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Research article

Framing future trajectories of human activities in the German North Sea to inform cumulative effects assessments and marine spatial planning

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ABSTRACT

The global industrialization of seascapes and climate change leads to an increased risk of severe impacts on marine ecosystem functioning. While broad scale spatio-temporal assessments of human pressures on marine ecosystems become more available, future trajectories of human activities at regional and local scales remain often speculative. Here we introduce a stepwise process to integrate bottom-up and expert-driven approaches for scenario development to inform cumulative effects assessments and related marine spatial planning (MSP). Following this guidance, we developed optimistic, realistic, and pessimistic scenarios for major human pressures in the German North Sea such as bottom trawling, offshore wind, nutrient discharge, and aggregate extraction. The forecasts comprise quantitative estimates in relation to spatial footprint, intensity, and technological advancements of those pressures for the years 2030 and 2060. Using network analyses, we assessed interactions of the current and future trajectories of pressures thereby accounting for climate change and the growing need for marine conservation. Our results show that future scenarios of spatial distributions could be developed for activities that are spatially refined and included in the current MSP process. Further our detailed analyses of interdependencies of development components revealed that forecasts regarding specific targets and intensities of human activities depend also strongly on future technological advances. For fisheries and nutrient discharge estimates were less certain due to critical socio-ecological interactions in the marine and terrestrial realm. Overall, our approach unraveled such trade-offs and sources of uncertainties. Yet, our quantitative predictive scenarios were built under a sustainability narrative on a profound knowledge of interactions with other sectors and components in and outside the management boundaries. We advocate that they enable a better preparedness for future changes of cumulative pressure on marine ecosystems.

1. Introduction

The globally progressing industrialization of seascapes and climate change lead to an increased risk of severe impacts on ecosystem functioning and viability in coastal and offshore areas (Bugnot et al., 2020; Johnston et al., 2022; Setter et al., 2022). Most of these areas face an increasing exploitation by people who depend on services, goods and benefits. Hence, balancing the conservation and restoration of ecosystem functioning with human resource usages is one of today's most pressing challenges in marine and coastal management. Integrated decision-making has to be based on (i) current and future trajectories of human activities at sea and their associated pressures (Allan et al., 2013), (ii) knowledge of tipping points in social-ecological systems at which they shift to undesirable states, and (iii) a quantification of the risk of cumulative effects of pressures on ecosystem states (Bates et al., 2018; Hodgson and Halpern, 2019; Rilov et al., 2019). In recent years, state-of-the-art approaches to quantify cumulative effects on various ecosystem components to inform management have evolved rapidly (Gissi et al., 2017; Hodgson and Halpern, 2019; Piet et al., 2021; Quemmerais-Amice et al., 2020; Rullens et al., 2022; Stelzenmüller

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et al., 2018; Thrush et al., 2021).

In theory, the risk of adverse effects of multiple human pressures and climate change on the ecosystem state in European seas should be kept at bay through the implementation of the EU Marine Strategy Framework Directive (MSFD) (EC, 2008). The MSFD requires member states to implement programs of measures to achieve a "good environmental status" (GES). In turn, these programs of measures or regulations should come into force with the help of the EU Maritime Spatial Planning Directive (MSPD, EU, /89/EU, 2014) requiring member states to implement legally binding maritime or marine spatial planning (MSP), which targets a sustainable blue growth and an ecosystem-based management approach. Ideally, the spatial and temporal allocations of human activities through MSP should reduce spatial use conflicts, promote synergies, the efficient use of space, and safety (Gissi et al., 2021).

Cumulative effect assessments (CEAs) are inherently complex and should incorporate multiple steps such as risk identification, risk analysis, and risk management to ultimately produce outcomes that are of direct use to decision-making (Stelzenmüller et al., 2018). Risk identification and risk analysis entail the establishment of robust causal pathways linking human activities to pressures, and to the ecosystem states or components being affected by the associated pressures. Moreover, it requires an understanding of the "dose-response" relationship between the intensities of combined pressures and state changes. Risk management entails also the assessment of the effectiveness of potential management measures comprising for instance spatial, temporal, or technical restrictions. In this context, scenario evaluation should deliver best available estimates that can underpin the actual decision-making in managing the risk of adverse cumulative effects, therefore bridging science inputs and policy needs (Stelzenmüller et al., 2020).

As indicated by Stock and Micheli (2016), the uncertainty of spatio-temporal data of human activities can have significant effects on CEA outcomes. In recent years, the number and precision of spatio-temporal assessments of human pressures on marine ecosystems increased (Borgwardt et al., 2019; Knights et al., 2015), together with a better understanding of the dynamics of regional (Korpinen et al., 2021) and global patterns of human activities at sea (Allan et al., 2013; Halpern et al., 2015, 2019). But, future trajectories of human activities and their associated pressures at regional and local scales remain often speculative and require transdisciplinary approaches to understand the drivers, policy requirements, societal demands, and economic factors that directly or indirectly affect their development (Pinnegar et al., 2021) Thus, this lack of knowledge is one reason why the analysis of plausible future management measures is often left out in empirical CEAs (Stelzenmüller et al., 2018, 2020).

Here, we address this gap of future projections of human activities that can be directly used in CEAs to inform decision-making. We present a step-wise process that guides the development of future scenarios for selected human activities regarding their spatial footprint, intensity, and technological advancements. Further, we illustrate the proposed step-wise process for the German North Sea and developed transdisciplinary and integrative future scenarios (2030, 2060) of key human activities. Our predictive scenarios are aimed to inform CEA or the set-up of regional ecosystem models to enable the assessment of current and future cumulative effects of human activities on benthic communities and functions and therefore national implementations of the EU policies (MSFD and MSPD). Here we focus on the future trajectories of fisheries, sand and gravel extraction, offshore wind development, and nutrient discharge because of their commonly accepted relevance for this heavily used marine area (Emeis et al., 2015). We combine reviews with expert elicitations to identify components that are directly or indirectly affecting those pressures. Further, we assess interactions of their current and future trajectories with the help of network analysis, accounting also for climate change and marine conservation. In addition, we developed the likely advancements for each human activity in the German North Sea with focus on the spatial footprints, intensity and technical developments for the years 2030 and 2060. Finally, we discuss implications of the here described future developments and conclude on key requirements for building scenarios that can inform CEAs and related MSP processes.

2. Methods

2.1. Step-wise development of future scenarios

Scenario development entails the generation of data and knowledge, the integration of information and the review of consistency (Börjeson et al., 2006). Any forecast or prediction of future developments requires a description of the structure of the system and relies on the defined causalities within the system. Following the comprehensive typology provided by Börjeson et al. (2006), scenarios can be either predictive, explorative, or normative. The authors define predictive scenarios as scenarios aiming to answer the question "What will happen in the future?", thereby distinguishing forecast and what-if scenarios. Forecast scenarios are conditioned by most likely developments and should refer to the near future and be presented with some expression of their probability (e.g. "high", "low"). In contrast, what-if scenarios are conditioned by external factors or events, hence, reflecting what will happen, if one or more determining events occur.

Here, we develop predictive scenarios, to be directly used in CEA and the underlying respective ecosystem-models or assessment approaches. Our step-wise process integrates bottom-up and expert-based knowledge. The first step denotes the definition of the scenario scope and the associated spatial and temporal boundaries. It further entails the definition of an overarching narrative under which the predictive scenarios will be advanced. The scope and management boundaries of the scenarios allow for a succeeding selection of the human activities for which future trajectories should be developed. In a second step, the documentation regarding the current spatial extent, frequency or intensity of each activity, the main regulations and policies, and, where possible, existing scenarios should be reviewed and mapped.

Based on this information, key development components can be defined. Development components here refer to economic, ecological, or socio-cultural factors within and outside the defined boundaries that affect the future trajectories of human activities. Factors external to the management boundaries encompass e.g. oil prices, supply and demand or market dynamics, technological innovations, or energy costs, which can directly influence the spatial spread, intensity or technical development of the selected human activities.

To enable a standardized development of scenarios we defined optimistic, realistic, and pessimistic future scenarios for each assessed activity regarding the spatial footprint, intensity, and technical innovation. Knowledge generation with experts is an integral part of the scenario development process. In the fourth step of our process, experts produce a forecast of optimistic, realistic, and pessimistic scenarios. These scenarios are quantitative, thus use metrics such as surface coverage, or frequencies. This step also comprises a review of the consistency of information. The final step consists of an expert-based analysis of interactions of future trajectories of human activities, marine conservation and climate change.

2.2. Predictive scenarios of selected human activities in the German North Sea

2.2.1. Scenario scope, human activities and drivers of change

Our scope was to develop predictive scenarios of human activities that can be expected to impact benthic communities and ecosystem functions in a coastal and regional sea. The scenario development for the years 2030 and 2060 followed a "sustainability" narrative (Table 1), which we have defined. This narrative addresses a highly-plausible near and far future given the past trajectories and the contemporary vision for a more sustainable future as laid out in the existing policies such as the EU Green Deal (European Commission, 2019), the EU Biodiversity

Table 1
Description of the overarching narrative providing the framework for scenario development.

Sustainability - narrative	
National and international developments	Continued globalization and climate agreements implemented
Political vision for clean energy[a]	Greenhouse gas neutrality in 2045 (RCP 4.5)
Political vision for biodiversity and ecosystem resilience[b,c]	MSFD measures are implemented and improve the health of marine ecosystems: "Good Environmental Status" (GES) achieved for the North Sea in 2030. Marine protected area targets are implemented and well managed: 30% of the North Sea is under marine conservation in 2030
Sustainable food supply from the oceans[d]	Responsible consumption of animal protein from the ocean and improved fisheries management restores and maintains fish stocks: MSY targets reached in 2030

[a] European Green Deal (European Commission, 2019).
[b] Marine Strategy Framework Directive (European Commission, 2008).
[c] European Biodiversity Strategy 2030 (European Commission, 2020).
[d] Sustainable Development Goals 14 (United Nations, 2018).

Strategy for 2030 (European Commission, 2020), and the Sustainable Development Goals (United Nations, 2018).

Following the overall scope, we selected four human activities: (1) benthic trawling, (2) offshore wind development, (3) nutrient discharge, and (4) sand and gravel extraction. The current spatial allocation of those human activities, marine conservation measures as well as the current average bottom temperature and nutrient load are shown for the German North Sea in Fig. 1.

Benthic trawling is a chronic pressure in the southern North Sea and is known to have caused an increase in the abundance of small-sized, short-lived, and early-maturing fish via selective extraction (Rijnsdorp et al., 2018). Climate change was here considered through the detailed representation of surface and bottom temperatures, as it has similarly been identified as potential driver of the distribution of these fish traits (ter Hofstede and Rijnsdorp, 2011; Pecuchet et al., 2017), amplifying the effect of fishing on demersal fish communities in the North Sea (Jones et al., 2023). In the German North Sea, fisheries with a physical impact on the seabed comprise mainly beam and otter trawlers having spatially distinct fishing grounds due to both their target species and prevailing fisheries restrictions in coastal waters (Beare et al., 2013; Hintzen et al., 2021; Rijnsdorp et al., 2020). Fig. 1 exemplifies the spatial distribution of international fishing pressure with a physical impact on the sea floor in 2020 as subsurface swept area ratios (ICES, 2021).

The development and allocation of offshore wind energy falls under sectoral management at a national level in the German North Sea and needs to be placed within the European vision to reach greenhouse gas neutrality by 2050 (COM, 2018). This vision dictates the German Renewable Energies Act (Act, 2014), which encompasses the Offshore Wind Energy Act (WindSeeG, 2017), specifying the targets for the offshore production of renewable energy in the German EEZ (Annex 1). These targets have been set in 2022 by the German government to 30 GW by 2030 and 70 GW by 2045. While the Offshore Wind Energy Act dictates the amount of energy that has to be produced offshore, the spatial plan organises all maritime activities (with the exception of fisheries) in the German EEZ, thereby providing the spatial frame for the expansion targets of the offshore wind energy sector. The Site Development Plan (Hydrographie, 2021), being an instrument of sectoral planning, makes determinations for offshore wind farms and grid connection systems. The current expansion of offshore wind is shown in Fig. 1 using commercial data (www.4coffshore.com).

The extraction of sand and gravel may lead to habitat loss and a long-term shift of benthic communities (Mielck et al., 2021). Sand and gravel in the North Sea are extracted for coastal defense and construction purposes (Bonne, 2010). In the German North Sea, this activity is largely

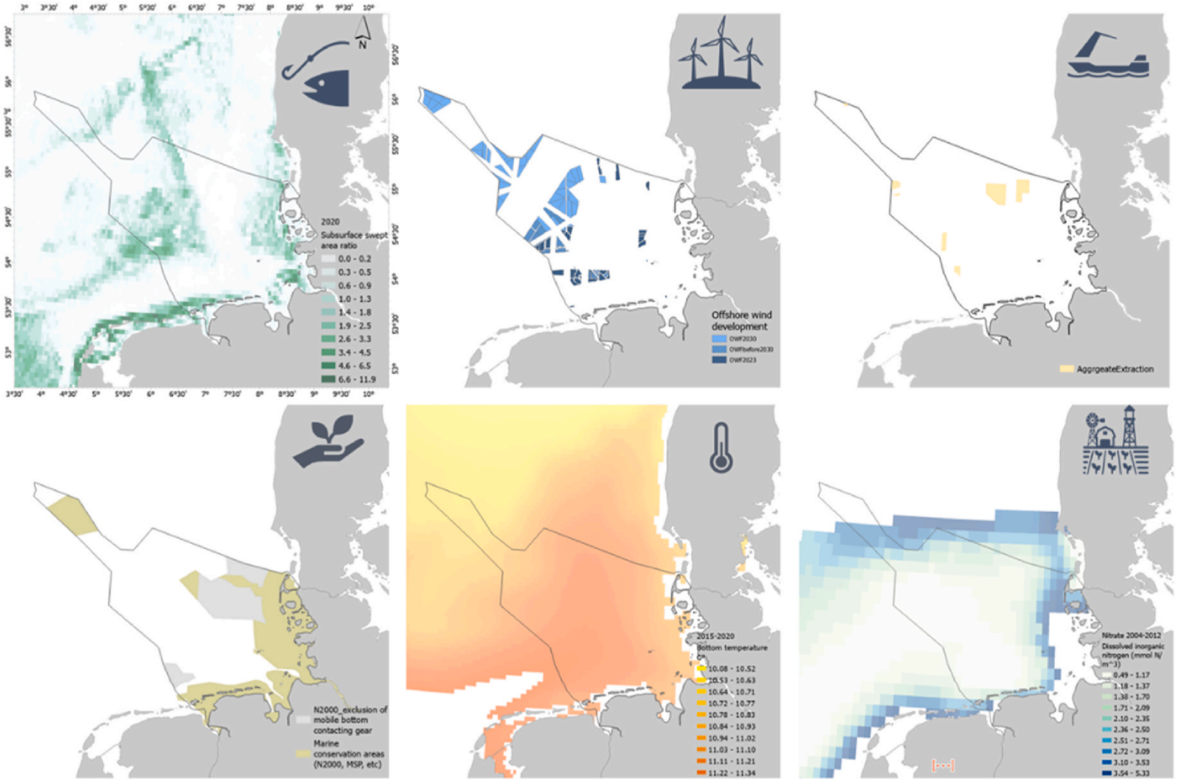


Fig. 1. Map of study area with the current spatial distribution of international subsurface fishing pressure in 2020, offshore wind development (www.4coffshore.com), sand and gravel extraction (BMI, 2021), marine conservation areas and fisheries measures within Natura2000 sites (EC, 2022), average bottom temperature (°C) (2015–2020) (Marsland et al., 2003), and average dissolved inorganic nitrogen (mmol/m^3) (2004–2012) (Jungclaus et al., 2013).

regulated through MSP and limited to specific areas designated for extraction (see Fig. 1; BMI, 2021). The shortage of onshore sand and gravel in combination with the increasing demand for such material, particularly for coastal protection, will likely increase future extraction activities in the North Sea. This situation is reflected in the current search of the federal state Schleswig Holstein for additional extraction areas. There are two active licensed extraction sites in German waters (Fig. 1). OAM III is used for the extraction of material for industrial construction and Westerland III, with an extraction volume of 1.5–4 million tons annually, is used for the extraction of material for coastal defense. An overview of key policies and regulations controlling the extraction of sand and gravel in the German North Sea is provided in Annex 3.

We also consider marine conservation measures to be human activities in the sense that they are regulated or excluded thereby reducing the cumulative pressure load on benthic communities. Conservation in the German North Sea is dominated by marine protected areas (MPA) combined into the Natura2000 network under the Habitats (HD) and Birds Directives (BD) (Fig. 1). The Natura2000-MPAs in the German coastal seas are also part of the Wadden Sea National Park, a UNESCO world heritage site. Within the MPAs of the Wadden Sea National Park, fishing is only restricted for otter board trawling and large beam trawls, while significant effort with small beam trawls (up to 7 m beam width) is allowed (Janβen et al., 2018). In the German Exclusive Economic Zone (EEZ) the Natura2000-MPAs will include significant fishing restrictions such as a no-use area on Amrum-Bank and the exclusion of bottom trawling in large areas of the Sylter Outer Reef, the Borkum Bank and the Dogger Bank (Janβen et al., 2018). The implementation of fisheries restrictions in the Natura2000-MPAs within the German EEZ has been a long process and while the MPA sites were designated in 2007, the actual fisheries regulations were only legally implemented in 2023 (Dureuil et al., 2018). In the current Natura2000-network, no-use zones are only implemented on the Amrum bank and between the islands of Sylt and Föhr (Fig. 1).

We have also selected climate change as a factor outside of the system boundaries that cannot be managed directly, but needs to be considered in the prediction of future development of human activities and their combined pressures. The North Sea, along with other European shelf seas, has exhibited a faster rate of climate heating than the surrounding land and the global ocean (MacKenzie and Schiedek, 2007). Xu et al. (2020) showed that the annual mean sea surface temperature in the North Sea increased by 0.5 °C over a span of 25 years, while (Dulvy et al., 2008) found that winter bottom temperatures rose by 1.6 °C over the same period. This warming trend has led to changes in the region's ecosystem components, including the movement of demersal fish to deeper waters at a rate of 36 cm a^{-1} (op. cit.) and the outward migration of benthic invertebrates by 5 km a^{-1}, tracking the bottom temperature (Hiddink et al., 2015). These increasing temperatures are expected to exacerbate the decline of cod (Clark et al., 2003) and alter the composition of harmful algal blooms (Peperzak, 2003); benthic bioturbation may intensify (Weinert et al., 2022), and there could be a rise in the abundance of jellyfish due to both observed (Omar et al., 2019) and predicted (Blackford and Gilbert, 2007) carbon dioxide-induced acidification of North Sea waters. The average bottom temperature (°C) reflecting climate change effects (2015–2020) is exemplified in Fig. 1 (Marsland et al., 2003).

We further considered nutrient discharge as a relevant pressure for benthic communities because of direct and indirect dependencies to pelagic production such as food availability, optical water properties important for seagrass growth, but also oxygen levels in the sediments. Moreover, high nutrient loads can have detrimental effects on food web dynamics by interacting with other climate change-related and human-induced stressors (Radach and Pätsch, 2007). Land-borne (mostly riverine) nutrient discharge is resulting from multiple land-based human activities (Rousseau et al., 2000; Smith et al., 2006). The major contributor to nutrient discharge in the southern North Sea is the agricultural sector, accounting for 60% of the total nitrogen input (EEA, 2019). The fertilizers and pesticides used in farms enter the marine realm through rivers and by groundwater leaching. An especially large contribution to nitrogen pollution originates from the meat industry: in the Netherlands and in the German state of Lower Saxony, the contribution of animal farms is higher than that of crop-based farms. Animal dung and soy soil, which is often imported from abroad (e.g., Brazil) to nourish animals, have significantly high concentrations of inorganic nitrogen. Atmospheric deposition is the second biggest contributor (~20%) to nutrient pollution in the southern North Sea (Troost et al., 2013). The emissions from automobiles, ships, and aircrafts constitute a large part of the nitrogen (N) and phosphorus (P) depositions. Climate change also plays a role, an increase in precipitation events triggers higher N and P inputs to the southern North Sea both from river runoffs and from the atmosphere. Furthermore, industries also contribute significant N and P loads either by emissions or in the form of untreated discharge (Dubaish and Liebezeit, 2013). There has been a considerable reduction in nutrient concentrations in the southern North Sea compared to the period 1970–1990. However, no water body of the coastal and transitional waters of the German North Sea has achieved good or very good ecological status in terms of DIN concentrations (Voβ et al., 2009). The target set by the European Water Framework Directive (COM, 2000) has been largely missed. The primary reason for missing the target is the excessive input of nutrients in the North Sea by the rivers, with agriculture-based activities being the main contributor. This is supported by the flow-weighted annual total nitrogen load (TN) data from the rivers draining into the southern and northern Wadden Sea, which show only a marginal decrease in the loads from 1980 to 2020 (van Beusekom et al., 2019). Fig. 1 shows the average dissolved inorganic nitrogen (mmol/m^3) (2004–2012) (Jungclaus et al., 2013).

2.2.2. *Future predictions and interactions of human activities*

Steps three to five of our framework comprise an expert-based review of development components and factors influencing future development of human activities, development of predictive scenarios, and an analysis of the interaction of the here selected human activities. For this we conducted a transdisciplinary expert workshop on the 28th of March 2022 in Hamburg, Germany. Next to the project team, workshop participants comprised recognized experts in the fields of fisheries (n = 7), offshore wind energy production (n = 5), nutrient discharge (n = 6), and sand and gravel extraction (n = 3). All experts work either on the impacts, regulation or innovation potential of the respective sectors. Experts were informed about the activities in the workshop, the scope and the narrative prior to the workshop. For each activity we formed subgroups to define and prioritize the development components affecting the future trajectories of fisheries, sand and gravel extraction, offshore wind development and nutrient discharge, considering thereby also long-term consequences of climate change, the growing need for marine conservation, and technological innovation or the potential of nature-based solutions. The development components were categorized into directly impacting policies (i.e., policy framework, directives, and laws), management processes or measures, technological aspects, socio-economic and socio-cultural factors, environmental factors, and other aspects. In a next step, the sub-groups defined three alternative pathways (pessimistic, realistic and optimistic) according to the *a priori* defined "sustainability" narrative. Thus, for the years 2030 and 2060, the scenarios were defined with metrics representing the respective spatial footprints, intensities and technological developments.

The license areas also reflect the optimistic view of reaching the set national targets. The future development of aggregate extraction license areas refer to the sites defined by the German maritime spatial plan for the EEZ of the North Sea (BMI, 2021), hence reflecting rather the realistic scenario of area designation. Data on marine conservation areas were extracted from the European Environmental Agency and refer to the fisheries regulations regarding the deployment of bottom contacting gears in German N2000 sites (EC, 2022). Since nutrient loads will not be managed through spatial measures or zoning we did omit the future mapping of nutrient load forecasts.

After having gained an in-depth understanding of which internal and external factors influence the respective future developments we assessed the direct interactions of all human activities, marine conservation and climate change. For this, we used a matrix layout, where the human activities, marine conservation and climate change specifications were arranged in rows and columns so as to form a rectangular array. Each workshop participant (including the project team) identified positive and negative interactions between pairs of combinations. Negative interactions were further characterized as i) could be mitigated through management measures, ii) could be resolved through technological solutions or iii) “hard to resolve”. The final interaction matrix reflects the number of times where interactions (positive and negative) have been identified. In an analogy to social network analysis (Borgatti et al., 2009), we analyzed and visualized patterns of aggregated interactions with the R library “igraph” (Csárdi et al., 2023). Hence, human activities, marine conservation measures and climate change are represented as vertices and the respective interactions as edges.

We illustrated the potentials and limitations of the identified trajectories of change for selected human activities and marine conservation measures for the years 2023, 2030 and 2060. Since our scenario scope is to forecast the development of future human pressures on benthic communities, we represented benthic trawling as the subsurface swept area (km^2) (ICES/OSSPAR (Eigaard et al., 2015). Following the optimistic view, we implemented the simplified assumption of a constant overall intensity of fishing pressure within the system boundaries, but with a reduction of its spatial footprint. Hence, we calculated the future distribution of subsurface fishing pressure through a homogenous redistribution of the fishing effort displaced by fisheries exclusion measures (offshore wind, marine conservation) to grid cells with a value $\geq$ the 5th quantile (22.5) in 2020. Further, we illustrated current and future offshore wind development with the help of the 4C offshore data (www.4coffshore.com).

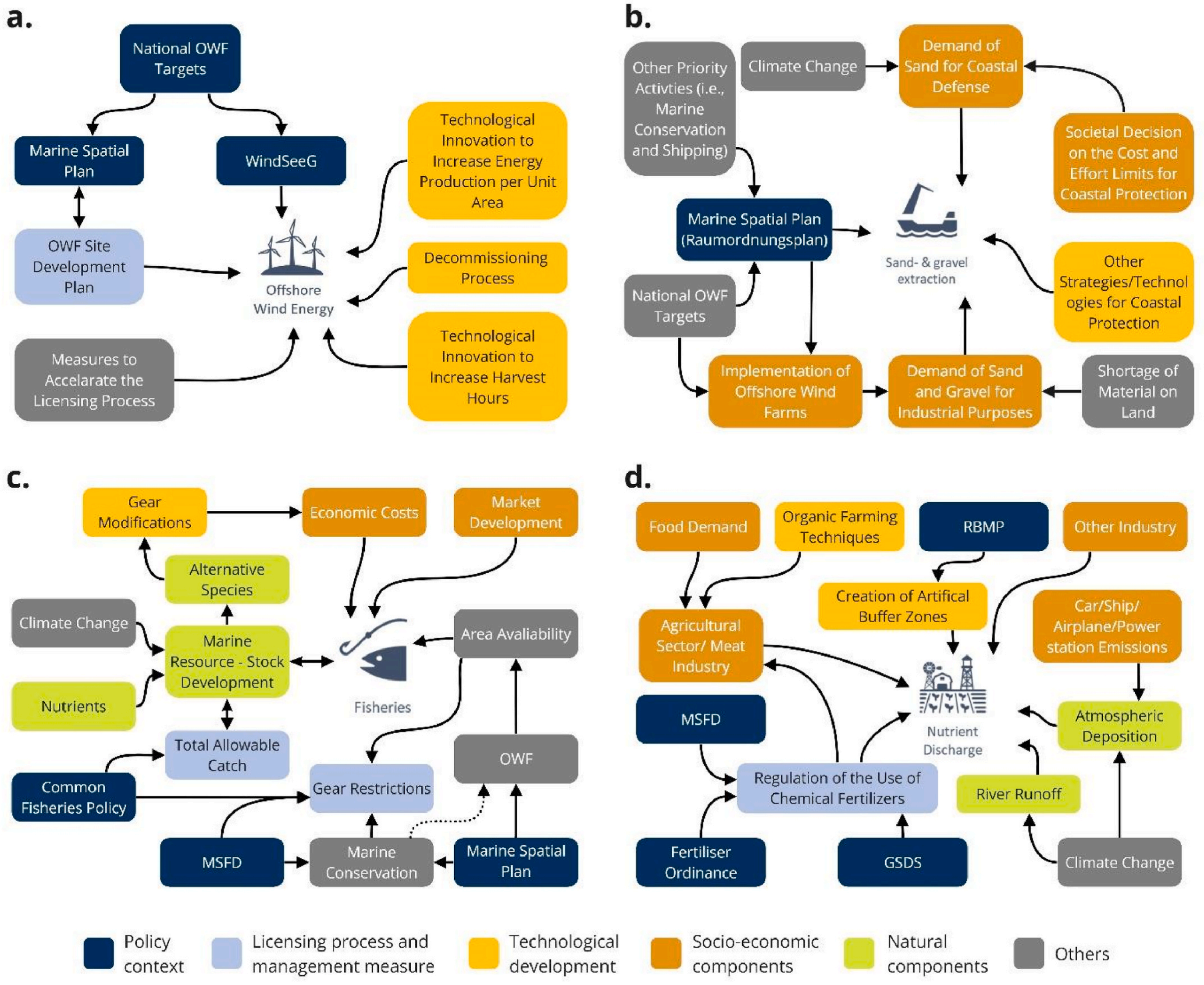


Fig. 2. The main development components for fisheries (upper left), offshore wind energy production (upper right), sand and gravel extraction (lower left), and nutrient discharge (lower right) in the German North Sea. Components were categorized into directly impacting policies (i.e., policy framework, directives, and laws, dark blue), management process/measures (light blue), technological aspects (yellow), socio-economic and socio-cultural factors (orange), environmental components (light green), and other aspects (grey). TAC = Total Allowable Catch. OWF = Offshore Wind Farms. MSFD = Marine Strategy Framework Directive. GSDS = German Sustainable Development Strategy. RBMP = River Basin Management Plan. WindSeeG = Offshore Wind Energy Act. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results

3.1. Components influencing future trajectories of human activities in the German North Sea

The development components were identified at the expert workshop. Those development components were categorized and partly simplified to map out such complex relationships (Fig. 2). A first comparison across the considered activities indicates that the development of fisheries depends on how the political vision and the regulatory framework will be implemented effecting both catch restrictions and area availability. However, fisheries highly depend on many additional factors other than the political vision and the regulatory framework including socio-economic factors such as the demand for fish and the costs of the activity (Fig. 2). Environmental factors such as the availability and exploitation of alternative resources (e.g. extending pot fisheries on brown crab (*Cancer pagurus*) in the vicinity of offshore wind farms) or changes in target species due to climate change are deemed to have a strong influence on the development of fisheries. Hence, they depend on the health and distribution of fish stocks, which are affected by increasing temperatures and pollution, the introduction of nutrients and invasive species, and the activity itself. Overall, the trends of these factors are highly uncertain. For instance, economic costs may potentially increase to the point where they exceed revenues and accelerate the current decrease in the number of active vessels. However, it is also possible that the economic situation stabilizes, or fishers may adapt their activity accordingly.

In contrast, the offshore wind energy sector depends strongly on technical innovations: the strong political push towards the expansion of offshore wind energy production has resulted in clear targets of the activity, which are reflected in the marine spatial plan and the site development plan. To ensure the timely implementation of the targets for offshore wind production, measures to accelerate the licensing process are discussed (Fig. 2).

The future development of sand and gravel and nutrient discharge was deemed to be influenced mostly by socio-economic and socio-cultural factors, but also by impacts of climate change, i.e. coastal defense or protection measures necessary to account for rising sea levels. Since the extraction of sand and gravel is also regulated through MSP and falls into the political vision of sustainability, the trajectories of change are largely determined by the sand needed for the coastal protection of the Wadden Sea (Fig. 2).

Nutrient concentrations are dependent on the mobility sector (emissions from cars and ships) and food demand (agricultural sector), thus nutrient discharge is related to land-based activities, in contrast to the other activities (Fig. 2). Nutrient concentrations in the North Sea are ultimately contingent on environmental components such as river runoff and atmospheric depositions, which in turn are affected by climate change, e.g. through increasing precipitation events. To make matters more complex, the nutrient concentrations in the rivers and the North Sea are affected by regulations at different levels: ranging from target levels in the rivers and groundwaters to nitrogen surplus limits in the agriculture sector and atmospheric deposition thresholds.

3.2. Future trajectories of human activities

In Fig. 3 the developed pessimistic, realistic and optimistic scenarios are shown for 2030 and 2060, respectively. Given the high uncertainty in the defined development components for fisheries, participants only expressed their estimates for 2030 and predicted only a few values for 2060 (realistic scenario, Fig. 3). Experts determined the restricted availability of space or fishing opportunities in the German North Sea as the most critical factor in the development and subsequent transformation of the fishing sector. Given the political vision for climate neutrality, the expansion of offshore wind energy production is given a high priority and the activity will claim a large area (~12%) of the North Sea until 2060 (Fig. 3). Furthermore, marine conservation areas will also expand in the North Sea limiting potential fishing opportunities and/or the use of certain gears. Past and current spatial restrictions, increasing economic costs, and the competition for space have already challenged the fishing sector in the North Sea. This trend is expected to continue in 2030 and 2060 with estimated fishing intensity dropping by 12 % and 30 % compared to the selected reference year 2020 (Fig. 3). Current intensities of fishing effort were foreseen to be maintained only in the most optimistic case, in which co-use options between the fishery, offshore wind farms, and marine conservation areas prevail, and possible priority areas for fisheries are created so that key fishing grounds remain accessible (Fig. 3).

Given the clearly defined boundary conditions, the production targets for offshore renewables are expected to be achieved by 2030 and 2060 in the optimistic and realistic scenarios (Fig. 3). While for offshore wind energy production participants foresee a strong increase in intensity and spatial footprint, the previous reduction of construction capacity (personnel and material) has led to the expectation that strong technological development and innovations towards more efficient use of space will only be seen in 2060 (Fig. 3).

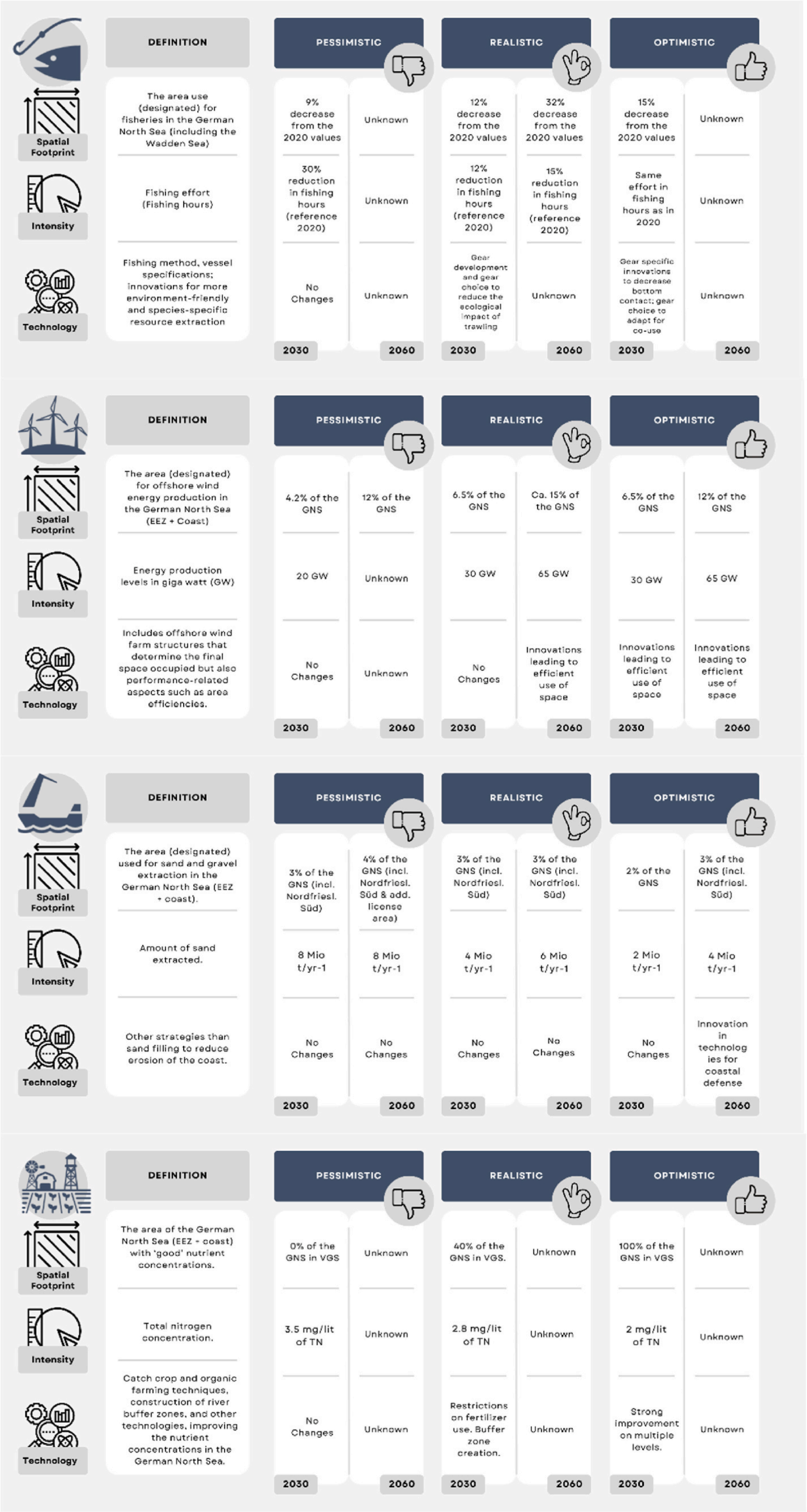
Experts forecasted a clear increasing trend in aggregate extraction due to the socio-political desire to protect the Wadden Sea, sea level rise, increasing flooding risks and storms. However, there is the expectation that the activity will reach a plateau as the protection of the coast may not be conducted at all costs, especially as it is not considered a priority activity and space may be limited (Figs. 3 and 4). Shortage of space and the push for offshore wind energy expansion and marine conservation areas also lead to the expectation that not many additional concession areas for sand and gravel extraction will be designated until 2030 and 2060 (Figs. 3 and 4). The least change particularly in technological development was expected for sand and gravel extraction (Fig. 3).

The political will to reach a Good Environmental Status for the German water bodies leads to the expectation that nutrient concentrations will decrease until 2030, optimistically even falling below the current target levels (Fig. 3). Nutrient discharge contrasts with the other activities in that its spatial footprint is hard to predict. Strong technological development in the near future (2030) was expected for nutrient discharge (Fig. 4). The reduction of fertilizer use and the creation of buffer zones were seen as realistic and in the optimistic scenario, it was also predicted that improvements would be made in animal waste treatment, organic farming techniques, and technology to reduce atmospheric emissions. The complexity of the problem and dependence on so many factors resulted in such a large uncertainty of potential nutrient concentrations in the North Sea in 2060, that participants withdrew from making any predictions (Fig. 3).

The mapped scenarios for selected human activities are illustrated in Fig. 4. The designated areas for offshore wind and aggregate extraction will increase according to the designated marine spatial plan. The redistribution of subsurface fishing effort based on 2020 has been illustrated for 2030 and 2060. In 2030, we found that 30 % of the highest values for subsurface fishing pressure were overlapping with the fisheries exclusion areas. For 2030 and 2060, due to the here applied redistribution rules the subsurface fishing pressure led to an increase of intensity in areas where fishing effort was already increased.

3.3. Patterns of interactions of human activities

The produced interaction matrix was converted into a directed network with six vertices. Summing up only the negative and positive effects for incoming values per vertices showed that most links were connected to fisheries(69), followed by marine conservation (31), sand and gravel extraction (23), climate change (18), nutrient discharge (14), and offshore wind (11). Outgoing values per vertices ordered as such: climate change (51), offshore wind (37), marine conservation (30), sand and gravel extraction (20), nutrient discharge (17), and fisheries (11) (Fig. 5). The links between the human activities (in dark blue) show



	DEFINITION	PESSIMISTIC		REALISTIC		OPTIMISTIC	
		2030	2060	2030	2060	2030	2060
Spatial Footprint	The area use (designated) for fisheries in the German North Sea (including the Wadden Sea)	9% decrease from the 2020 values	Unknown	12% decrease from the 2020 values	32% decrease from the 2020 values	15% decrease from the 2020 values	Unknown
Intensity	Fishing effort (Fishing hours)	30% reduction in fishing hours (reference 2020)	Unknown	12% reduction in fishing hours (reference 2020)	15% reduction in fishing hours (reference 2020)	Same effort in fishing hours as in 2020	Unknown
Technology	Fishing method, vessel specifications; innovations for more environment-friendly and species-specific resource extraction	No Changes	Unknown	Gear development and gear choice to reduce the ecological impact of trawling	Unknown	Gear specific innovations to decrease bottom contact; gear choice to adapt for co-use	Unknown

	DEFINITION	PESSIMISTIC		REALISTIC		OPTIMISTIC	
		2030	2060	2030	2060	2030	2060
Spatial Footprint	The area (designated) for offshore wind energy production in the German North Sea (EEZ + Coast)	4.2% of the GNS	12% of the GNS	6.5% of the GNS	Ca. 15% of the GNS	6.5% of the GNS	12% of the GNS
Intensity	Energy production levels in giga watt (GW)	20 GW	Unknown	30 GW	65 GW	30 GW	65 GW
Technology	Includes offshore wind farm structures that determine the final space occupied but also performance-related aspects such as area efficiencies.	No Changes	Unknown	No Changes	Innovations leading to efficient use of space	Innovations leading to efficient use of space	Innovations leading to efficient use of space

	DEFINITION	PESSIMISTIC		REALISTIC		OPTIMISTIC	
		2030	2060	2030	2060	2030	2060
Spatial Footprint	The area (designated) used for sand and gravel extraction in the German North Sea (EEZ + coast).	3% of the GNS (incl. Nordfriesl. Süd)	4% of the GNS (incl. Nordfriesl. Süd & add. license area)	3% of the GNS (incl. Nordfriesl. Süd)	3% of the GNS (incl. Nordfriesl. Süd)	2% of the GNS	3% of the GNS (incl. Nordfriesl. Süd)
Intensity	Amount of sand extracted.	8 Mio t/yr-1	8 Mio t/yr-1	4 Mio t/yr-1	6 Mio t/yr-1	2 Mio t/yr-1	4 Mio t/yr-1
Technology	Other strategies than sand filling to reduce erosion of the coast.	No Changes	No Changes	No Changes	No Changes	No Changes	Innovation in technologies for coastal defense

	DEFINITION	PESSIMISTIC		REALISTIC		OPTIMISTIC	
		2030	2060	2030	2060	2030	2060
Spatial Footprint	The area of the German North Sea (EEZ + coast) with 'good' nutrient concentrations.	0% of the GNS in VGS	Unknown	40% of the GNS in VGS.	Unknown	100% of the GNS in VGS	Unknown
Intensity	Total nitrogen concentration.	3.5 mg/lit of TN	Unknown	2.8 mg/lit of TN	Unknown	2 mg/lit of TN	Unknown
Technology	Catch crop and organic farming techniques, construction of river buffer zones, and other technologies, improving the nutrient concentrations in the German North Sea.	No Changes	Unknown	Restrictions on fertilizer use. Buffer zone creation.	Unknown	Strong improvement on multiple levels.	Unknown

Fig. 3. Definition of the metrics for the spatial footprint, intensity, and technology used to describe the future development of the activities together with pessimistic, realistic and optimistic scenarios for 2030 and 2060 scenarios for fisheries, offshore wind energy production, sand and gravel extraction, and nutrient for fisheries, offshore wind energy production, sand and gravel extraction, and nutrient discharge; GNS = German North Sea. VGS = Very Good Status. GW = Gigawatt.

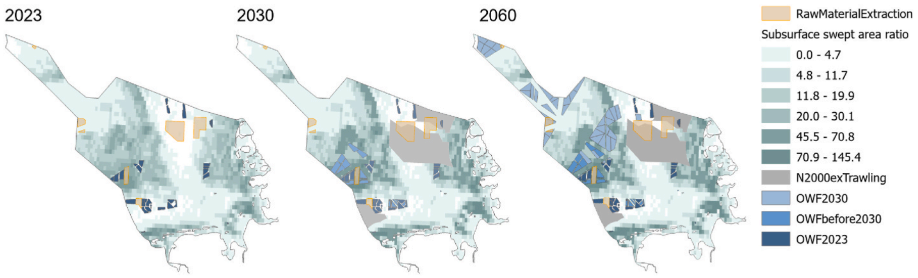


Fig. 4. Example of mapped current and future development (2030, 2060) of international subsurface fishing effort, offshore wind areas, aggregate extraction license areas and marine conservation measures in the German North Sea.

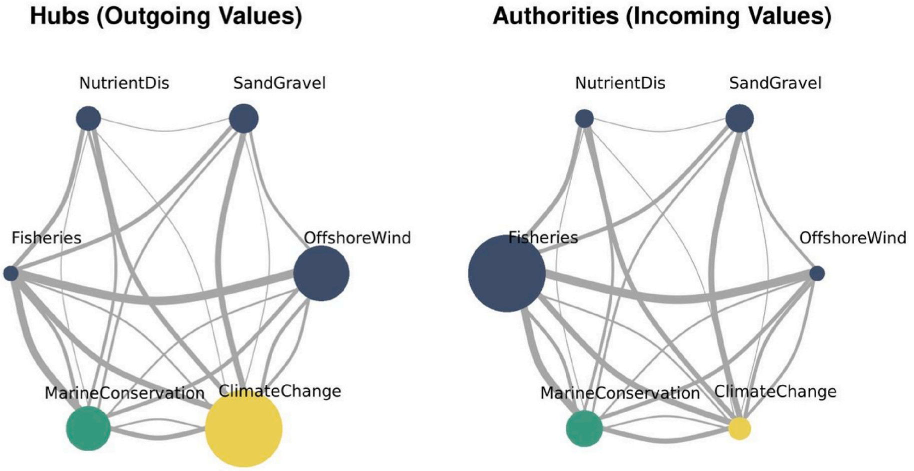


Fig. 5. Networks summarising the negative and positive interactions between fisheries, offshore wind development, nutrient discharge, sand and gravel extraction, marine conservation and climate change in the German North Sea; whereby the size of hubs reflects the relative proportion of outgoing edges (top left), the size of authorities embodies the relative proportion of incoming links (top right). The thickness of the edges corresponds to the number of links, although the arrows are omitted to draw attention to the hub sizes. To facilitate interpretation, hubs are color-coded, with dark blue representing a manageable human activity, green for spatial conservation measures, and yellow for climate change. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

mutual interactions, and when characterizing the components by incoming and outgoing links it becomes clear that fishing has the least outgoing links (affecting others), but the most incoming links (being affected by others) (Fig. 5). Many negative interactions (in the sense that one activity has negative effects on the respective other activity) between the selected human activities, climate change, and marine conservation were identified by the workshop participants (Fig. 6). For instance, Fig. 6 shows that climate change, sand and gravel extraction, and nutrient discharge have been identified as negatively affecting marine conservation and fisheries. Several of the negative effects on fisheries result from the competition for space due to the expansion of offshore wind energy production and marine protected areas, and the subsequent loss of fishing opportunities. However, several participants indicated that such negative effects could be mitigated through management and partly technological solutions (Fig. 6). In particular, climate change effects on marine conservation and fisheries were considered as difficult to resolve (Fig. 6).

While there is a clear spatial conflict between marine conservation and fisheries leading to short-term negative effects, participants also recognized that marine conservation helps to maintain healthy fish stocks and can therefore result in long-term positive effects on fisheries (Fig. 6). Furthermore, increased biodiversity in marine protected areas was identified as a potential CO_2-storage mitigating climate change. Similarly, offshore wind farms were suggested to have a positive effect on fisheries by acting as a protected area, a feeding ground, or a stepping stone for invasive species that might become of commercial interest to the fishery. Co-use of offshore wind farms and fisheries as well as nature-based solutions within wind farms were also seen as important mitigation strategies to area conflicts between the activities. The negative effect of nutrient discharge on marine conservation (Fig. 6) was related to potential increases in harmful algal blooms and hypoxic conditions in coastal waters which are reported to have detrimental effects on the ecosystem health. Even though, the interactions between nutrient discharge and fisheries were not only expected to be negative but participants also suggested positive effects (Fig. 6) through potential increases in biological production resulting in increased fisheries yields. Overall, the interactions between nutrient discharge and fisheries were estimated to be difficult to resolve because one would need to understand the direction of impact and define thresholds.

While sand and gravel extraction were identified to contribute to climate change due to the CO_2 emissions during the activity, fisheries were predominantly identified to potentially mitigate climate change (Fig. 6). Although counterintuitive, this was explained by the perception that fish protein has a smaller CO_2 footprint than land-based animal protein. Predominantly positive interactions between human activities (excluding effects from climate change on sand and gravel extraction and offshore wind energy expansion) were only seen between offshore wind energy production and marine conservation through protection effects of wind energy infrastructures on the ecosystem as a whole (Fig. 6).

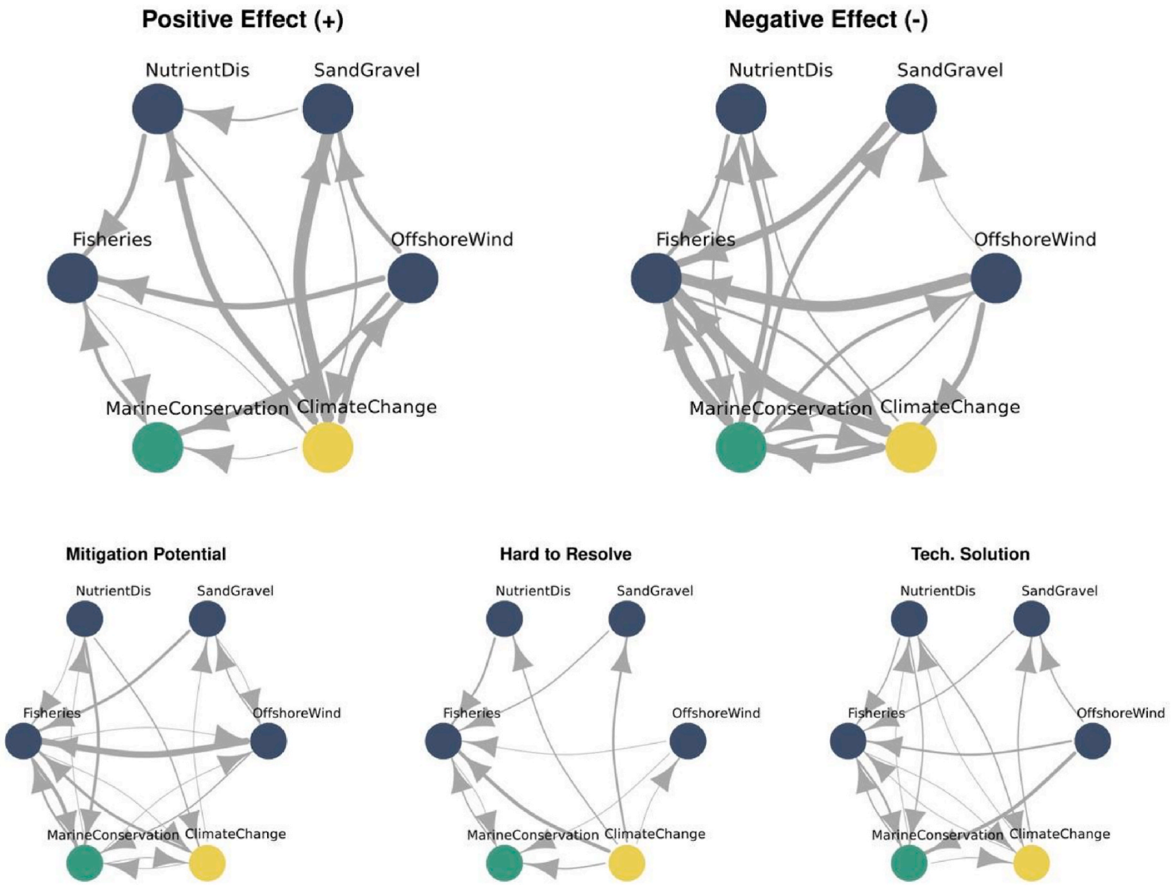


Fig. 6. Directed networks with the thickness of the edges reflecting the number of times a link was attributed by experts to a positive effect (top left), negative effect (top right), be resolvable by mitigation measures (bottom left), be unresolvable (bottom middle), and be resolvable by technical solutions (bottom right). Hub sizes are represented as the same to focus more on the edge thickness. To facilitate interpretation, hubs are color-coded, with dark blue representing a manageable human activity, green for spatial conservation measures, and yellow for climate change. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Future trajectories for human activities in the German North Sea

This study introduces a step-wise process to both prioritize and develop bottom-up descriptions of future trajectories of human activities at sea which can inform e.g. assessments of future cumulative effects of human pressures on the seabed. We applied this approach in the German North Sea, acknowledging the potential effects of climate change and the implementation of marine conservation measures. We illustrated how the here considered activities differ substantially in the complexity and uncertainty of components that determine their future. Our scenarios of human activities exhibited a gradual increase for the years 2030 and 2060 in the intensity and spatial expansion of sea use. Given the uncertain nature of human activities, our predictive scenarios also address the uncertainty of future developments by giving estimates for pessimistic, realistic and optimistic outcomes.

In general, scenarios could be best developed for the near future in 2030, while, with the exception of offshore wind, 2060 forecasts remained vague or impossible. This exemplifies that sectoral plans, integrated in the national MSP process, allow for a more certain description of future trajectories with regard to spatial requirements. However, the efficient of offshore wind energy production will depend on the expansion targets and on the technological development within the sector. For example, the trade-off between the power intensity of wind farms and the potential reductions in the full load hours due to shadowing effects will determine the number of wind turbines set per square meter. At present, the designated areas for offshore wind in the German EEZs of the North Sea and Baltic Sea are not able to implement the envisioned 70 GW. The newly launched revised site development plan proposes new areas to increase the production from 57 GW to 70 GW. Suggestions include the use of the marine conservation area “Doggerbank” and the extension into foreign EEZs of the North Sea. Hence, our results highlighted that in the next decade, technological developments and potential innovations could have a severe impact on the spatial development of the here-considered human activities. Furthermore, we flagged effects that could be potentially overlooked, such as the future increasing intensity of sand and gravel extraction due to the growing demand for sand for building offshore wind turbines.

The expert-based process showed that the expansion of offshore wind has both negative effects on fisheries within the boundaries of the German North Sea such as fishing effort displacements and potential long-term fisheries benefits due to the conservation of marine biodiversity as a result of fisheries restrictions. The regional trajectories shown here therefore reflect well the increasing pressure on the European fishing sector and the expected general loss of fishing opportunities through the expansion of offshore wind (Stelzenmüller et al., 2022) and conservation measures (Probst et al., 2021). Also, the expected benefits for fisheries resources are in line with recent studies addressing ecological impacts of offshore wind in the North Sea (Dannheim et al., 2019; Degraer et al., 2020).

The expected decreasing future nutrient discharge is in line with the political will to reach a Good Environmental Status for the German water bodies by 2030. Overall experts described the definition of spatial footprints of nutrient discharge as the greatest challenge. The transport of nutrients from the terrestrial to the marine system is strongly affected by spatio-temporal factors and it is key to understand relative contributions that control nutrient transport (Díaz et al., 2021; Reichmann et al., 2013; Smith et al., 2006). Mapping nutrient loads requires complex approaches, such as measuring stable isotopes in jellyfish and derive subsequent spatial prediction models of nutrients (St. John Glew et al., 2019). Acknowledging both the need to represent the spatial footprints to support spatial explicit management processes and to apply complex modeling approaches to derive sound estimates, we expressed in our scenarios' spatial footprints as percentage surface area of the management boundaries.

Comparing the scenarios and the development components across the human activities clearly shows that future projections for fisheries were the most difficult ones. Fisheries in the German North Sea strongly depend on future environmental change and socio-economic factors outside the system boundaries such as availability of resources, demand for fish, societal acceptance of certain fishing techniques, and the costs of the activity (Letschert et al., 2023). Hence, fisheries reflect social-ecological systems where human well-being depends directly on the ecosystem's health and its ability to withstand ecological and socio-economic change (Cinner et al., 2019; Colding and Barthel, 2019). One of the key challenges was to derive quantitative metrics for the spatial footprint and aggregated intensity of fisheries within the system boundaries. There are complex models and approaches such as bio-economic models (Maina et al., 2021), integrated food-web models (Püts et al., 2023) or probabilistic models such as Bayesian belief networks (Rambo et al., 2022) that are much better suited to explore impacts of management strategies or ecological change on fisheries. The estimates presented here are based on expert knowledge and cannot be compared to the results of such complex modeling efforts, nevertheless, they are deemed as being informative since they can be immediately compared to other human activities. Thus, mapping the future development of the sectors is essential for the communication of scenarios. Here we presented maps for 2030 and 2060 reflecting the expected developments of three sectors. However, our redistribution of fishing effort is simplified and does not account for climate change, and socio-economic change in the sector. Process models such as agent-based models would be needed to simulate future spatial adaptations of fishing activities (Bastardie et al., 2017).

4.2. *Requirements for scenarios to inform CEA and marine spatial planning*

In general, there are numerous tools that support the development of scenarios comprising e.g. mental models allowing in particular the reflection of complexities (Olsen et al., 2023) or stakeholder surveys that enable the collection of different viewpoints (Cronan et al., 2022). But often the direct use of such model outputs or scenarios in MSP processes is hampered by the lack of standardization and quantitative metrics. Other studies showed that mixed method approaches such as combining stakeholder build scenarios with dynamic models could lead to robust scenarios that can inform governance processes (Hamon et al., 2021; Withycombe Keeler et al., 2015). Consistent with such previous studies, we highlight the importance to frame the scenario requirements well. Hence, the first step of our process was aligned with the need to inform MSP processes regarding the future development of the risk of cumulative effects of human activities on the seabed (Stelzenmüller et al., 2018).

An ecosystem-based MSP process seeks to integrate planning for socio-economic objectives with marine conservation and restoration measures to move towards a sustainable supply of marine goods and services, which in turn depend on healthy ecosystems (Ansong et al., 2017). Achieving this would require to imbed cumulative effects assessment in an MSP process (Piet et al., 2021; Stelzenmüller et al., 2018; Stephenson et al., 2019). Furthermore, the explicit integration of marine conservation targets in MSP process and objectives is increasingly debated (Reimer et al., 2023). Our network analysis clearly revealed marine conservation as a key component influencing and interacting with the here-considered human activities. Our results confirmed the conclusions drawn in (Zuercher et al., 2023), that future MSP processes have to cope with an increasing complexity with regard to goals and objectives, actors, governance setting and factors outside the system boundaries such as climate change or unexpected events such as the European energy crises.

In the past, the German MSP process focused primarily on the future development of offshore wind energy production in the German North Sea, thereby reflecting societal goals and targets (Stelzenmüller et al., 2021a). But future MSP processes need to increasingly seek for pathways to implement an ecosystem-based approach. In doing so, scenarios are needed that address multiple criteria problems such as spatial-prioritization and trade-offs between e.g. offshore wind, fisheries and marine conservation (Boussarie et al., 2023). Analyzing the interactions between fisheries and offshore wind, revealed that negative effects for the fishing sector might be mitigated through technical solutions such as the co-use of space between offshore wind farms and fisheries. While first feasibility studies indicate the potential for local co-location solutions (Stelzenmüller et al., 2021b), practical questions such as the integration of co-location measures in MSP processes or the consideration of local ecosystem impacts of co-location solutions in regional scale CEA remain to be addressed. Thus, an in-depth analysis of the interactions between sectors and other development components is a key requirement to understand such trade-offs and sources of uncertainty. Such knowledge is not necessarily gained by a stakeholder-driven process as considered good practice in MSP. In fact, this demands technical expertise and a transdisciplinary setting as proposed by our stepwise process.

5. Conclusions

Here we suggest a step-wise process that integrates bottom-up and expert-driven approaches to develop predictive future scenarios of human activities to inform CEAs and related MSP processes. Applying the structured process in the German North Sea led to expert-based forecasts in relation to the spatial footprint, intensity, and technological development of fisheries, offshore wind energy production, nutrient discharge and aggregate extraction. This study provides for the first-time consistent pathways of change and scenarios for four human activities in the German North Sea considering climate change and marine conservation measures. The analyses of interactions between the selected stressors or human activities showed in many cases not only a high level of complexity, but it illustrated that specific interactions can accelerate change within a sector thereby impacting future trajectories. This highlights the need for modeling or experimental approaches that can shed light on the strength of those specific interactions. We conclude that future scenarios of human activities should be built on a profound understanding of interactions with other sectors and components in and outside the management boundaries including marine conservation needs and climate change. Using such predictive scenarios to assess the potential future change of human pressures on marine ecosystems are important steps towards the implementation of ecosystem-based MSP.

Ethics statement

Ethical approval was not required for this research.

CRediT authorship contribution statement

V. Stelzenmüller: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **J. Rehren:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **S. Örey:** Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization. **C. Lemmen:** Investigation, Writing – review & editing, Funding acquisition. **S. Krishna:** Investigation, Writing – review & editing. **M. Hasenbein:** Investigation, Writing – review & editing. **M. Püts:** Investigation, Writing – review & editing. **W. N. Probst:** Investigation, Writing – review & editing. **R. Diekmann:** Investigation, Writing – review & editing, Funding acquisition. **J. Scheffran:** Investigation, Resources, Writing – review & editing, Funding acquisition. **O.G. Bos:** Investigation, Writing – review & editing. **K. Wirtz:** Investigation, Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119507.

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