



A paradigm for understanding whole ecosystem effects of offshore wind farms in shelf seas

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Abstract

With the rapid expansion of offshore windfarms (OWFs) globally, there is an urgent need to assess and predict effects on marine species, habitats, and ecosystem functioning. Doing so at shelf-wide scale while simultaneously accounting for the concurrent influence of climate change will require dynamic, multitrophic, multiscalar, ecosystem-centric approaches. However, as such studies and the study system itself (shelf seas) are complex, we propose to structure future environmental research according to the investigative cycle framework. This will allow the formulation and testing of specific hypotheses built on ecological theory, thereby streamlining the process, and allowing adaptability in the face of technological advancements (e.g. floating offshore wind) and shifting socio-economic and political climates. We outline a strategy by which to accelerate our understanding of environmental effects of OWF development on shelf seas, which is illustrated throughout by a North Sea case study. Priorities for future studies include ascertaining the extent to which OWFs may change levels of primary production; whether wind energy extraction will have knock-on effects on biophysical ecosystem drivers; whether pelagic fishes mediate changes in top predator distributions over space and time; and how any effects observed at localized levels will scale and interact with climate change and fisheries displacement effects.

Keywords: marine renewable energy; bio-physical indicators; predator–prey interactions; scaling; multitrophic; autonomous platforms; dynamic Bayesian network modelling; cumulative impact assessment

Background: the need for (structured) speed

The timeframe with which to achieve climate-resilient development is rapidly narrowing (IPCC 2023). Therefore, governing bodies have increasingly turned to renewable energy technologies to try and meet electricity demands sustainably. In the marine space, this has resulted in the unprecedented growth of the offshore wind sector. Global offshore capacity is forecasted to increase by a factor of 10 by 2030 to reach 330 gigawatts (GW); this amount is projected to treble again by 2050 (IRENA 2019). Recent progress in the development of floating offshore wind technology, allowing turbines to be deployed in deeper waters, as well as hybridization with existing offshore infrastructure (e.g. using wind energy to power oil and gas installations) is also contributing to this burgeoning industry (Leporini et al. 2019). Consequently, more offshore windfarms (OWFs) are projected to occupy larger areas of midlatitude coastal and shelf-sea space (Díaz and Guedes Soares 2020). While OWFs are widely acknowledged to be part of the climate resilient development portfolio, any such resiliency will depend on the ability to safeguard biodiversity and ecosystem functioning, especially salient given the

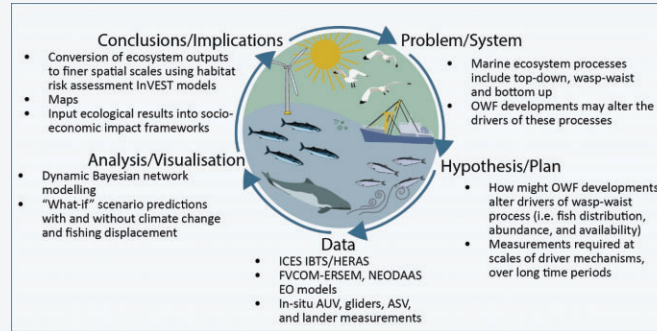
concurrent pressures of ocean warming, acidification, and de-oxygenation (Williamson and Guinder 2021). Therefore, as we speed up offshore wind development of shelf seas, so too do we need to accelerate our understanding and ability to predict their effects on shelf sea ecosystems.

It is also important to be able to distinguish between the different potential causes of any measured and predicted effects, including those from OWFs, climate change, and the natural variability of shelf seas over multiple spatial and temporal scales (Trifonova et al. 2022a). Achieving this at the rapid pace of industry development will necessitate a shift towards more explicit ecosystem-wide and cumulative effects theory and implementation (Trifonova et al. 2022b, Declerck et al. 2023). This will require prioritizing hypothesis-driven study of ecosystem processes, as well as individual species' populations and the trophic level interactions between populations at spatial and temporal scales relevant to all these processes and OWFs. Performing such science has been limited so far due to the constraints, chiefly economic, logistic, and technological, that come with studying the sea (Godø et al. 2014a). Fortunately, in the past decade, there have been huge

Box 1. Fish as the fulcrum

Problem/Background: OWFs are increasing in number in the North Sea, while simultaneously our understanding of this sea remains limited. However, in temperate shelf seas, just a few pelagic fish species play a pivotal role at intermediate trophic levels by exerting top-down control on zooplankton and bottom-up control on top predators ('wasp-waist' processes). These species occupy multiple habitats throughout their life cycle and have migratory routes between spawning and nursery habitats which are influenced by a range of bio-physical drivers (e.g., currents, temperature, levels of stratification, tidal mixing fronts and plankton production). The abundance, distribution and growth rates of these fishes, therefore, provide the link for regulating trophic dynamics between primary producers and top-predators. Should OWF developments alter, either indirectly or directly, any of the drivers of the fish life cycle, then any resultant changes to fish are likely to propagate across shelf-sea food webs.

Hypothesis/Plan: By measuring effects of OWFs on fish, it will be possible to, with necessary levels of certainty, predict effects of OWF on lower and higher trophic levels simultaneously, for the entirety of the North Sea. To do so will require identifying and characterizing the drivers of key pelagic fish species' abundance, availability (to top predators), distribution and growth rates. Measurements will need to be taken at the scales of driver mechanisms, throughout the year, thereby capturing the full life cycle of fish and the habitats they influence and are influenced by.



Data: Historical data on fish, seabird and marine mammal distributions will be used to identify optimal sampling areas. The ICES IBTS and HERAS surveys as well as commercial catch data can provide data on herring, sandeel, sprat and mackerel. NEODAAS Earth Observation data synthesized from satellites on ocean temperature and colour from products such as chlorophyll-a, and provided output on locations of fronts.

Bio-physical coupled oceanographic models (FVCOM + ERSEM) can predict changes in levels of primary production, changes in stratification and hydrodynamic regimes. Mechanistic changes in the subsurface pelagic environment will be measured *in situ* using AUVs, gliders, ASVs, and landers equipped with hydroacoustic and oceanographic sensors (e.g., multifrequency echosounder, ADCP, CTD, fluorometer). These will be strategically deployed in areas previously identified from historical data during periods of contrasting biophysical regimes in the North Sea (spring, summer and autumn).

A range of "what-if" scenario predictions with and without climate change and fisheries displacement effects will be modelled with the DBN and compared to the baseline runs to be able to separate these co-occurring yet potentially obfuscating effects from those of OWFs.

Conclusions/Implications:

Outputs from the ecological analysis will be fed into the development of holistic risk-benefit maps using the InVEST model. The evidence generated will also influence the generation of strategic frameworks to structure and improve Cumulative Impact Assessments; the scientific evidence-base will thereby facilitate transparent communications between academia, developers, decision-makers, and the wider public. Finally, any insights gleaned from the process as well as the results themselves will inform the generation and testing of further hypotheses. As technologies, and the socio-economic and geopolitical climate evolves, these will form the basis of a new iteration of the investigative cycle.

advancements in sensors (remote as well as *in situ*) and autonomous platforms that can concurrently measure ecosystem processes, but also in statistical modelling approaches and the computing power required to run them. The resultant temptation towards abundant data collection resulting in 'data-rich but information-poor' (DRIP) syndrome (Wilding *et al.* 2017), must and can be avoided by formulating concrete hypotheses rooted in ecological theory.

Adapting established frameworks for conducting investigative science is a useful starting point, one widely recognized framework within this cycle is the PPDAC model, which stands for Problem, Plan, Data, Analysis, and Conclusions (Tukey 1980, Mackay and Oldford 1994, Wild and Pfannkuch 1999) (Fig. 1). The cycle begins by identifying and defining the problem (hypothesis generation), after which, experiments are designed, data are collected, analysed, and finally, interpreted. The conclusions reached in the final stage then become the basis for the next iteration of the cycle. In the face of urgency, PPDAC provides a systematic framework, ensuring a thorough understanding of the problem before developing a well-considered plan. The iterative nature allows for flexibility in adjusting strategies based on evolving data and insights, crucial for addressing the dynamic and interconnected nature of complex issues. Notably, the statistics and data science community advocate for PPDAC as it improves data literacy in an age of 'big data' (Gehrke *et al.* 2021). The following sections detail how applying such a framework to the specific context of expanding OWF development can accelerate our understanding of and ability to predict effects on shelf-sea ecosystems. A case study exemplifying the cycle in the context of OWF effects on wasp-waist processes in the North Sea is also provided, to facilitate similar necessary research (Box 1).

The problem: the seascape of OWF effects

Numerous reviews of the potential environmental effects of OWFs in various seas have identified a multitude of concerns, including biodiversity loss, nonindigenous species propagation, fishery resource management, increases/decreases in primary production and chemical and noise pollution, degradation/enhancement of the seafloor, and alterations in food webs and ocean hydrodynamics (e.g. Galparsoro *et al.* 2022). Positive effects such as functional habitat increase for benthopelagic organisms have also been described (Gill *et al.* 2020). Further information is now readily retrievable via the Offshore Wind Farm Environmental Evidence Database (<https://ories.pml.space>). However, the bulk of evidence reviewed comes from studies conducted at individual turbine or single windfarm level, often on a particular species or community of interest (i.e. visible top predators).

The expansion of large-scale OWF into deeper waters has the potential to alter local and regional shelf-sea hydrodynamics and subsequently bio-physical processes, particularly in seasonally stratified areas that play a vital role in regulating prey availability for higher trophic levels (Dorrell *et al.* 2022). Changes to water currents, wind wakes (i.e. reduced kinetic energy on the leeward side of OWF), and turbulence induced by OWF may modify vertical stratification, changing mixed layer depths immediately 'downwind' of developments as well as vertical mixing levels over large spatial scales (Carpenter *et al.* 2016, Gill *et al.* 2020, van Berkel *et al.* 2020). This may have subsequent effects on the stability and strength of oceanographic features such as tidal mixing fronts (Simpson and Sharples 2012), which occur at the interface between well-mixed and stratified waters, as well as finer-scale internal waves occurring on the depth(s) of the edges of offshore banks that are localized sources of new primary production

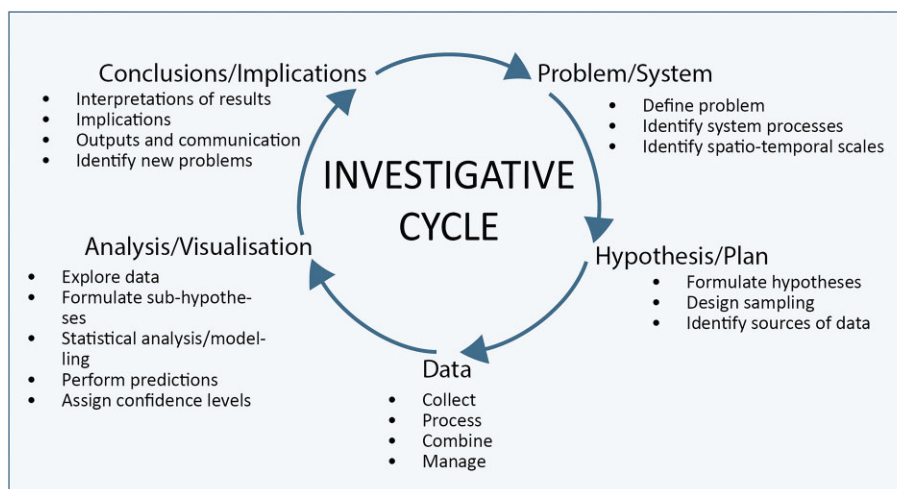


Figure 1. Visualization of the scientific investigative cycle, adapted from the PPDAC cycle proposed by Wild and Pfannkuch (1999).

(Palmer et al. 2008). These, in turn, have the potential to affect the timing and strength of diapycnal mixing, which subsequently controls the supply of nutrients in surface waters to create temporally persistent and predictable foraging areas for pelagic fishes and top predators (Cazenave et al. 2016). Changes in hydrodynamic regimes (i.e. levels of mixing, surface wave energy, and upwelling) could thus affect the nutrient supply to the euphotic layer and change its spatial pattern, with important knock-on effects for primary and secondary production (Floeter et al. 2017).

Therefore, while valuable, the focus on documenting distributional changes of few species does not necessarily scale to predictions about ecosystem-wide effects in shelf seas, an inherently complex system (Steele et al. 1989). This, in turn, hampers the ability to attribute a cause-and-effect relationship between offshore wind developments and receptor populations of interest; this also contributes to critical levels of uncertainty in cumulative effects studies (Goodale and Milman 2016). Furthermore, it cannot be assumed that the summation of changes in cumulative effects studies to individual species under worst-case scenarios accurately predicts outcomes at population levels, let alone ecosystem or regional scales (Nogues et al. 2023). To be able to do so requires studying and understanding the physical and biological processes underlying the changes in species distributions and abundances, from bottom-up drivers to top-down pressure as well as trophic interactions (Levin 1992). Put simply, we need to study the processes that drive distributions at the spatial and temporal scales at which they occur. Only then will the environmental evidence base be able to support holistic cumulative effects assessments at the large scales and at the rapid pace proposed for the offshore wind industry (Box 1).

The plan: ecosystem processes and indicators of change in space and time

Ecosystems in temperate midlatitude shelf seas are characterized by three processes: (1) bottom-up processes that regulate primary production dynamics (Simpson and Sharples 2012); (2) top-down processes arising from predation and anthropogenic pressures (e.g. via commercial fishing) (Lynam and Mackinson 2015); and (3) wasp-waist processes regu-

lated by a few midtrophic pelagic fish species, which provide the critical fulcrum in linking (1) and (2) (Cury et al. 2000) (Fig. 2). Testing these ecological theories in the context of offshore wind effects is therefore merited; an expedient approach is to focus on studying wasp-waist processes as they mediate both lower and higher trophic levels (Box 1).

Due to the dynamic and mobile nature of the marine environment and its wildlife, indicators and mechanisms of the three ecosystem processes (bottom-up, top-down, and wasp-waist) operate at distinct yet interconnected ranges in space and time. These scales at which the processes and main species within trophic levels occur and interact at are almost linear: primary level (<1–10 km, hours to days); secondary level (10–100s km, days to months); and tertiary level (100s–1000s km, months to years). Therefore, any studies aimed at assessing shelf-sea-wide effects will need to take these relevant scales into account (Pittman et al. 2021). The following section suggests definitions of spatial and temporal scales (adapted from Trifonova et al. 2022a) relevant to OWF and temperate midlatitude shelf sea systems and expands on important bio-physical features and indicators and their corresponding scales (Fig. 3).

Space

The fine spatial scale (<1 km) provides a mechanistic understanding of processes underlying both the production of plankton (primary trophic level) and the foraging behaviour of individual prey and predators (i.e. fishes, marine mammals, seabirds), including conditions for successful foraging connected to local (temporally varying) hydrodynamic conditions. Physical and topographic controls on local primary production, such as shelf edges, tidal mixing fronts, and internal waves are important at this scale, especially highly predictable productive areas, such as the edges of banks where internal waves enhance the aggregation of prey (Embling et al. 2013), which can influence top-predator distributions (Scales et al. 2014). These features are temporally ephemeral but predictable, as they are driven by daily (ebb-flood) as well as bi-weekly (neap-spring) tidal cycles and seasonal solar and wind field changes (Simpson and Sharples 2012). Competing effects of local scouring and changes in downstream mixing also alter how sediment is resuspended from the seabed, with

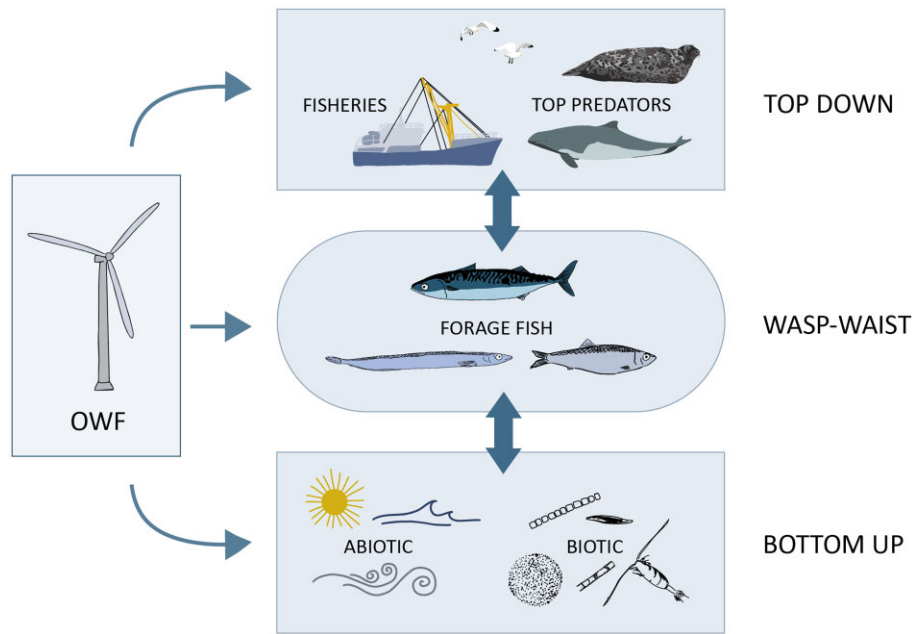


Figure 2. Pathways of OWF effects on top-down, wasp-waist, and bottom-up environmental processes in shelf seas.

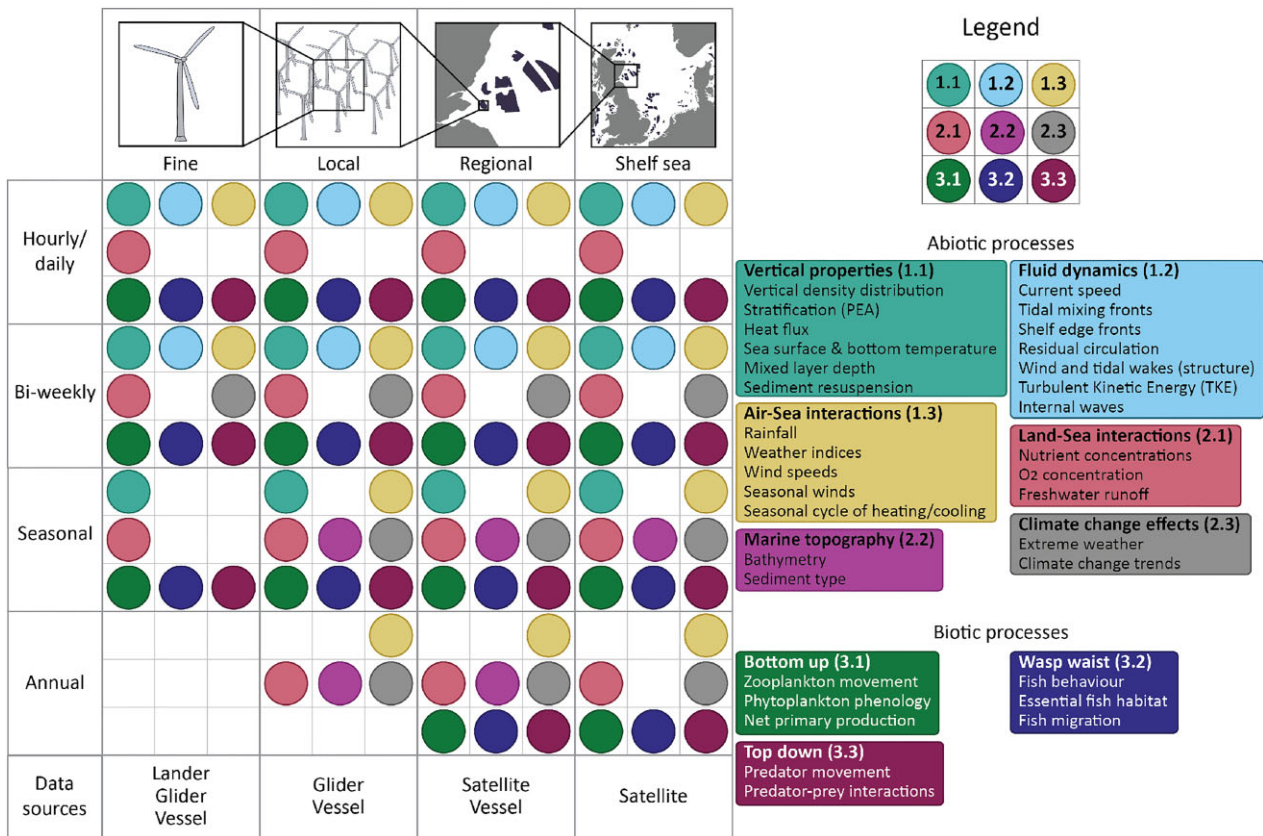


Figure 3. Shelf sea biophysical processes and the principal space and time scales at which they operate, including recommendations for how experimental data can be collected; each circle in the table represents the full range of the process in question, although specific subprocesses (i.e. zooplankton movement) may operate within fewer grid squares. PEA = Potential Energy Anomaly.

potential impacts on fluxes of greenhouse gases, nutrients, and light penetration, therefore, all effecting primary production with knock-on effects on ‘blue carbon’ storage (Dorrell et al. 2022). At the very fine scale (i.e. changes in turbulence from

the subsurface mixing around pylons or jackets and the wind wake of turbine structures from wind energy extraction), interactions between currents and turbines may produce physical features that influence top predators targeting of locations

due to changes in the level of turbulence in the water column (Lieber et al. 2019, Schultze et al. 2020). How these physical processes develop at the scale of the wind farm array and for multiple arrays, and how they might affect top predator foraging [e.g. by structures acting as fish aggregation devices (van Berkel et al. 2020), and/or by locally changing levels of primary production (Slavik et al. 2019)], require further study.

Net primary productivity and the depth and biomass concentration of the subsurface chlorophyll-a maximum (SCM) are relevant indicators at local spatial scales (1–100 km), as are variables linked to physical aspects such as seabed topography, stratification, and weather (e.g. rainfall, wind speed, heat exchange) (Holt et al. 2012, Sharples et al. 2013a). The survival and community structure of phytoplankton are dependent upon the marginally stable pycnocline being maintained by weak levels of diapycnal mixing that injects nutrients upward (Palmer et al. 2008). Small changes may have dramatic but nonlinear effects on physical water column structure, the timing, and magnitude of primary productivity, and thereby primary ecosystem function. Such effects may be monitored as changes in dissolved oxygen concentration, a key indicator of ocean health, which is regulated by both physical mixing and biological production and consumption rates (Williams et al. 2022). Fine-scale features and mechanisms are likely to inform on bottom-up regulations of marine ecosystem functioning and are likely to predict the distributions of fish, top predators, and fisheries (Trifonova et al. 2017).

The regional domain (100s–1000s of km) is characterized by populations and meta-populations of large mobile species (seabirds and marine mammals), where seasonal mean stratification, bottom temperature (BT), net primary production, and maximum chlorophyll-a values appear as principal indicators of their density distribution (Scott et al. 2010, Cox et al. 2018). Stratification and BT are also important for the abundance, distribution, and diversity of many fish species (Sagarese et al. 2014).

Finally, the largest scale extends over most of the world's shallow shelf seas (1000s of km, e.g. the North Sea, China Sea, etc.), where interconnectivity between regions is provided by the migrations of large mobile nekton (i.e. fish, seabirds, marine mammals) (Hammond et al. 2013, Rutterford et al. 2015). Net primary production, mean BT, and maximum chlorophyll-a are still important indicators at this scale, where the timing of seasonal phytoplankton blooms is an extremely important indicator for marine food web functioning and energy flow (Friedland et al. 2018, Silva et al. 2021). Predator–prey interactions at this scale and how they vary on a seasonal and inter-annual basis is also vital, as changes in migration patterns of pelagic fish species may have important knock-on effects for higher trophic levels (Samarra and Foote 2015). Top-down control via fisheries exclusion by OWFs may also result in population-level effects; the dynamics between fisheries, stocks, and offshore wind will be increasingly relevant to ascertain as floating wind technology allowing for expansion of wind developments into deeper waters progresses (Gill et al. 2020, Farr et al. 2021).

Time

There are various temporal scales to consider where there are processes that are linearly linked to the increasing spatial scales discussed above. The daily ebb-flood tidal cycle (ca. 12.5 hours) and diurnal cycle (24 hours) are the smaller

timescales during which behaviours such as the diel vertical migration (DVM) of fish and zooplankton through the water column have consequences for energy transfer and interactions between predator and prey, and therefore, energy transfer across trophic levels (Castellani et al. 2013, Brierley 2014). The influence of tides (both the flood/ebb and spring/neap cycles) is especially important at local and fine spatial scales generally nearer the coast where tidally driven horizontal current speed and physical features both attract and make prey more available to top predators (Zamon et al. 2003, Cox et al. 2013).

At the seasonal scale of months, the annual timing of the spring phytoplankton bloom affects the survival of larval and juvenile fish (Platt et al. 2003), with consequences for higher trophic levels, as it has also been found to affect the breeding success of seabirds (Scott et al. 2006). This raises the question of whether trophic mismatches due to discrepancies between the timing of available prey and the start of breeding seasons will have implications for top predator population viability (Howells et al. 2017). Since phytoplankton blooms are dependent on the timing of stratification during spring in temperate continental shelves (Sharples et al. 2006), changes to the timing and strength of seasonal stratification of the water column will also affect critical links such as nutrient fluxes between benthic and pelagic habitats (Nunnally 2019).

On longer time scales (seasonal and annual), abiotic factors such as salinity, oxygen levels, and BT as well as biotic factors such as food availability has been found to affect the distribution, abundance, and species richness of fishes at a regional and shelf-wide scales (Sagarese et al. 2014, Merilley et al. 2020). Interannual variability in the timing and duration of the spring phytoplankton bloom and then subsequent summer season interactions with the spring–neap tidal cycle, and weather conditions, control the intensity of subsurface blooms ('biweekly blooms'). These are likely to affect fish recruitment and survivability, and through this influence fisheries production and (the predictability of) top predator distributions (Box 1). Notably, climate change is expected to disrupt the existing phenology between fish larvae and availability of zooplankton due to changes in timing of spring blooms (Dulvy et al. 2008). At the annual scale, some commercially important pelagic fish species (e.g. Atlantic herring *Clupea harengus*) have highly predictable annual migration routes to and from spawning and feeding grounds that help long-lived mobile predators learn when and where they will be available (Roff 1988). Predictable species-specific variation in annual and seasonal locations of fish migration routes and their links to frontal and surface primary production is likely to drive variation in top-predator (seabird and mammal) distributions (Warwick-Evans et al. 2016).

The data: fisheries and Earth observation datasets and advances in *in-situ* measurement techniques

Several existing fishery independent and dependent datasets are spatially explicit time-series that allow for the dynamic changes of fish distributions and abundances over large spatio-temporal scales to be quantified. These range from internationally coordinated fisheries independent scientific campaigns such as the North Sea International Council for the Exploration of the Sea (ICES) International Bottom Trawl Surveys (IBTS) to acoustic surveys for pelagic fish species such

as the Herring Acoustic Survey (HERAS). Fishery-dependant data such as monthly commercial landings are generally available only as an aggregate product on a larger scale (i.e. an ICES square 30×30 nmi) and therefore represent less explicit locations of catch. However, these are still a valuable alternative or addition for examining temporally changing fish distributions in regions where fishery-independent surveys are unavailable (e.g. Marine Management Organization commercial landing by Exclusive Economic Zone; Dixon *et al.* 2019). Complementing these datasets with satellite-based vessel monitoring system (VMS) data (e.g. Alemany *et al.* 2014) and automatic identification system (AIS) data can also offer insights on fishing activity distribution and therefore top-down pressure in the ecosystem (Thoya *et al.* 2021).

Combining such fish datasets with remotely sensed Earth observation (EO) oceanographic data is especially conducive to the study of bottom-up processes. EO data provide continuous information of submesoscale (<10 km) through to microscale (<100 m) details of the global ocean's colour, structure, and circulation including discrete oceanographic features such as fronts and eddies (Belkin 2021). Therefore, the spatial and temporal scales over which these features persist and vary can be tracked, although this is only possible where distinct surface signatures are present (Miller 2009, Cox *et al.* 2018). While sea surface temperature (SST) and chlorophyll-a concentrations (colour fronts) derived from satellites are widely used to identify productivity hotspots for pelagic species, the continuous features of oceanographic fronts are typically not explicitly extracted despite their ecological significance (Belkin 2021). Studies combining frontal datasets with individual biotelemetry data have revealed the tendency of large fish species to track fronts and associated features during migration (Luo *et al.* 2015, Miller *et al.* 2015a); such approaches should increasingly be used for temperate pelagic fish species (Spondylidis *et al.* 2023). At much smaller spatial and temporal scales (i.e. <1 km, <1 week), the timing and location of surface concentrations and strong gradients can be derived from higher-resolution (300 m) ocean colour data [e.g. ESA's Medium Resolution Imaging Spectrometer (MERIS)]. The combined use of thermal and colour frontal distributions provides a more complete analysis of persistent biological and physical processes in shelf seas (Miller *et al.* 2015b). This can further provide a more holistic picture of pelagic frontal dynamics to facilitate the planning of future offshore renewable developments (Medina-Lopez *et al.* 2021).

To be able to elucidate the fine-scale mechanisms of drivers in marine ecosystems and capture any (predictable) variation, it is also necessary to study them in place and at the scales at which these operate. Advances in *in-situ* measurement techniques over the past decade now make it possible to study environmental drivers of ecosystem processes at these resolutions (Supplementary Tables S1 and S2). These include well-established active and passive acoustic techniques that allow for measurement of the spatio-temporal distribution and abundance of organisms as well as physical structuring such as the mixed layer depth and internal waves to be characterized (reviewed in Horne 2000, Godø *et al.* 2014a). Deploying echosounders (active) and hydrophones (passive) in tandem maximizes species discrimination capability and allows for the movements of organisms to be tracked (Williamson *et al.* 2021, Gillespie *et al.* 2022). Combining acoustic sensors with concurrent environmental measurements allows for multitrophic monitoring; this approach deployed on static landers

is already well documented in the marine renewable energy industry (see e.g. Williamson *et al.* 2016, Cotter *et al.* 2017). As the offshore wind industry increasingly moves towards floating wind technology in deeper waters, the development of similar multisensor floating platforms and subsequent combination/integration with turbine structures and observation systems will become increasingly relevant.

Recent advances in uncrewed and autonomous vehicle technologies also offer huge potential to deliver a more complete understanding of shelf-sea ecosystems, as they allow for concurrent measurements of multiple trophic levels over large distances and durations at high spatial resolutions (Ludvigsen and Sørensen 2016). For instance, novel wind and wave-powered gliders that are acoustically silent as well as low fossil fuel emitting are now capable of long duration missions with both active and passive acoustic sensing (Verfuss *et al.* 2019). Attachment of oceanographic sensors (e.g. CTDs, chlorophyll and backscatter sensor, nutrient sensors, eDNA samplers) to gliders and Autonomous Underwater Vehicles (AUVs) is also recently made possible (Palmer *et al.* 2021). When deployed on AUVs, such data can be sent in near real-time, and thus assimilated into high resolution 3D oceanographic forecasting models (Cossarini *et al.* 2019). The attachment of eDNA samplers to AUVs in particular promises to open up new possibilities for biological monitoring as this technique allows for simultaneous multitrophic measurements, including occurrence of microbes, plankton, invertebrates, and fish (Yamahara *et al.* 2019). The development of new Photosynthetically Active Radiation (PAR) sensors combined with chlorophyll fluorescence measurements will also allow for rates of primary production to be calculated *in situ* (Loveday *et al.* 2022). As measuring rates of primary production is normally a time-consuming (and ship-based) process, measurements are sparse; this new *in-situ* method therefore has great potential to deliver data with better spatial coverage that progress understanding.

Returning to the bigger picture, it is the combination of measurements from fisheries trawls/surveys, EO sensing, as well as *in-situ* AUVs, ASVs, and static platforms that will offer the greatest potential to enhance our understanding of shelf sea ecosystem mechanisms (Box 1). Together, these approaches allow for drivers to be studied concurrently, in the locations and time scales most appropriate or least understood. However, the increasing demand for space in shelf seas due to the rapid expansion of OWFs, will introduce bias to several of these data sources. Spatial overlap between future OWF development and fishery surveys may result in changes to survey designs as well as reduce sampling effort, with subsequent implications on data quality (e.g. data gaps) that support our long-term understanding of such mechanisms (Haase *et al.* 2023, Methratta *et al.* 2023). On the other hand, OWF development presents an opportunity to encourage allocation of resources for assessment and monitoring efforts. Increasingly, the use of strategic networks of distributed ocean observatories interconnected by mobile platforms should be considered (Venkatesan *et al.* 2018). Such networks are possible at the regional scales of planned offshore wind (see the existing Lofoten-Vesterålen Ocean Observatory) as well as hypothetically within windfarms (Godø *et al.* 2014b). Placed at strategic locations and augmented with mobile surveys, the data generated (and shared) would have the potential to greatly enhance our understanding of key oceanographic processes and of relevance to industry, governments, and the wider scientific community (Camus *et al.* 2021). The growing stream of

and need to efficiently integrate information from such sensors and platforms means that the concurrent development, adaptation, and application of automated techniques (e.g. machine learning, neural networks, artificial intelligence) for processing and filtering data will continue to be a priority (Beyan and Browman 2020).

Analysis: advances in ecological modelling

To be able to use detailed local data to predict at regional and shelf-wide scales, ecosystem modelling approaches that include the representation of drivers of ecosystem function at all scales are needed. While strides have been made in the last decade in the realm of Agent- and Individual-based Models (i.e. SeaBORD (Searle et al. 2018), iPCOD (Harwood et al. 2014), DEPONS (Nabe-Nielsen et al. 2018), these typically focus on one species of top predator at a time, are highly sensitive to dynamic changes in pelagic fish (prey) distribution (Searle et al. 2023) and may even be nonspatial (iPCOD). While fundamental niche and distribution models are ideal for the prediction of cumulative effects of wildlife responses and population dynamics in the face of multiple pressures (i.e. climate change, energy development, fisheries), these are constrained due to habitat heterogeneity and plasticity in animal abundance and behaviour across space and time (Matthiopoulos et al. 2022). However, as rapid yet robust predictions of the environmental effects of offshore wind are needed, ecological modelling offers valid alternatives. Mechanistic approaches include the parameter-rich food web modelling framework EwE: Ecopath with Ecosim that can be run in space (Ecospace) once different regions are identified (Nogues et al. 2023) or the ‘end-to-end’ functional group framework implemented in StrathE2E2 (Thorpe et al. 2022). Another even more promising approach is that of dynamic Bayesian Network (DBN) modelling, an extension of the well-established Bayesian Network technique for modelling time series (Friedman et al. 1999).

DBN is a parsimonious graphical modelling technique that can be used to capture ecological as well as spatio-temporal patterns between variables (Tucker and Duplisea 2012). Such probabilistic models allow predictions to be made across different spatial and temporal scales in response to stressors while simultaneously including a range of indicator species or functional groups to represent all trophic levels. Coupling physical dynamics from high resolution oceanographic models such as Finite Volume Community Ocean Model (FVCOM) into ecosystem models allows for critical habitat variables from local to regional and shelf-wide scales to be considered including physical (mixing and stratification: Chatzirodou et al. 2016, De Dominicis et al. 2018), biogeochemical (nutrients, oxygen: Tweddle et al. 2013, Hull et al. 2021), and ecological (plankton biomass and vertical distributions: Loveday et al. 2021) (Fig. 3). Crucially, dynamic Bayesian ecosystem models allows for predictions of both species-specific population trends at ecosystem-wide scales in different habitat types, as well as the main drivers of strong changes in any of these trends to be identified (Trifonova et al. 2021). Outputs from ecosystem models can be integrated into finer-scale models, such as niche and distribution models and the Habitat Risk Assessment (HRA) model (Declerck et al. 2022, InVEST: <https://naturalcapitalproject.stanford.edu/>). The use of such ecosystem model outputs as explanatory habitat variables has already enabled advances in the develop-

ment of distribution models for higher trophic levels such as seabirds and marine mammals (Waggitt et al. 2018). For highly mobile, linked predator–prey species such as seabirds and fish, implementing Bayesian hierarchical joint models (using Integrated Nested Laplace Approximation: INLA) is now both robust and computationally efficient (Sadykova et al. 2017), allowing for high-resolution top-predator distributions to be predicted from the drivers (representing true cumulative effects) outputted from the DBN models (Box 1). DBNs can also readily be used to explore a range of ‘what-if?’ scenarios, based on potential changes in climate (e.g. temperature), OWF developments (e.g. stratification), and anthropogenic practices (e.g. commercial fisheries), as well as the specific trends (increases or declines) of different ecosystem components in response to these changes (Trifonova and Scott 2023). By providing an understanding of the reactive responses across and within all trophic levels, tractable predictions of the true dynamic nature of bottom-up (e.g. driven by temperature) versus top-down (e.g. driven by fishing) effects across trophic levels and habitats can be made (Trifonova et al. 2017). This, in turn, will allow for ecosystem-wide (true) cumulative effects to be predicted under multiple scenarios, at scales relevant to Environmental Impact Assessments and with assigned levels of confidence (Caro et al. 2020).

Implications and conclusions: priorities for studies

As the offshore wind industry continues to grow, there is a concurrent need for the scientific community to build the ecological evidence base so that practitioners can make informed decisions. Our North Sea case study demonstrates how to streamline this process through a hypothesis-driven investigative cycle that accounts for the inherent complexities of the marine environment (Box 1). Importantly, as shelf seas slated for increased OWF development differ in biophysical regimes and properties, it will be necessary to identify and measure indicators relevant to the specific region and/or basin of interest (‘Problem/System’ in Fig. 1).

Bottom-up forcing from ‘physics to fish’ (Sharples et al. 2013b) suggests that limited top-predator foraging locations are due to fish availability being tied to locations of new primary production as these are also limited areas where fish are actively foraging in space. As the introduction of OWF structures are suggested to be potential sites of new primary production and/or to promote large-scale changes of primary production, testing whether this is indeed the case at a local scale will be important in extrapolating effects at the shelf-wide scale (Dorrell et al. 2022). Furthermore, the type, configuration, and number of OWFs is likely to have varying impacts on spatially explicit levels of primary productivity due to the combination of local and regional changes to the available mixing energy (Daewel et al. 2022). As many fish species are linked to predictable seasonal changes in feeding and spawning grounds that are likely tied to locations of new primary productivity, investigating predictable variations in annual migration routes with monthly, seasonal and climate factors could provide predictions for top-predator distributions throughout the annual cycle and for the shelf-sea ecosystem, from which predictions on cumulative and combined effects of multiple wind farms can be made (Box 1).

The cumulative ecological effects of changes from OWF may impact how ecosystems function by pushing bio-physical

variables and species interactions beyond natural variability; understanding how these changes interact with and impact/are impacted by the wider socio-economic landscape will also be critical (Methratta *et al.* 2020, Piet *et al.* 2021). Existing cumulative assessment frameworks (e.g. Cumulative Impact Assessment, CIA, Cumulative Effects Assessment) in theory allow for large-scale OWF effects to be evaluated in relation with other marine management sectors (e.g. fisheries) (Cavallo *et al.* 2017). However, these frameworks do not currently include dynamic links between different trophic levels, and interactions between stressors, thereby over-simplifying marine ecosystem processes and functioning (Willstead *et al.* 2018). This contributes to uncertain assessments with a limited understanding of ecosystem-scale impacts to inform future OWF leasing rounds (Tweddle *et al.* 2018). It is therefore important to develop cumulative effects assessments to be able to integrate predicted ecosystem effects across the range of spatio-temporal scales at which changes can occur as shown can be done with the DBN modelling approach above and outlined in detail in Declerck *et al.* (2023).

The emergence of floating wind technology, that allows for extraction of wind energy further offshore in deeper more stratified waters, adds new challenges and opportunities for research (Farr *et al.* 2021, Lloret *et al.* 2022). Similar to fixed wind, floating developments will make alterations to localized wind (Wise and Bachynski 2020) with energy extraction creating wind wake effects, altering the degree of seasonal stratification, and but the differences in primary production may be opposite to those found at the shallower depths (< 50 m) of most static wind farms (Carpenter *et al.* 2016). As well, the difference in the depths of the main components of the sub-structures of floating wind turbines may affect plankton production differently due to the structures' movements increasing mixing within pycnoclines (Dorrell *et al.* 2022). Floating turbines have suspended cables in the water column, which may act differently to static turbine systems as Fish Aggregating Devices (FADs), attracting fish as well as providing many more surfaces within the whole water column for colonization by algae and invertebrates and other opportunistic species (Karlsson *et al.* 2022). However, new studies show differences between the sounds produced with fixed and floating wind developments, with the moving components of the moorings creates impulsive and unpredictable sounds which may alter the expected FAD effects (Risch *et al.* 2023).

The expansion of floating offshore wind will also add to the spatial restrictions already imposed on fisheries due to fixed wind farms and other areas (Gill *et al.* 2020). There is a history of conflict between offshore wind and fisheries in space usage and socio-economic interests (Haggett *et al.* 2020); there is also concern about increased uncertainties in fish stock assessments due to displacement by offshore wind (Haase *et al.* 2023). Investigating the potential for co-location of floating turbines and a selection of fishing gear (e.g. creels, fish traps) has been identified as a research priority. The extent to which OWF developments act as *de facto* marine reserves (MPAs) that increase local fish stocks (Raoux *et al.* 2017), or complicate the achievement of conservation and biodiversity objectives (Lloret *et al.* 2023) has also yet to be determined; however, such effects can be predicted within the DBN modelling approach via what-if scenarios detailed above.

Moving forward, it will therefore be necessary to disentangle environmental effects from and investigate relationships between OWF development, concurrent climate change

effects, and fisheries. Multitrophic, multiscale, and above all hypothesis-driven studies rooted in ecological theory, recall the investigative cycle in Fig. 1, will be more important than ever, as these provide structure for the design of studies, counteract the increasingly untenable data mortgage scenario in marine science, and are adaptable to shifting baselines (i.e. climate change, emergence of new technologies). The resulting enhanced understanding of ecosystem-wide and cumulative OWF effects will be able to provide the empirical evidence-base to increase transferability of and certainty in CIAs, as well as inform marine spatial planning and management strategies.

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Supplementary data

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Data availability

The data underlying this article are available in the article and in its online supplementary material.

Author contributions

N.I., B.S., and B.W.: conceptualization; N.I., G.H., C.H., S.S., A.Z., M.D., K.G., and N.I.: investigation; N.I.: writing—original draft; N.I., B.S., G.H., M.D., K.G., C.H., S.S., N.T., J.J.W., J.U.W., C.W., A.Z., and B.W.: writing—review and editing; E.B., S.S., N.I., and B.S.: visualization; B.S. and B.W.: project administration; and B.S. and B.W.: funding acquisition.

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