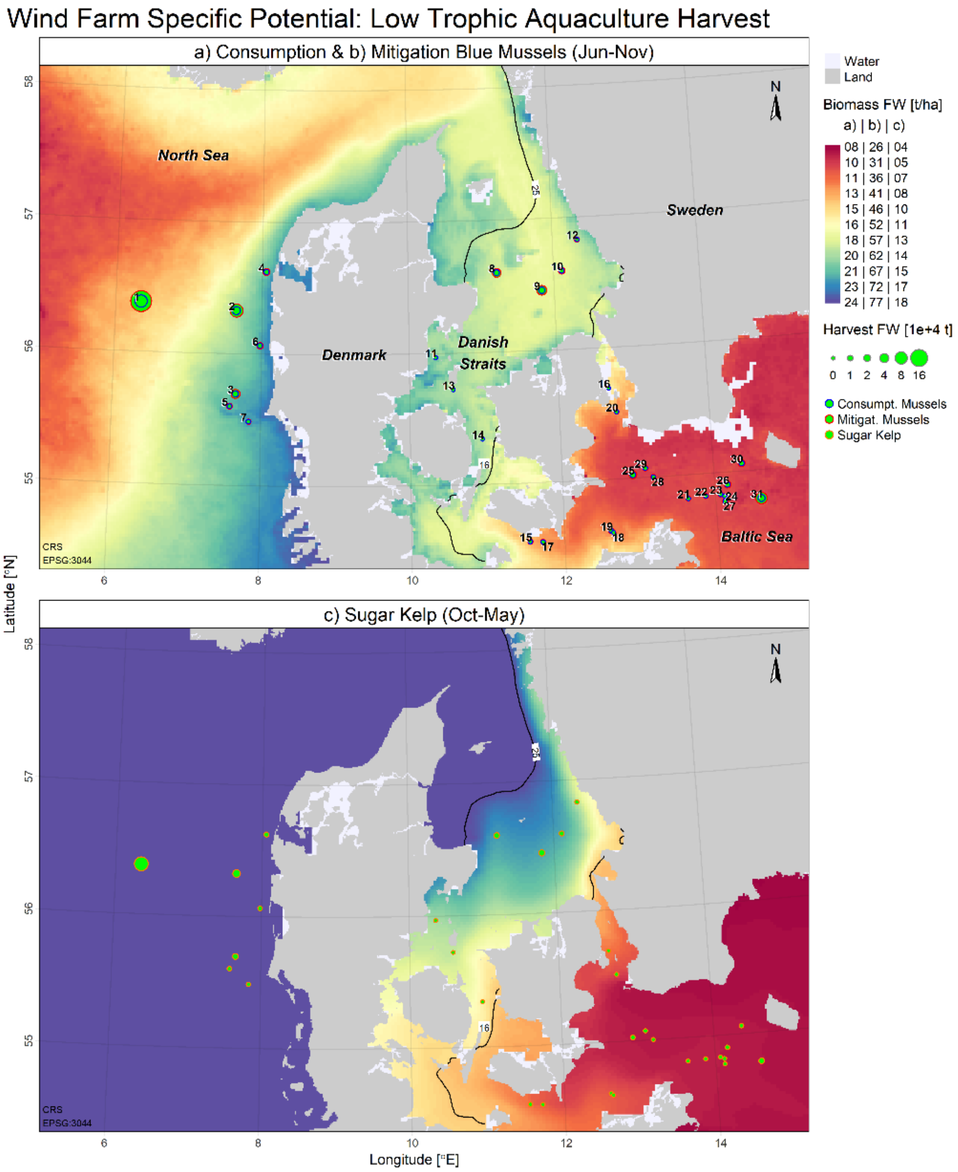

Figure 5. Harvest potential in the study area. Maps showing the harvest potential (10^4 t-FW y^{-1}) of a) commercial mussel culture for consumption, b) mussel mitigation culture, and c) sugar kelp for each OWF (green circles) indicated with an ID number sorted after decreasing average salinity (#1 to #31). The background colors show the area-specific harvest potential (t-FW ha^{-1} y^{-1}). The solid lines indicate the salinity borders between the three areas: the North Sea (west, >25 psu), the Danish Straits (middle, 16-25 psu), and the Baltic Sea (east, 8-16 psu). Above 25 psu, sugar kelp is assumed to grow optimally with respect to salinity, but other growth determining factors are not included here.

Nutrient and carbon removal by harvesting blue mussels and sugar kelp followed the pattern of FW-biomass production (Figure 6). Carbon capture was assessed here as CO_2 incorporated in seaweed biomass through photosynthesis and growth, and in mussel shells by bio-calcification. The CNP removal was the highest for mussels in the Baltic Sea due to the high potential biomass yield of small mitigation mussels. The overall potential CNP removal by LTA was highest in the North Sea followed by the Baltic Sea and was lowest in the Danish Straits due to the small allocated OWF area. The total NPC removal of LTA farms was 6 kt-N y^{-1}, 0.4 kt-P y^{-1} and 28 kt-C y^{-1} (102 kt-CO_2 y^{-1}) (Figure 6).

We are aware that the carbon capture potential of shellfish aquaculture remains a topic of debate, largely due to uncertainties surrounding the fate of carbon during shell formation. Bivalve shells form through biogenic calcification, where calcium ions (Ca^{2+}) and bicarbonate (HCO_3^-) combine to create calcium carbonate ($CaCO_3$), releasing CO_2 into the surrounding water (Frankignoulle et al., 1994; Emerson and Hedges, 2008). This process involves two carbon pathways: a short-term release of CO_2, which may be used by primary producers or re-enter the atmosphere (Heinze et al., 2015), and a long-term pathway where carbon is immobilized in shells for decades or centuries (Berner, 2003; Alonso et al., 2021). Humans can prevent the release of captured carbon in shells by harvesting mussels and using their shells for construction materials on roads and other land-based applications, grinding mussel shells and using them in agriculture, or releasing them back into the water column in areas where increasing alkalinity is needed (Alonso et al., 2021; Alvarez-Salgado et al., 2022).

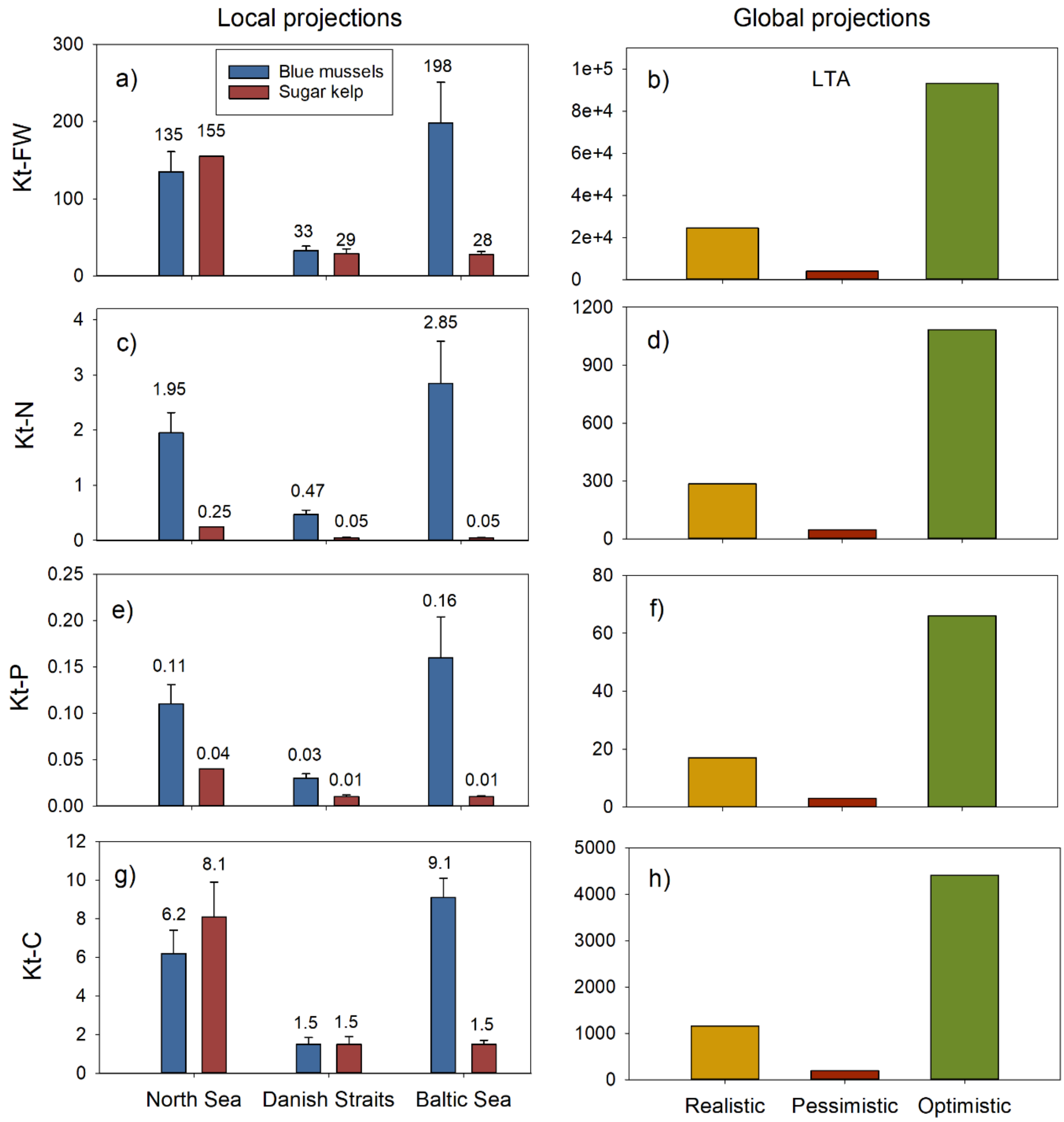

Figure 6. Projected LTA harvest and NPC removal potential. Potential total FW-harvest (kt-FW y^{-1}) (a-b) and related removal of N (c-d), P (e-f) and C (g-h) by blue mussels and sugar kelp in the three study areas (left column) and by LTA in the three global projections (right column). Note the different scales. The error bars indicate the 25th/75th percentiles based on 500 random mussel growth scenarios of monthly salinity, temperature, and chlorophyll a conditions ± respective natural variability and of the range of field harvest within the salinity range for the sugar kelp model (left column).

When assessing global wind farm projections for potential multi-use with LTA, information on OWF development was sourced from the 4C global offshore database to create three scenarios (realistic, pessimistic, and optimistic) for marine waters. In all regions, the current LTA involves mussel species from the Mytilidae family and brown seaweeds, with harvest yields similar to those in the study area. Northern Europe showed the greatest potential for OWF-LTA due to the anticipated rapid expansion of both OWF and LTA.

Under the realistic projection for 2030, global OWF-LTA could yield an estimated 24,487 kt-FW y^{-1} of LTA production, representing 132% of current global LTA output (Table 2). The pessimistic and optimistic projections estimate OWF-LTA production at 22% and 400% of current levels, respectively. The realistic scenario also predicts substantial nutrients and carbon uptake and removal potential, with 285 kt-N y^{-1}, 17 kt-P y^{-1}, and 1160 kt-C y^{-1} (equivalent to 4,226 kt-CO_2 y^{-1}, corresponding to approximately 15% of Denmark's total CO_2 emissions) (Figure 7).

Table 2. Overview of current and projected LTA harvest in the different regions (kt-FW y^{-1}). Ten percent of the OWF area was designated for LTA. The potential OWF-LTA harvest is shown for the realistic, pessimistic, and optimistic 2030 projections.

Region	Current LTA	2030 Realistic	2030 Pessimistic	2030 Optimistic
Africa	2.9	22	0	84
Asia	17,732	5,281	1661	15,680
Australia-NZ	2.5	2,594	0	9,148
North America	24.2	2,644	52	18,054
South America	404	3,868	0	8,183
Northern Europe	91.6	8,717	2,135	37,456
Southern Europe	361	1,361	158	4,583
Total	18,618	24,487	4,007	93,146

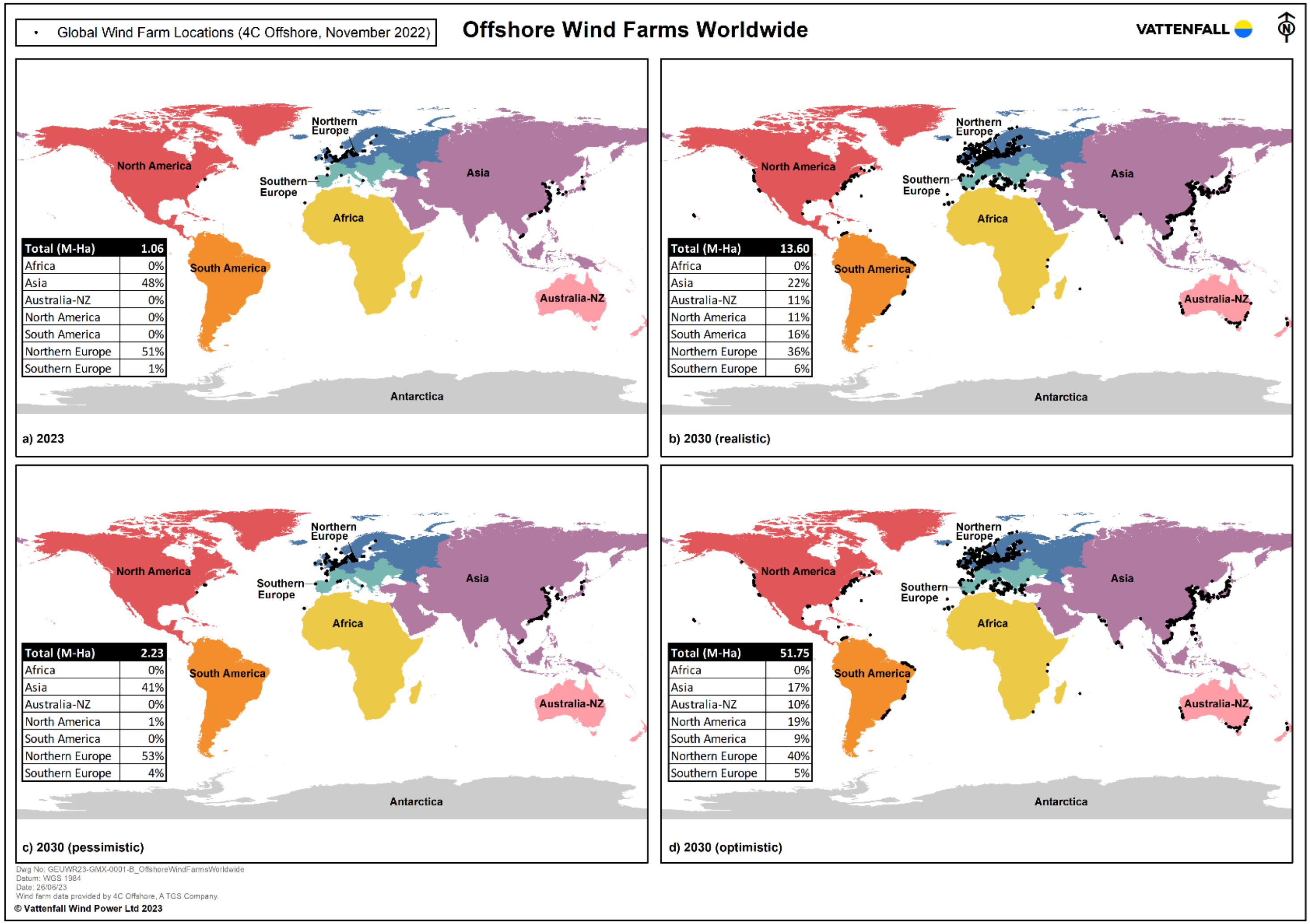

Figure 7. Offshore wind farms worldwide. Global locations of the OWF for a) the 2023 situation, b) the realistic 2030 projection, c) the pessimistic projection, and d) the optimistic projection. The tables show total OWF area (M-ha) and percentage distribution across the regions.

Case study 2: Carbon capture in mussel farms in the Baltic Sea region

This case study presents a regional Dynamic Energy Budget (DEB) model tailored to the Baltic Sea, incorporating biocalcification to assess carbon capture dynamics in blue mussel farms. By accounting for biocalcification, this model enables precise predictions of carbon capture in environments marked by steep salinity gradients and strong seasonality (for further details, see also Vaher et al., 2024). Our findings offer the first detailed spatial and temporal analysis of carbon capture within blue mussel shells under farming conditions in the Baltic Sea, showcasing the influence of environmental factors on carbon sequestration. This application stresses the need for location-specific mussel farming strategies that consider local and regional conditions for optimized carbon capture (Filgueira et al., 2015; Turolla et al., 2020).

We selected on a commercial *M. edulis/trossulus* mussel farm in Tagalaht Bay as a 'standard' farm representative of typical Baltic Sea conditions. The farm operates a self-sustaining cycle relying on wild mussel larvae recruitment, with larvae passively dispersing from natural reefs and attaching to farm substrates. The farm spans 0.25 hectares with six 100-meter lines, stocked at approximately 40 million mussels on nets placed at 1–5 meters depth and anchored to buoyancy lines. Over a 17-month growth period, carbon capture in shells progressively increases, accelerating in the second summer and reaching a plateau by fall harvest. The model predicts regional variations in carbon capture, with the highest rates in the outer Baltic regions, particularly in the Kattegat and Danish Straits (30–90 tons of carbon), where salinity is highest. Capture rates drop to 10–30 tons in central regions and as low as ≤1–10 tons in the inner Baltic regions (Gulf of Finland and Bothnia Bay), where salinity reaches the mussels' tolerance limit (Tamburini et al., 2022).

Salinity was identified as the primary factor influencing carbon capture across inner and central Baltic regions, with temperature and chlorophyll a playing lesser roles. However, temperature is a significant predictor in outer regions. Salinity's impact on carbon capture grows with spatial scale, while temperature and chlorophyll a show more localized effects. Although we did not attempt a full carbon budget or life cycle analysis for farmed mussels, this DEB model provides a reliable tool for quantifying carbon sequestration potential by blue mussel shells across Baltic regions. In this scope, we focused on estimating long-term carbon immobilization in mussel shells as $CaCO_3$, which delays carbon release into the water and could support climate mitigation efforts (Filgueira et al., 2015; Turolla et al., 2020).

Our model suggests that the most favorable areas for maximizing long-term carbon capture are in the outer Baltic subbasins (Danish Straits, Belt, and Kattegat), where higher salinity supports greater sequestration potential. In brackish waters of central and inner subbasins, the carbon capture potential remains significantly lower (<10 tons). While carbon sequestration in these regions is modest, mussel farming provides additional ecosystem benefits by sequestering excess nutrients, which is particularly valuable given that many other food production systems contribute to high carbon emissions (Kotta et al., 2020). Extending the cultivation period may enhance carbon capture in low-salinity areas, though this would necessitate further evaluation of economic trade-offs for delayed harvests to balance environmental and economic goals.

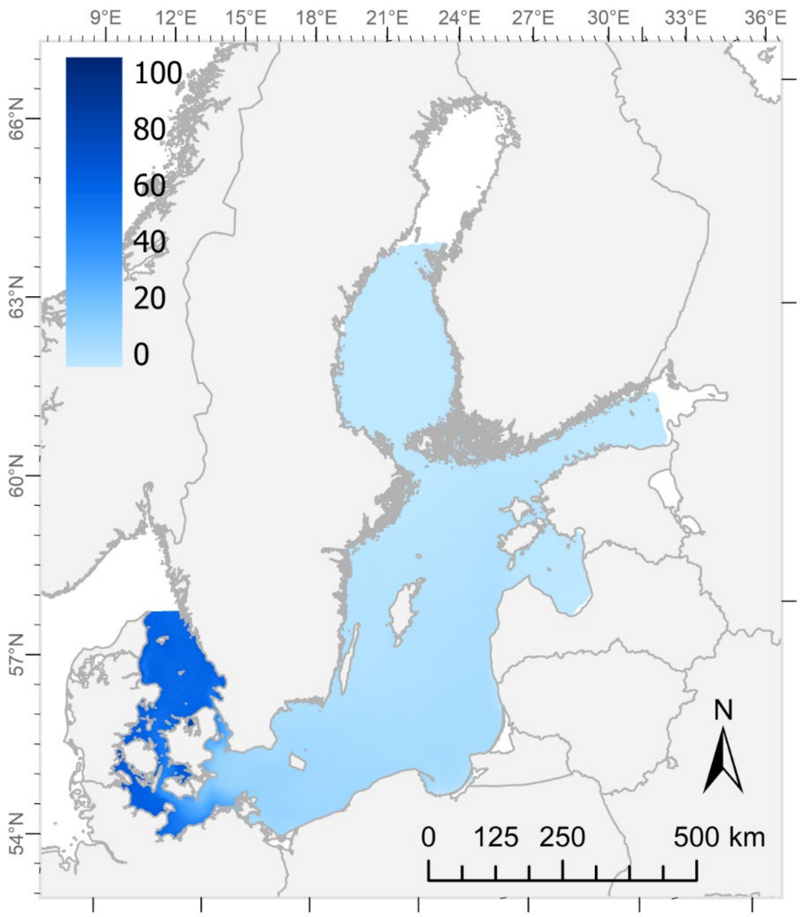

Figure 8. Projected total carbon sequestered in farmed blue mussel shells (expressed in tonnes per standard farm).

Beyond its immediate findings, this DEB model is a powerful resource for stakeholders and policymakers, offering quantitative data on carbon capture dynamics and supporting region-specific decision-making across the Baltic Sea. The model's adaptability allows application beyond the Baltic Sea to evaluate carbon capture in other bivalve species globally, both in cultivated and natural populations. Assessing and optimizing carbon storage in bivalve-dominated systems under diverse environmental conditions is essential for understanding and maintaining ecosystem services, guiding conservation and restoration efforts, and advancing mitigation measures through biological activity of marine calcifiers.

Case study 3: Assessing sustainable IMTA practices for finfish and blue mussel farming in the northeastern Baltic Sea

Aquaculture is increasingly regarded as a solution to meet growing fish demand, but only if it can reduce its reliance on wild fish for feed and lessen its environmental impact. Integrating extractive species with fish farming through IMTA holds promise for mitigating the adverse environmental effects of traditional fish farming (Naylor et al., 2000, 2021; Duarte et al., 2009; Chopin et al., 2012, Maar et al. 2020). Although macroalgal and mussel farming are valued for their ecosystem services, these benefits are often underexplored and not yet widely realized in temperate coastal regions, where few countries operate IMTA at commercial scale. The environmental benefits of low trophic aquaculture remain underutilized as a strategy for managing fish farming impacts in these areas (Barrington et al., 2009; Duarte et al., 2009). To expand IMTA, it is essential to quantify these environmental benefits and raise awareness among stakeholders.

In the Baltic Sea region, finfish farming is not yet considered sustainable due to the severe eutrophication exacerbated by phosphorus (P) release and nitrogen (N) fixation (Vahtera et al., 2007; Conley et al., 2009, 2011). Consequently, finfish aquaculture must implement extensive measures to curb nutrient emissions. Blue mussel (*M. edulis/trossulus*) farming has emerged as a potential strategy for eutrophication control in this brackish environment (Buer et al., 2020; Holbach et al., 2020; Kotta et al., 2020), but economic feasibility remains challenging due to low salinity levels that limit production yield (Gren, 2019). Integrating mussel farming with finfish aquaculture, however, can offer mutual benefits: finfish farming can subsidize mussel farming costs, making it economically viable, while mussel farming can help mitigate nutrient discharge, supporting fish farm licensing.

Evaluating energy and nutrient flows in IMTA systems requires precise tools like dynamic energy budget (DEB) modeling. DEB models, when coupled with hydrodynamic-biogeochemical models, allow realistic assessment of aquaculture impacts on nutrient cycles in coastal waters, aligning with the European Commission's Blue Growth goals (Kooijman, 2010; Holbach et al., 2020). DEB models quantify physiological processes (feeding, growth, metabolism) in farmed finfish and mussels. For instance, finfish release nutrients via excretion (NH_4 and PO_4) and defecation (organic N and P), and uneaten feed adds additional nutrients. These emissions influence different marine ecosystem components: larger waste settles in sediments, impacting benthic communities, while dissolved nutrients can fuel pelagic algal blooms (Dalsgaard & Krause-Jensen, 2006). By modeling such emissions, DEB models offer valuable insights into nutrient dynamics within IMTA systems.

In this case study, DEB models for blue mussels (*Mytilus edulis/trossulus*) and rainbow trout (*Oncorhynchus mykiss*) were integrated with a regional hydrodynamic-biogeochemical model to explore the potential of mussel farming in offsetting finfish farm effluents in the Baltic Sea's low-salinity areas (for further details, see also Kotta et al., 2023). These DEB models accounted for species responses to local salinity, temperature, and food availability, generating spatially explicit projections of mussel farm sizes needed for net-zero emissions in the highly eutrophicated waters of the Baltic Sea. Mussel nutrient sequestration capacity was found to vary widely by region, with higher yields predicted in the more saline southwestern parts of the study area and negligible results in lower-salinity eastern areas (Figure 9). The potential for finfish farming, and consequently its contribution to nutrient emissions, remained relatively consistent across the study area. Variations were primarily influenced by spatial differences in temperature regimes and, to a lesser extent, wave conditions (Figure 10).

The analysis revealed that mussel farms are more effective at sequestering nitrogen (N) than phosphorus (P). In optimal locations, an 8-hectare mussel farm could fully offset N and P emissions from a finfish farm, supporting the potential for sustainable finfish farming in the Baltic Sea through in-situ nutrient management (Figure 11). While mussel farming is not yet economically viable in the Baltic Sea, this approach offers a more circular aquaculture model, supporting nutrient reuse and enhancing sustainability. Mussels provide ecosystem services like increased water clarity, nutrient reduction, and habitat restoration for biodiversity (Petersen et al., 2014; Hedberg et al., 2018).

Further innovation in finfish feed can also reduce nutrient emissions. In this case study, we used BioMar feed, which binds P in hydroxyapatite that settles on the seabed, effectively reducing its bioavailability. Consequently, only a 0.8-hectare mussel farm would be required to offset P emissions. Although blue mussel farming is still limited economically in the Baltic Sea, producing sufficient biomass could lead to higher revenues, especially if mussels are marketed for human consumption, thus improving financial sustainability (Adler et al., 2022). Moreover, mussels that are too small for human consumption can serve as a sustainable and circular ingredient for fish meal production. While mussels may only provide a small fraction of the feed, this practice links nutrient recovery directly to a reduction in the farming footprint. By using mussels grown for nutrient mitigation in feed production, the process recycles resources, reducing the reliance on external nutrient inputs and enhancing the sustainability of aquaculture systems.

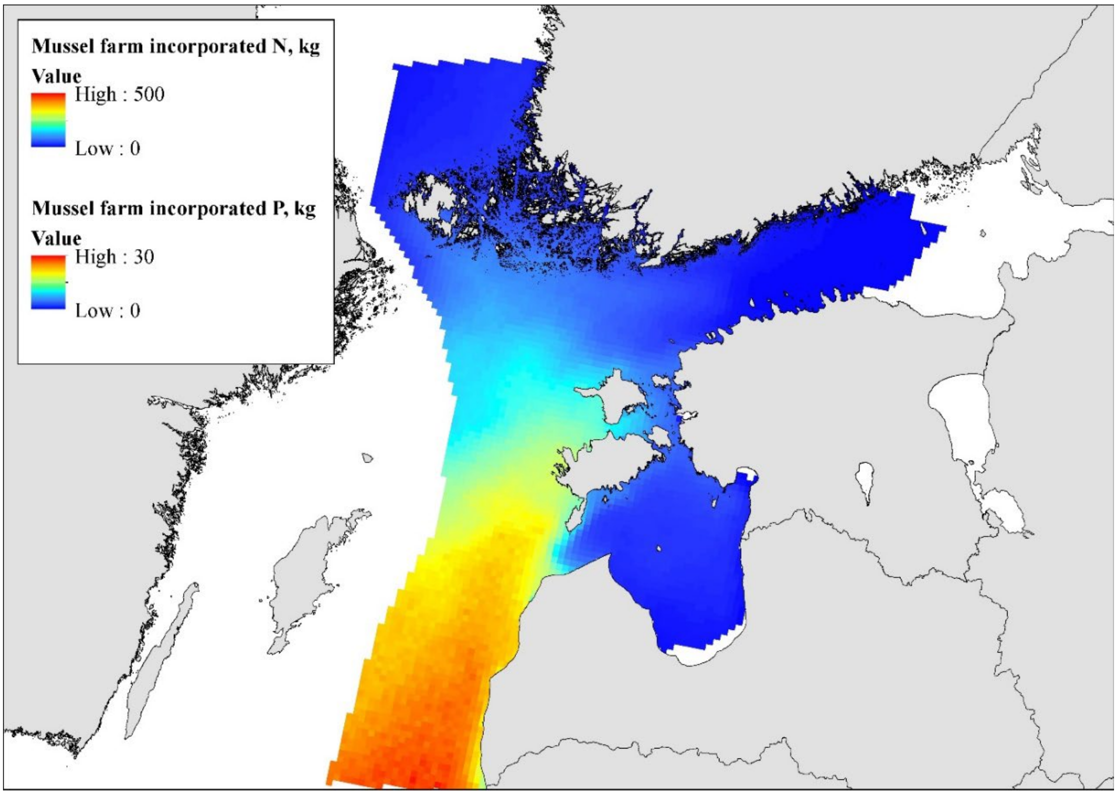

Figure 9. Spatial variability in total nitrogen (N) and phosphorus (P) incorporation (kg) per cultivation cycle in the standard mussel farm. Since the spatial patterns of N and P incorporation are identical, a single figure is provided to display both values. Please refer to the specific legends for the exact nutrient incorporation values.

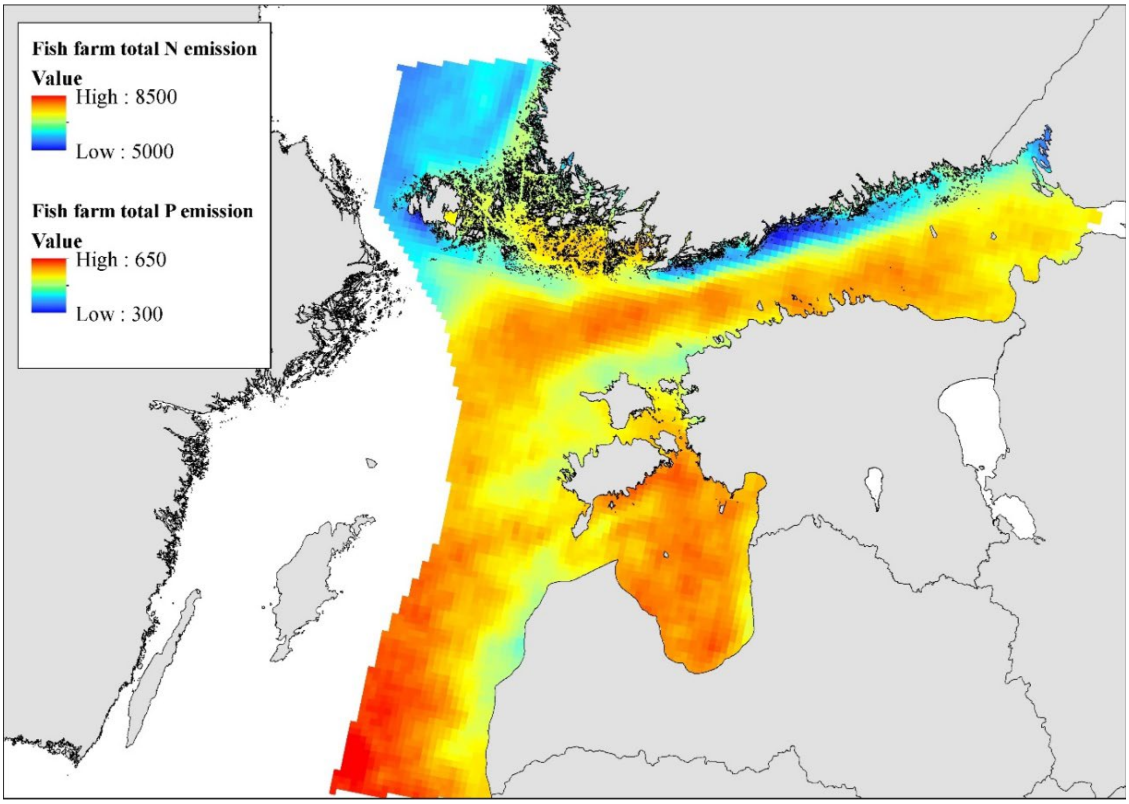

Figure 10. Spatial variability in total nitrogen (N) and phosphorus (P) emissions (kg) (from excretion and defecation) in the standard finfish farm per cultivation cycle. Since the spatial patterns of N and P emissions are identical, a single figure is used to represent both values. Refer to the specific legends for the exact nutrient emission values.

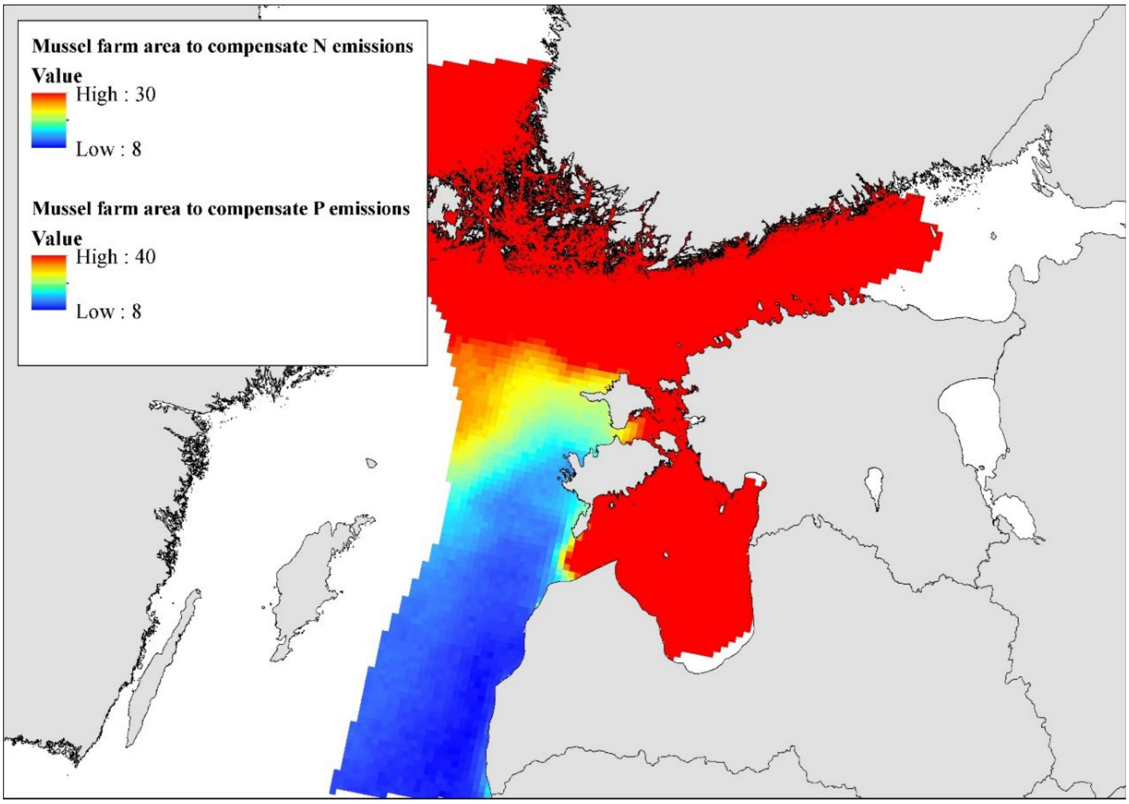

Figure 11. Spatial variability in the required surface area of a mussel farm (ha) needed to fully offset nutrient emissions from the standard finfish farm. Since the spatial patterns for nitrogen

(N) and phosphorus (P) compensation potential are identical, a single figure represents both values. Please refer to the legend for the specific nutrient to see the exact compensation values.

The DEB modeling framework has strong transferability potential; its core principles, assumptions, and parameters can apply to other aquaculture species with minor adjustments. DEB models are already recognized in EU standardized ecotoxicology tests (EFSA, 2018) and show promise for advancing sustainable aquaculture in diverse settings aligned with the European Commission's Blue Growth strategy (European Commission, 2012). Suitable IMTA sites should feature adequate water currents to maintain fish health and enhance mussel farm nutrient removal efficiency (Kotta et al., 2020). Low current regimes, however, risk anaerobic sedimentation beneath farms (Olsen et al., 2008; Zhang et al., 2019). Nutrient recycling capacities also vary by environment, with hydrodynamics and primary productivity playing critical roles in defining fish farm impacts at the ecosystem level. Following IMTA farm establishment, continuous environmental monitoring is crucial to ensure stable bottom conditions and protect benthic flora and fauna.

7. Conclusions

The expansion of the Operational Decision Support System (ODSS) to include both the Baltic and North Sea regions advances sustainable marine spatial planning. The ODSS integrates essential spatial data on environmental conditions, human activities, and aquaculture yield potentials, enabling stakeholders to make informed decisions on multi-use areas, particularly for low-trophic aquaculture (LTA) and offshore wind farms (OWF). This tool supports basin-scale multi-use planning, providing managers and aqua-farmers with tailored site configurations that optimize the coexistence of aquaculture and renewable energy production.

The case studies in this report highlight the ODSS's potential in various applications. The first case study explored combining offshore wind farms with low trophic aquaculture species like blue mussels and sugar kelp. The ODSS analysis projected yields and nutrient cycling potential for LTA farms in future OWF areas, guiding towards improved environmental health through nutrient capture, carbon sequestration, and sustainable energy production. This study illustrates the scalability and global relevance of OWF-LTA integration for enhancing sustainability.

In the Baltic Sea, with its pronounced salinity gradient, the second case study employed a dynamic energy budget model to assess carbon capture in mussel farms. Findings showed that regions with higher salinity achieve greater carbon capture, primarily driven by increased mussel growth rates. This effect is particularly pronounced in the outer Baltic sub-basins, positioning mussel farming as a valuable climate mitigation strategy in nutrient-sensitive areas.

The third case examined IMTA's role in balancing nutrient cycles by combining finfish and mussel farming. Mussel farms offset nutrient outputs from finfish farming, supporting a circular aquaculture model in the Baltic Sea and reinforcing IMTA's economic viability as a nutrient mitigation and sustainable seafood strategy.

In sum, the ODSS advances regional aquaculture initiatives by offering accessible, model-based insights essential for effective multi-use marine planning. As the ODSS continues to incorporate new data, it will enhance regional collaborations and help stakeholders manage shared marine resources more sustainably.

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