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Research article

Operationalizing a fisheries social-ecological system through a Bayesian belief network reveals hotspots for its adaptive capacity in the southern North sea

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ABSTRACT

Fisheries social-ecological systems (SES) in the North Sea region confront multifaceted challenges stemming from environmental changes, offshore wind farm expansion, and marine protected area establishment. In this paper, we demonstrate the utility of a Bayesian Belief Network (BN) approach in comprehensively capturing and assessing the intricate spatial dynamics within the German plaice-related fisheries SES. The BN integrates ecological, economic, and socio-cultural factors to generate high-resolution maps of profitability and adaptive capacity potential (ACP) as prospective management targets. Our analysis of future scenarios, delineating changes in spatial constraints, economics, and socio-cultural aspects, identifies factors that will exert significant influence on this fisheries SES in the near future. These include the loss of fishing grounds due to the installation of offshore wind farms and marine protected areas, as well as reduced plaice landings due to climate change. The identified ACP hotspots hold the potential to guide the development of localized management strategies and sustainable planning efforts by highlighting the consequences of management decisions. Our findings emphasize the need to consider detailed spatial dynamics of fisheries SES within marine spatial planning (MSP) and illustrate how this information may assist decision-makers and practitioners in area prioritization. We, therefore, propose adopting the concept of fisheries SES within broader integrated management approaches to foster sustainable development of inherently dynamic SES in a rapidly evolving marine environment.

1. Introduction

Fisheries social-ecological systems (SES) worldwide are facing unprecedented challenges due to the rapid pace of environmental and social changes (Woods et al., 2022). In response, many marine governance processes have adopted an ecosystem-based approach, incorporating adaptive management strategies to strengthen SES viability and their capacity to adapt (Douvere, 2008; Katsanevakis et al., 2011; Woods et al., 2022). This shift in focus represents a significant step towards more effective fisheries management. It acknowledges that vulnerabilities within fisheries SES constantly arise due to their complexities and confinement by ecosystem boundaries, necessitating ongoing adaptations in management (Partelow, 2018; Perry et al., 2011, Stelzenmüller et al. under review). Nonetheless, the successful implementation of marine ecosystem-based management approaches remains challenging, requiring the development of supporting tools to assess consequences and trade-offs among different activities (Leslie and McLeod, 2007).

In Europe, fisheries are governed by the Common Fisheries Policy (CFP) of the European Union (EU), while fisheries SES in this region are also subject to area-based management measures implemented through EU environmental policies (Probst et al., 2021; Püts et al., 2023) and the EU Marine Spatial Planning Directive (MSPD; EU, 2014/89/EU) (Stelzenmüller et al., 2021a). Contemporary governance systems have recognized the inherent complexity of fisheries SES (Hare, 2020). However, the current challenge lies in understanding the intricate spatial dynamics of these systems and integrating them into

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comprehensive spatial management processes, such as marine spatial planning (MSP) (Zuercher et al., 2023)

MSP aims to attain sustainable and equitable use of maritime space by balancing current and future human activities with the imperative need for marine conservation measures (Reimer et al., 2023; Trouillet and Jay, 2021). Moreover, MSP processes may facilitate transboundary planning by taking into account broader regional considerations (Galparsoro et al., 2021; Jentoft and Knol, 2014), which are essentially an ecosystem-based governance approach to marine ecosystems (Platjouw, 2018). To ensure their effectiveness and success, MSP processes not only need to explicitly address the intrinsic dynamics of fisheries SES and the resulting vulnerabilities of fishers (Janβen et al., 2018). They also require spatial information about marine areas that are presently or will be vital in the future for SES to withstand the consequences of complex interactions between economic and environmental factors. Therefore, the definition and analysis of spatially explicit scenarios depicting the impact of future changes in both the environment and the social landscape is indispensable.

Notably, fisheries SES in the North Sea region face multifaceted challenges as the North Sea is one of the busiest marine areas in the world (Jentoft and Knol, 2014). Among the most prominent are challenges arising from environmental changes impacting food web structure and ecosystem functioning (Beaugrand, 2004; Kenny et al., 2009; Lynam et al., 2017; McQuatters-Gollop et al., 2007; Möllmann and Diekmann, 2012; Reid et al., 2001; Weijerman et al., 2005). These environmental shifts can lead to regime shifts (Engelhard et al., 2014; Fock et al., 2014; Frelat et al., 2017; Sguotti et al., 2022) with cascading effects on dependent fisheries SES and their capacity to adapt. Furthermore, fisheries SES are confronted by the rapid expansion of offshore wind farms (OWFs) driven by the growing demand for renewable energy sources. This development significantly intensifies competition for limited space among various stakeholders (Gușatu et al., 2022; Stelzenmüller et al., 2022). Simultaneously, the establishment of marine protected areas (MPAs), which often necessitates spatial fishing restrictions (Campbell et al., 2014; Püts et al., 2023), sharpens the space use conflicts and impacts fisheries SES. As a result, many fishing vessels operating in the North Sea region will need to relocate their efforts or adapt their fishing practices to remain economically viable (Hamon et al., 2021; Stelzenmüller et al., 2021a).

Given the impending spatial constraints, fisheries SES find themselves compelled to undergo profound transformations (Gușatu et al., 2022; Stelzenmüller et al., 2022) which raise a crucial question: How can fishers, policy, and management processes within these systems best accommodate the imminent changes? Part of the solution lies in the adaptive capacity of the SES, denoting the ability to effectively adjust to future pressures and environmental change while safeguarding human welfare (Refulio-Coronado et al., 2021; Tiller et al., 2016). This definition implies that adaptive capacity is related to the well-being of the social and ecological elements rather than avoiding large changes (Charles, 2012; Refulio-Coronado et al., 2021): A fisheries SES with high adaptive capacity may significantly change, e.g., by diversifying its target resources and thereby reducing its dependence on traditional resources (Refulio-Coronado et al., 2021). While studies thus far have mostly focused on the vulnerabilities of fisheries SES to climate change as a single aspect (Johnson et al., 2016; Payne et al., 2021; Thiault et al., 2018, 2019), understanding how SES can adjust to multiple disturbances or "shocks" and how integrated management processes can strengthen the potential for its adaptive capacity is becoming increasingly important (Hidalgo et al., 2022; Salgueiro-Otero and Ojea, 2020; Woods et al., 2022).

Here, we aim to go beyond considering adaptive capacity as a mere system characteristic by providing spatially explicit estimates of the *adaptive capacity potential* (ACP) of a fisheries SES. This novel ACP metric characterises marine space based on its significance in enhancing the adaptive capacity of the SES and provides a spatially resolved assessment of adaptive capacity. Additionally, we evaluate future changes in SES components, their potential consequences, and implications for the SES and its ACP. To accomplish this, we defined future scenarios, considering the expected expansion of OWFs and MPAs, the anticipated effects of climate change on fisheries resources, and economic fluctuations. Using these standardised scenarios, we assess the spatial changes in adaptive capacity within the SES and examine how ACP hotspots evolve under increasing constraints, gaining a spatial perspective on SES adaptive capacity.

As a case study, we operationalized the German plaice-related fisheries SES in the southern North Sea through a spatial explicit Bayesian Belief Network (BN). The European plaice (*Pleuronectes platessa*) is an important species for North Sea fisheries, often caught alongside other valuable species such as sole (*Solea solea*), and Norwegian lobster (*Nephrops norwegicus*) hereafter called Nephrops (Letschert et al., 2021). This fishery serves as a representative example of the challenges faced by coastal fisheries, including the potential impacts of climate-driven fish distribution shifts and the expansion of OWFs on traditional fishing grounds.

We selected a BN approach because it allowed us to comprehensively capture economic, environmental, and socio-cultural aspects of the SES and analyse its dynamics. This methodology is adept at integrating diverse data types and modelling complex systems with uncertain variables (Marcot and Penman, 2019; McCann et al., 2006), including fishers' choices (Naranjo-Madrigal et al., 2015; van Putten et al., 2013). It further enables the observation of system changes and serves as a powerful yet pragmatic tool for scenario analysis, assisting informed decision-making in dynamic environments. A BN comprises a conceptual model illustrating the links (statistical dependencies) between variables (nodes), and conditional probability tables (CPTs) for each node, providing information about the link strength (McCann et al., 2006; Rambo et al., 2022). Every node encompasses several discrete and mutually exclusive states, each with a certain probability of occurrence (referred to as beliefs). By considering all possible combinations and weighing them according to their likelihood, BNs support probabilistic scenario analysis (Kaikkonen et al., 2021; Pihlajamäki et al., 2020). Furthermore, BNs can integrate new knowledge as it becomes available (belief updating), facilitating the evaluation of existing management measures and their adaptations (McCann et al., 2006), e.g., to enhance SES adaptive capacity.

By applying the BN, we examined (i) both the current and future state of ACP within the SES's spatial boundaries, (ii) assessed trade-offs and uncertainties of factors influencing ACP, (iii) identified ACP hotspots critical for the overall adaptive capacity of the SES, and (iv) evaluated the effects of future spatial use scenarios on ACP. The results provide valuable insights into the role of marine space in bolstering adaptive capacity and we conclude on potential management strategies that may aid to stabilise or strengthen the SES.

2. Material and methods

2.1. Operationalisation of the fisheries SES through a Bayesian belief network (BN)

To set up a Bayesian Belief Network (BN) that operationalizes the abstract concept of a fisheries SES, i.e. translates it into specific measurable components representing different aspects of the SES concept within the BN, we followed the methodology described by Stelzenmüller et al. (2015, 2010). This process entailed developing a conceptual and fit-for-purpose model, compiling and training the BN, and performing a scenario analysis through BN inference. For BN construction we utilized the commercial software Netica 6.05. As all probabilistic inference in Netica is done with discrete tables a conversion of continuous variables to discrete ones was required. We opted for equal frequency as a discretisation approach because it ensures that each bin contains a comparable number of observations (Nojavan et al., 2017) mitigating the influence of outliers and skewed distributions on the estimation of conditional probabilities. This balanced approach provides a good method for large data sets with uneven distributions (Ropero et al., 2018) such as those utilized in our study. All variables were discretized into a maximum of six bins of equal frequency to balance complexity and interpretability of results.

We extracted the key ecological, economic, and socio-cultural components describing the German plaice-related fisheries SES from a general description of the SES provided by Stelzenmüller et al. (under review). We further assumed that fishing effort patterns are influenced not only by resource distributions and economic considerations but also by fishers' behaviour and socio-cultural factors that underpin their choices (Letschert et al., 2023; Naranjo-Madrigal et al., 2015). These drivers represent critical links between social and ecological subsystems, though their measurement often involves qualitative analysis, making them challenging to quantify (Naranjo-Madrigal et al., 2015).

We developed a directed acyclic graph (DAG) of the fisheries SES, defining key drivers and their interdependencies. Our work built upon previous research describing the SES subsystems and components (Letschert et al., 2021, 2023, Stelzenmüller et al. submitted), directly influencing the profitability and adaptive capacity potential (ACP) of plaice-related fisheries (Fig. 1). The output or target nodes (orange, Fig. 1) represented profitability and ACP as potential management objectives, which reflected the consequences of state changes in SES components. To train the BN, conditional probability tables (CPTs) of all nodes were learned from empirical data (for details on the data used see below), except for the nodes fishing effort (FE), ACP, and all eight socio-cultural nodes (pink, Fig. 1). CPTs for these were defined by expert scientists with ample experience in the fisheries SES of the study area, substantiated by detailed qualitative semi-structured interviews with individual German fishers (N = 18) and trainee fishers (N = 30) (Stelzenmüller et al. submitted). A comprehensive description of all BN nodes is presented in Table 1 and the detailed CPTs are summarised in Annex 1 (Tables 1–3).

We compiled spatio-temporal fisheries data obtained from four data sources: (1) Commercial fishing logbooks with information about fishing trips including start and end date, gear used, mesh sizes, landed weights, and revenue by species; (2) The vessel monitoring system (VMS), which is obligatory for all European fishing vessels larger than 12 m, providing geo-coordinates (so-called 'pings'), timestamps, and vessel speed; (3) The German Fishing Vessel Register and (4) the European Fleet Register providing vessel characteristics such as length and additional gear information. The data pre-processing procedure is described in detail in Letschert et al. (2023). We identified plaice-related fishing trips based on the spatial and temporal information from the VMS and logbook data (2012–2019) and complemented vessel characteristics with information from the German Fishing Vessel Register and European Fleet Register. To calculate fishing effort (FE) in hours per data point we used the VMS tools package (Hintzen et al., 2012), separating steaming from fishing pings. We calculated revenues by multiplying landings with market prices by species. We corrected revenues for inflation by using inflation levels of 2014, the same methodology that is applied in fisheries economic reports (STECF, 2020).

We then calculated fishing costs based on economic information from the latest STECF report (STECF, 2020). STECF costs are inflation-corrected and split into six different categories: labour costs, repair & maintenance, consumption of fixed capital, energy (fuel) costs, other variable costs, and other non-variable costs. All these variables, along with the number of days at sea (DAS), are available as vessel averages of annual sums of fleet segments. We used information from the STECF fleet segments TBB2440, DTS1824, and DTS2440 referring to beam trawlers (TBB) and demersal trawlers (DTS) with vessel lengths of 18–24m and 24–40m). We assigned cost data to our prepared fisheries data set based on gear and vessel length. We then calculated costs per DAS by summing up all costs and dividing them by the DAS. We multiplied the costs per DAS by the number of days of each fishing trip. Subsequently, we calculated the costs, landings, and revenue per fishing ping and sorted all fishing pings into a spatial grid of 0.045° longitude x 0.045° latitude. To be able to display and model the SES in space and

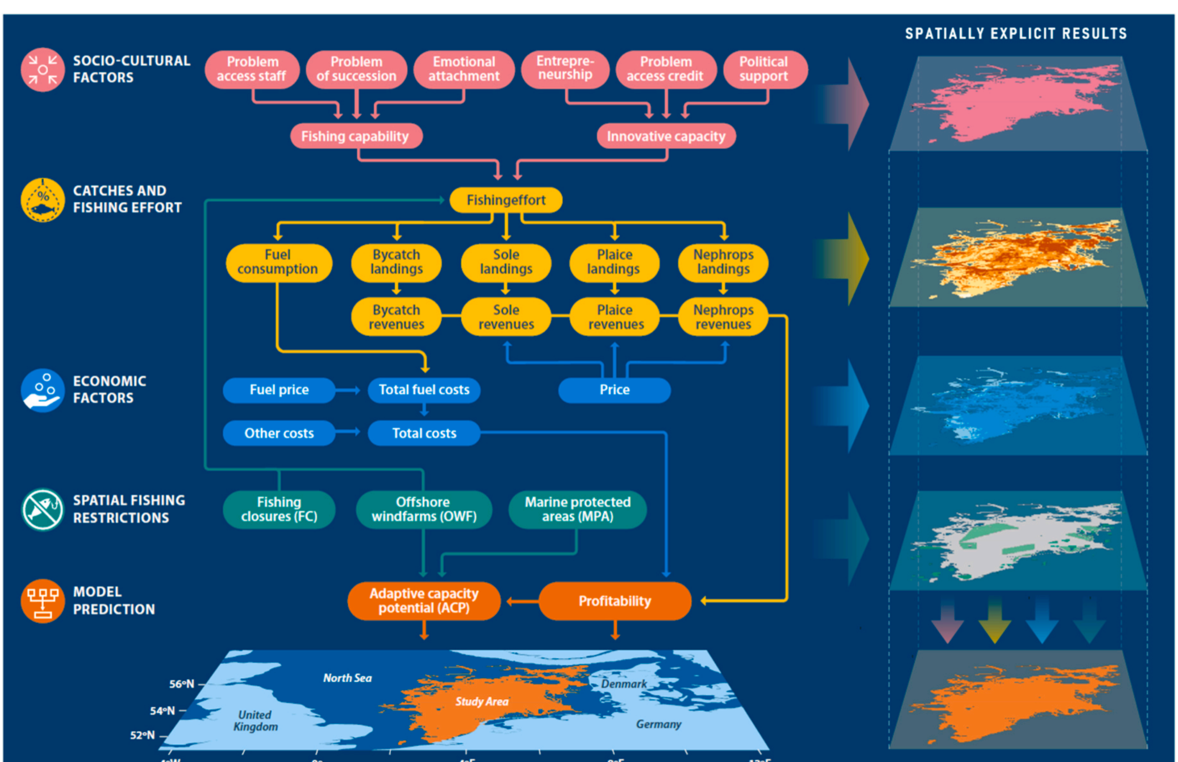

Fig. 1. Overview of key variables (nodes) representing the social-ecological system (SES) of the German plaice-related fisheries, which operate in the southern North Sea (orange area). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Description of all variables (nodes) of the Bayesian Belief Network (BN) operationalizing the German plaice-related fisheries social-ecological system (SES) in the southern North Sea.

Node name	Specification	States	Unit	Data source
Fishing-related data				
fishing effort (FE)	Mean annual fishing effort (h) of German vessels allocated to the two plaice-related demersal fleet 2012–2019 (otter board, beam trawl, pulse trawl)	(1) 0 (2) 0 to 0.5 (3) 0.5 to 2.5 (4) 2.5 to 5 (5) 5 to 10 (6) 10 to 178	h day^{-1}	VMS data
plaice landings (PLE_kg)	Mean annual landings (kg) of plaice (2012–2019)	(1) 0 (2) 0 to 270 (3) 270 to 700 (4) 700 to 32,300	kg $year^{-1}$	Logbook data
sole landings (SOL_kg)	Mean annual landings (kg) of sole (2012–2019)	(1) 0 (2) 0 to 13 (3) 13 to 90 (4) 90 to 5290	kg $year^{-1}$	Logbook data
Nephrops landings (NEP_kg)	Mean annual landings (kg) of Nephrops (2012–2019)	(1) 0 (2) 0 to 0.8 (3) 0.8 to 11 (4) 11 to 6310	kg $year^{-1}$	Logbook data
plaice revenues (PLE_eur)	Mean annual revenue (EUR) of plaice (2012–2019)	(1) 0 to 160 (2) 160 to 400 (3) 400 to 1100 (4) 1100 to 48,700	EUR $year^{-1}$	Logbook data
sole revenues (SOL_eur)	Mean annual revenue (EUR) of sole (2012–2019)	(1) 0 to 1.5 (2) 1.5 to 140 (3) 140 to 900 (4) 900 to 50,900	EUR $year^{-1}$	Logbook data
Nephrops revenues (NEP_eur)	Mean annual revenue (EUR) of Nephrops (2012–2019)	(1) 0 (2) 0 to 4 (3) 4 to 60 (4) 60 to 33,920	EUR $year^{-1}$	Logbook data
bycatch landings bycatch_kg	Bycatch landings calculated as difference kg_all (mean annual landings (kg) of all species 2012–2019 VMS data) and (PLE_kg + SOL_kg + NEP_kg)	(1) 0 (2) 0 to 80 (3) 80 to 200 (4) 200 to 7410	kg $year^{-1}$	Logbook data
bycatch revenues (bycatch_eur)	Bycatch revenues calculated as difference eur_all (mean annual revenues (eur) of all species 2012–2019, VMS data) and (PLE_eur + SOL_eur + NEP_eur)	(1) 0 to 90 (2) 90 to 270 (3) 270 to 700 (4) 700 to 17,100	EUR $year^{-1}$	Logbook data
Spatial fishery closures				
fisheries closures (FC)	Fishing closures = areas closed to fishing within MPAs or no-take-zones	(1) yes (2) no	n.a.	30 % within given MPAs (randomly assigned)
offshore wind farms (OWF)	Offshore wind farms	(1) yes (2) no	n.a.	Commercial data (4Coffshore)
marine protected areas (MPA)	Marine protected areas (Natura2000 areas)	(1) yes (2) no	n.a.	Marine Spatial Plan (BSH, 2021); EdmodNet
Economic data				
fuel consumption (fuel_total)	Annual total fuel used (fishing + steaming) by German plaice-related fleets, fuel costs per vessel and day evenly distributed over the grid cells	(1) 0 to 180 (2) 180 to 600 (3) 600 to 1600 (4) 1600 to 57,200		VMS data and calculated consumption based on Bastardie et al. (2013)
fuel price (fuel_price_mean)		(1) 0.27 to 0.33 (2) 0.33 to 0.6 (3) 0.8 to 34.6	EUR l^{-1}	EUMOFA marine gasoil prices
total fuel costs (total_fuel_costs)	Annual costs for fuel (fuel_total * fuel_price_mean)	(1) 0 to 80 (2) 80 to 250 (3) 250 to 700 (4) 700 to 39,300	EUR $year^{-1}$	
total costs (total_costs)	Annual sum of total fuel costs + other costs	(1) 0 to 280 (2) 280 to 900 (3) 900 to2400	EUR $year^{-1}$	STECF (2020)

(continued on next page)

Table 1 (*continued*)

Node name	Specification	States	Unit	Data source
		(4) 2400 to 66,200		
other costs (other_costs)	Other costs (than fuel) from STECF report (includes repair and maintenance, unpaid labour and other variable costs)	(1) 0 to 150 (2) 140 to 600 (3) 700 to 1700 (4) 1700 to 40,500		
plaice price (PLEprice_mean)	Market price for plaice standardised for inflation to the year 2015, Magnet?	(1) 1.1 to 1.3 (2) 1.3 to 1.8 (3) 1.8 to 2.6	EUR kg^{-1}	Logbook data
sole price (SOLprice_mean)	Market price for sole standardised for inflation to the year 2015	(1) 7.9 to 9.4 (2) 9.4 to 10.9 (3) 10.9 to 12.1	EUR kg^{-1}	Logbook data
Nephrops price (NEPprice_mean)	Market price for Nephrops standardised for inflation to the year 2015	(1) 5.004 to 5.48 (2) 5.48 to 5.6 (3) 5.6 to 6.6	EUR kg^{-1}	Logbook data
Socio-cultural information				
fishing capability (fc)	The capability to take out a boat to fish and to continue to do so in the future	(1) low (2) medium (3) high	n.a.	Expert knowledge/interviews
problem access to staff	The difficulty to find competent staff to be able go fishing (deck hands, other employees, people with a captain's patent)	(1) yes (2) no	n.a.	Expert knowledge/interviews
problem of succession	The difficulty to identify successors willing and able to take over the family business	(1) yes (2) no	n.a.	Expert knowledge/interviews
emotional attachment	Self-image and identification with the profession of, and activity of fishing	(1) yes (2) no	n.a.	Expert knowledge/interviews
innovative capacity (ic)	The capacity to pursue different avenues (in fishing, marketing, technology, etc.) and to adapt to changing circumstances	(1) low (2) medium (3) high	n.a.	Expert knowledge/interviews
political support	The support given to fishers and their profession at different political levels	(1) yes (2) no	n.a.	Expert knowledge/interviews
entrepreneurship	Motivation and capability to explore new ways of fishing, technology and marketing	(1) low (2) high	n.a.	Expert knowledge/interviews
problem accessing credit	The difficulty in accessing loans for investment	(1) yes (2) no	n.a.	Expert knowledge/interviews
Target nodes (output)				
profitability	Proxy for business viability (>10% high, <10% medium, <0 weak, source: STECF, 2020) and calculated as profitability = profit(EUR)/revenues(EUR) with profit (EUR) = revenue(EUR) - costs(EUR)	(1) -199.27 to −2.5 (2) -2.5 to 0.5 (3) 0.5 to 3.5 (4) 3.5 to 41.9	n.a.	Calculated based revenue and total costs (STECF, 2020)
adaptive capacity potential (ACP)	ACP reflects the importance of a given unit area to contribute to the overall adaptive capacity of the fisheries, which is a function of profitability and fisheries restrictions through marine conservation measures or offshore wind development.	(1) no (2) low (3) medium (4) high	n.a.	Expert knowledge/interviews

time and make highly resolved spatial predictions, we aggregated all variables (costs, fishing effort, landings, revenues, etc.) to annual means per grid cell.

To validate the BN, we used the model's error rate calculated by Netica (i.e., the number of times a tested classifier is misclassified, expressed as a percentage), which measures the accuracy of model predictions. A lower error rate indicates a better fit to the data and more accurate predictions of new cases (observation). We further assessed overall model performance using the spherical payoff value as a widely recommended performance (Marcot, 2012). A higher spherical payoff value indicates a more accurate and reliable model. To identify influential variables, and areas of uncertainty, and assess model robustness we performed a sensitivity analysis for the central nodes' profitability and fishing effort using Netica's measure for entropy reduction (Annex 1, Table X). The analysis involved changing the probabilities of one node and observing how the probabilities of other nodes are affected, helping

Table 2a
Overview of spatially explicitly evaluated scenarios.

Scenario name	OWF	FC	MPA	Fish prices	Fuel prices	SOL_kg	PLE_kg	NEP_kg	fishing effort	ACP	profitability
Baseline	2020	☒	☒☑	STECF data	STECF data	VMS data	VMS data	VMS data	VMS with displacement	*predicted*	*predicted*
(Predictive) spatial scenarios (2025, 2030, 2040)											
MSP2025	2025	☑	☑	–	–	–	–	–	displaced	*predicted*	*predicted*
MSP2030	2030	☑	☑	–	–	–	–	–	displaced	*predicted*	*predicted*
MSP2040	2040	☑	☑	↓	–	–	–	–	displaced	*predicted*	*predicted*
(Predictive) economic & climate change scenarios in 2030											
MSP2030_prices	2030	☑	☑	↓	↑	–	–	–	displaced	*predicted*	*predicted*
MSP2030_PLE	2030	☑	☑	↓	↑	–	↓	–	displaced	*predicted*	*predicted*
(Normative) management (mixed reasoning) scenarios											
MSP2030_ACP	2030	☑	☑	–	–	–	–	–	*predicted*	☑	*predicted*
MSP2030_prof	2030	☑	☑	–	–	–	–	–	*predicted*	*predicted*	☑

Table 2b
Overview of qualitatively evaluated socio-cultural scenarios.

Scenario name	OWF	FC	MPA	fishing capacity (fc)	innovative capacity (ic)
Under spatial settings of the baseline scenario					
fc ic baseline settings	2020	☒	2020	–	–
fc_low	2020	☒	2020	↓	–
ic_low	2020	☒	2020	–	↓
fc_ic_low	2020	☒	2020	↓	↓
fc_high	2020	☒	2020	↑	–
ic_high	2020	☒	2020	–	↑
fc_ic_high	2020	☒	2020	↑	↑
Under spatial settings in 2030 (*MSP2030 scenario*)					
fc ic baseline settings	2030	☑	☑	–	–
fc_low	2030	☑	☑	↓	–
ic_low	2030	☑	☑	–	↓
fc_ic_low	2030	☑	☑	↓	↓
fc_high	2030	☑	☑	☐	–
ic_high	2030	☑	☑	–	↑
fc_ic_high	2030	☑	☑	↑	↑

to identify potential weaknesses in the model that could affect its performance in real-world situations.

2.2. Future scenarios of the SES's adaptive capacity potential (ACP)

We formulated future scenarios (Calado et al., 2021; Hamon et al., 2021; Pinnegar et al., 2021) influencing profitability and ACP. These scenarios considered (i) future spatial restrictions for the plaice-related fishing fleets, (ii) price fluctuations for fish (plaice, sole, and Nephrops) and fuel, (iii) climate change-induced changes of plaice landings, and (iv) variations in the socio-cultural factors directly affecting fishing effort (Tables 2a and b, Annex 2). Through this scenario analysis, we aimed to elucidate potential futures of the German demersal fisheries in the years 2025, 2030, and 2040.

The first six scenarios can be classified as predictive (*sensu* Börjeson et al., 2006). They reflect realistic future developments of spatial management measures in the southern North Sea incorporating information from different data sources such as national maritime spatial plans, data on offshore wind farm development (source: 4Coffshore), and model predictions on future plaice distributions as well as realistic price fluctuations for fish and fuel. We further used the BN as a diagnostic tool (mixed reasoning) to explore how best to achieve specific management goals and assess its potential to aid in decision-making in integrated management. For this purpose, we defined two normative scenarios (*sensu* Börjeson et al., 2006) by setting two management objectives as starting points, namely maintaining medium levels of ACP (*MSP2030_ACP*) and profitability (*MSP2030_prof*), both under the spatial settings assumed for 2030.

To evaluate the impact of societal change and potential synergistic effects with spatial management measures, we compared high and low levels of fishing capability (fc) and innovative capacity (ic) (as the two key socio-cultural nodes, pink, Fig. 1) under the spatial settings of the *baseline* and the *MSP2030* scenario. In total, we examined six different combinations of fc and ic ranging from high, baseline settings to low levels of each, assessing their impacts on fishing effort, profitability, and ACP (Table 2b). Given the lack of spatially explicit data on socio-cultural changes, we evaluated the socio-cultural influence qualitatively by defining the probability distributions of the two nodes in the BN (for details see Annex 2) based on qualitative interviews with fishers (as described in Stelzenmüller et al. submitted).

All scenarios (except the socio-cultural ones) were resolved into separate grid-based case files with updated values according to scenario specifications. To assess the changes in ACP and profitability of the SES induced by the respective nodes, we updated the BN model to the new case files using Netica 6.05. We analysed and mapped the predicted beliefs (most probable states) of key nodes using RStudio with R version 4.1.2.

To identify hotspots of ACP, i.e., areas with the most severe changes in ACP across all scenarios and relevant to spatial management, we analysed changes in ACP over time and under the different simulated constraints. In this study, we categorised ACP into four states: high, medium, low, and zero. For the "hotspot analysis", we arbitrarily defined high ACP as +4, medium ACP as +3, low ACP as +2, and no ACP as +1 and represented each change in ACP from one state to the next as a plus one or minus one, with zero indicating no change. This convention allowed us to map and compare changes in ACP among scenarios.

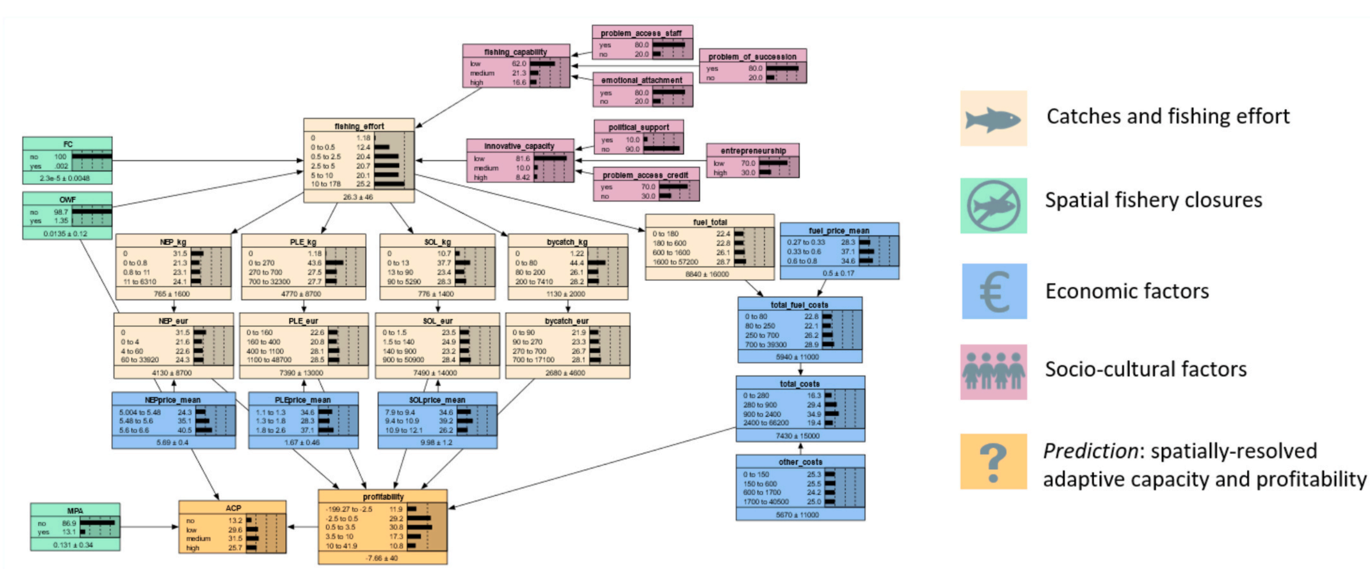

Fig. 2. Bayesian belief network (BN) representing the interdependencies between fishing effort, landings, and revenues (yellow, source: VMS), spatial constraints (green, source: commercial data), economic factors (blue, source: STECF), and socio-cultural factors (pink, source: expert knowledge/interviews) on the adaptive capacity potential (ACP) and profitability (orange) of the German plaice-related fisheries social-ecological system (SES). The posterior distributions reflect the average conditions of all node states between 2012 and 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

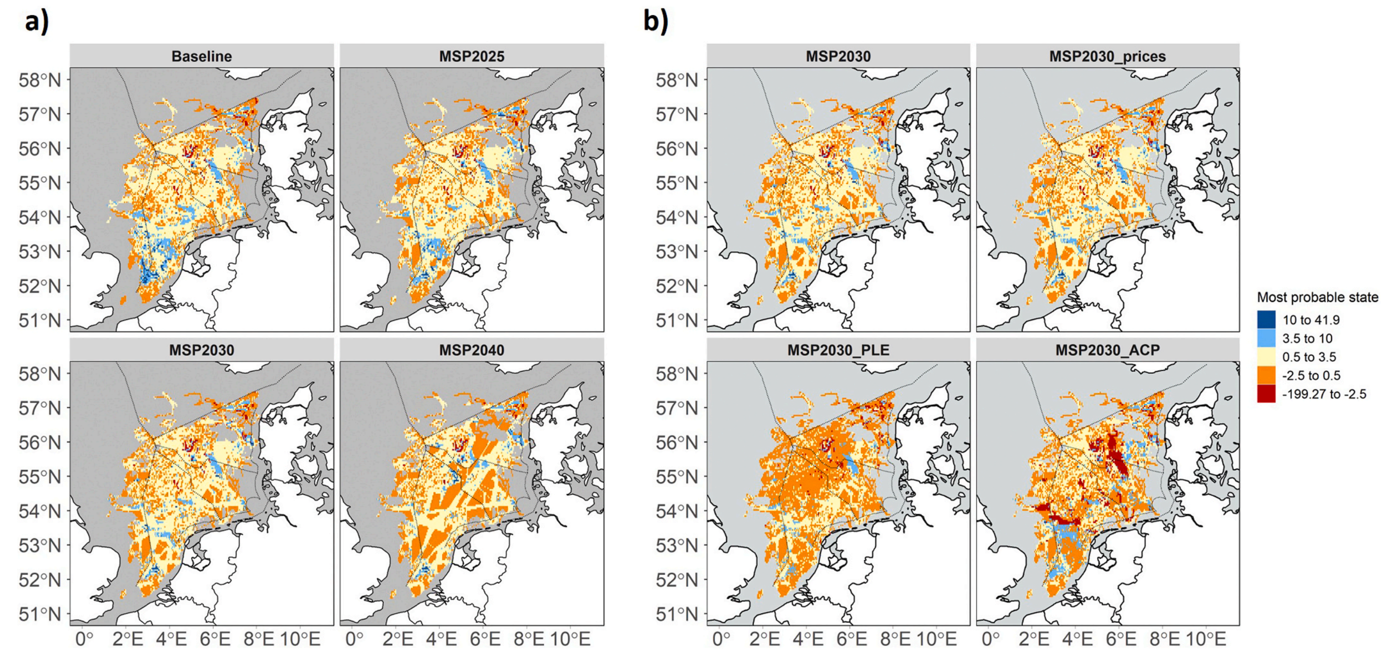

Fig. 3. Most probable state of **profitability** of the German plaice-related fisheries in the southern North Sea across **a)** spatial scenarios (MSP) in 2025, 2030, and 2040 and **b)** economic (*MSP2030_prices*), climate change (*MSP2030_PLE*) and mixed reasoning (*MSP2030_ACP*) scenarios under the spatial settings assumed in 2030.

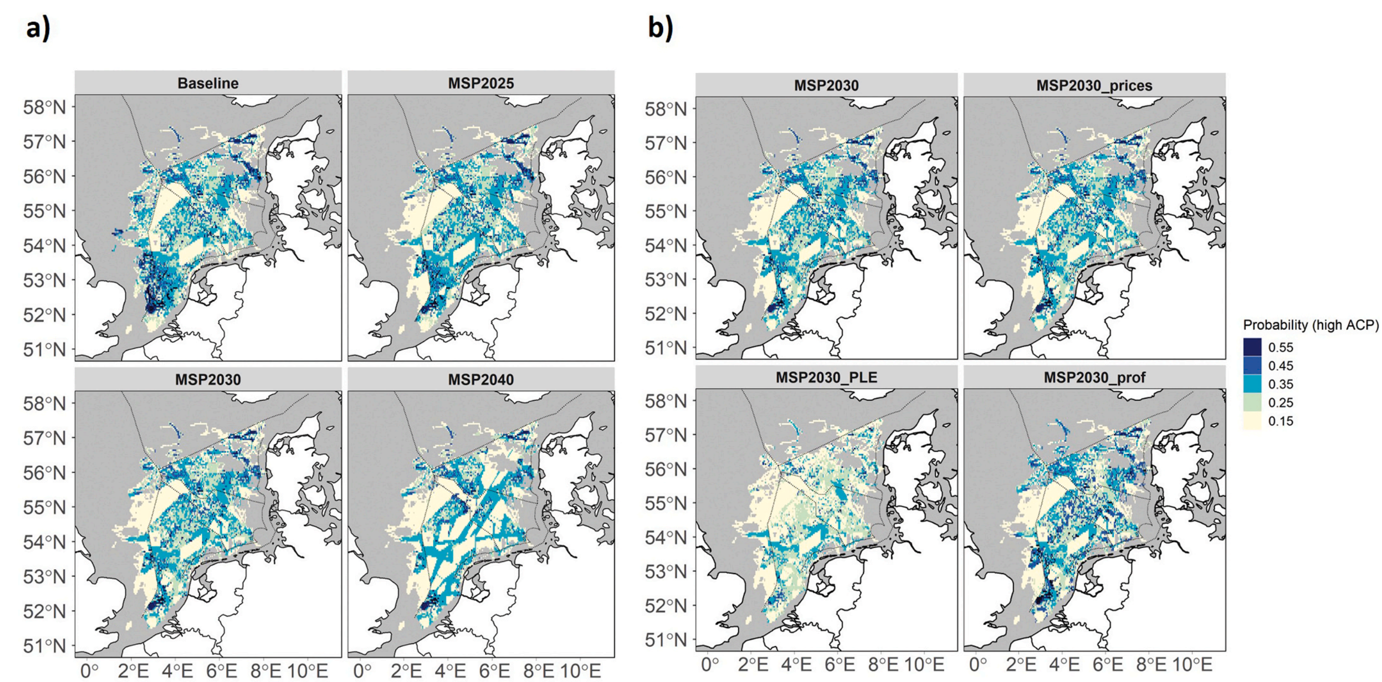

Fig. 4. Probability of marine space units in the southern North Sea (representing plaice fishing grounds) having a high **adaptive capacity potential (ACP)** across **a)** spatial scenarios (MSP) in 2025, 2030, and 2040 and **b)** economic (*MSP2030_prices*), climate change (*MSP2030_PLE*), and management scenarios (*MSP2030_prof*) under the spatial settings assumed in 2030.

3. Results

3.1. BN model validation and performance

Overall, the trained BN consisted of 30 nodes (variables), 34 links (statistical dependencies), and 5890 conditional probabilities. Fig. 2 displays the key nodes, their interdependencies, and posterior distributions, representing the average past conditions of each node state as our baseline scenario. To calculate the conditional probability tables (CPTs) of all nodes (except fishing effort, ACP, and socio-cultural nodes), we used a high-resolution dataset with 43,441 observations.

Under the *baseline* scenario, serving as our reference point for scenario analysis, the beliefs (posterior distributions) of the key node fishing effort were evenly distributed across all higher states (Fig. 2). This indicates medium (2.5–10 h day^{-1}) to high (up to 178 h day^{-1}) annual fishing effort between 2012 and 2019. Considering the price ranges between 2012 and 2019 for fish and fuel, as well as spatial restrictions, the predicted profitability was at an average level, with 59 %

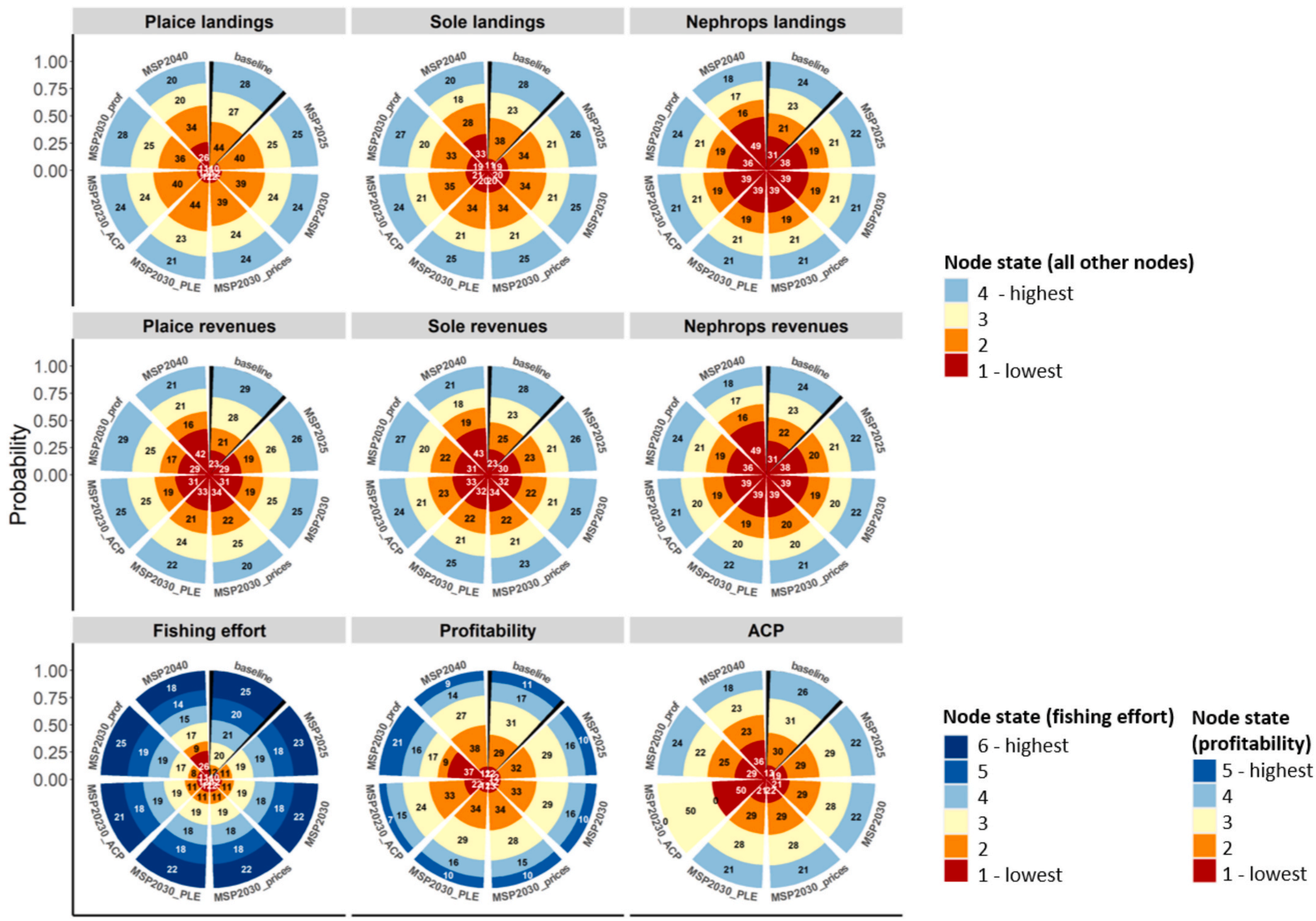

Fig. 5. Comparison of beliefs (posterior distributions) of nine key nodes across the eight tested scenarios in 2020 (*baseline*), 2025 (*MSP2025*), 2030 (*MSP2030, MSP2030_prices, MSP2030_PLE, MSP2030_ACP, MSP2030_prof*), and in 2040 (*MSP2040*).

of all cells in a profitability state of 0.5–3.5 or higher, as was the ACP (58 % of all cells were in a medium state or higher) (orange nodes in Fig. 2). Spatially resolved profitability and probability of high ACP for the baseline scenario, presented in Figs. 4 and 5 (upper left) reveal similar patterns, hinting at particularly high profitability and ACP values in the southern part of the study area.

The BN's error rate for the node profitability, at 39 %, indicates a satisfactory capacity to reproduce observed profitability values and predict new cases. The spherical payoff of 0.7 further suggests a good overall model performance, implying that the model's predictions are generally accurate and reliable. In a sensitivity analysis of the key nodes profitability and fishing effort, the node ACP had the most significant impact on profitability, suggesting that changes in the probability values of the ACP node can substantially affect those of profitability. Profitability was also slightly sensitive to the nodes total costs, other costs, sole revenues, and landings, and even less sensitive to Nephrops or plaice revenues and landings. Changes in fish prices and fuel prices did not influence profitability values. In contrast, the node fishing effort showed equal sensitivity to bycatch landings and revenues, as well as fuel consumption and costs, and higher sensitivity to plaice landings than to those of sole or Nephrops. Similar to profitability, fishing effort appeared insensitive to changes in fish and fuel prices. Overall, our analyses indicate that the BN accurately reflects the defined relationships among SES components and can provide reliable predictions within the range of observed values. All results of the sensitivity analysis are detailed in Annex 1 (Fig. 1).

3.2. Socio-ecological scenarios

We investigated different future trajectories of the SES concerning spatial fishery restrictions (in 2025, 2030, and 2040), economic, and ecological change, as well as different management targets in 2030, and the impact of societal change on the fisheries SES. We compared all scenarios to the *baseline* scenario, representing the past probability distributions of all node states and therefore reflecting the average SES state until 2020 (2012–2019). Except the socio-cultural scenarios, we assessed all scenario predictions by mapping and assessing state changes of the two target nodes ACP and profitability (Figs. 3–5). Specifically, we evaluated how the most probable state, i.e., the specific state of a node that has the highest probability (or belief) given the available evidence changed for each grid cell providing (information about) the most likely frequency distribution of the outcome given the scenario settings.

Under *baseline* conditions, approximately 30 % or 70,500 km^2 of the total area (ca. 137,000 km^2) fell into a low profitability state (−2.5 to 0.5), while about 57 % or 52,800 km^2 were categorised into a medium state (0.5–3.5) of profitability (Figs. 3 and 4). The *baseline* scenario exhibited the largest proportion of fishing grounds within the two most profitable states (3.5–10 and 10 to 41.9) compared to all other scenarios, suggesting past conditions were most favourable for commercially viable fishing. The proportions of areas with high profitability (3.5–10 and 10 to 41.9) declined continuously across spatial scenarios (*MSP2025* - *MSP2040*) dropping by almost half (from 11.5 % to 6 %) as more areas became inaccessible for fishing. Under the scenario *MSP2030_PLE*, combining spatial settings of 2030 with climate-change-induced

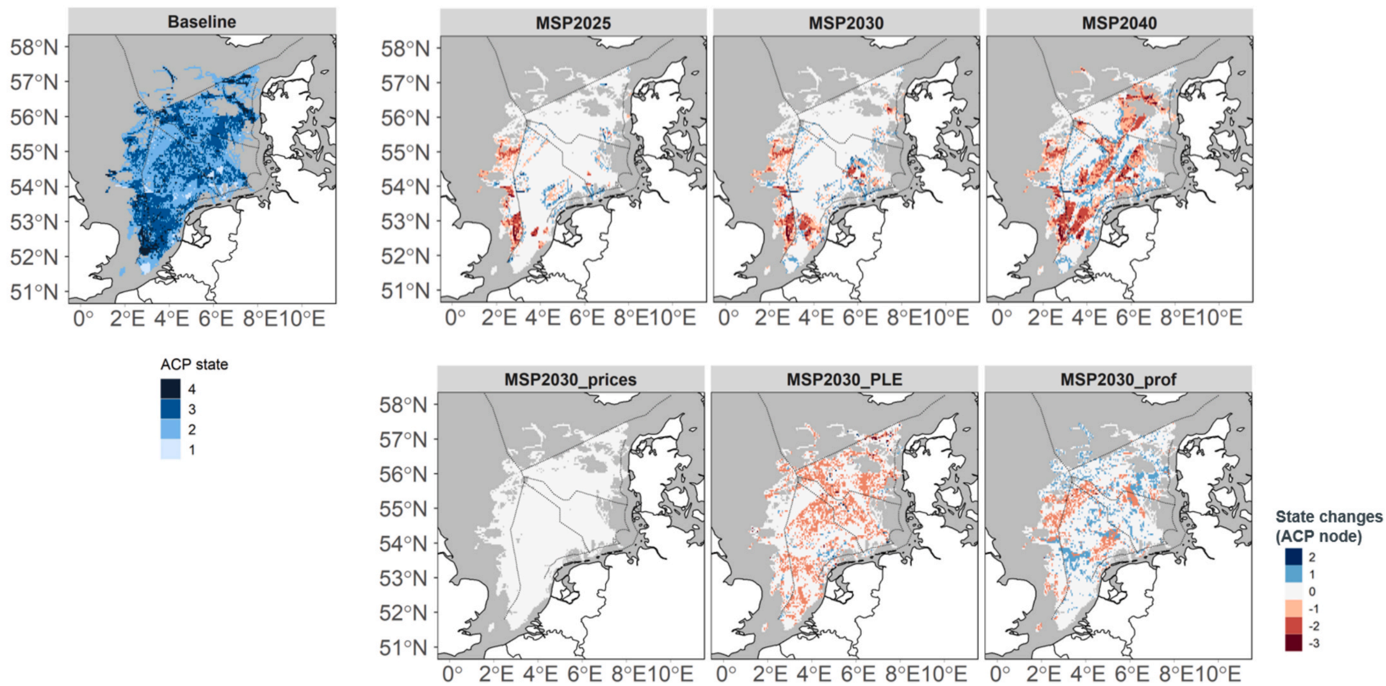

Fig. 6. Analysis of adaptive capacity potential (ACP) hotspots of the baseline scenario (left) and their spatial changes across the different scenarios in 2025 (*MSP2025*), in 2030 (*MSP2030, MSP2030_prices, MSP2030_PLE, MSP2030_ACP, MSP2030_prof*), and in 2040 (*MSP2040*).

reduced landings of plaice, the decline in high profitability states was most apparent (by almost 65 %). The economic scenario in 2030 (*MSP2030_prices*), assuming high fuel and low fish prices within the BN state boundaries, revealed little influence of economic fluctuations on overall profitability. In the mixed reasoning *MSP2030_ACP* scenario, simulating a management target of a medium level of ACP in 2030, profitability states were most evenly distributed among all tested scenarios: Approximately 46 % or 63,000 km^2 of the total area fell into a low state of profitability and another 36 % or 49,000 km^2, of the fishing grounds had a medium state of profitability.

Regarding the node ACP, similar patterns emerged, with spatial fishing restrictions in 2040 (*MSP2040*) and in 2030 combined with climate change effects (*MSP2030_PLE*) causing the most severe changes in ACP. In these scenarios, the proportion of areas with low and no ACP increased from 3 % (no) and 52 % (low) to 11 % and 71 % under *MSP2030_PLE* and 28 %, and 32 % under *MSP2040* suggesting a drastically decreased potential of the SES to successfully adapt to future constraints. As for profitability, the simulated economic fluctuations (*MSP2030_prices*) did not influence the ACP of the SES, and percentages across states were most evenly distributed in the mixed reasoning (management) scenario (*MSP2030_prof*) ranging from 17 % or 24,000 km^2 (state 'high') to 44 % or 60,000 km^2 (state 'low'). Additionally, areas exhibiting a high ACP notably increased by 10 % from 9400 km^2 under baseline conditions to 23,100 km^2. By spatially resolving the predictions of profitability and ACP across scenarios, it becomes evident how strongly spatial fishing restrictions can locally affect the SES, especially when adding climate change-induced effects such as reduced plaice landings (*MSP2030_PLE*). Regions in the southern part of the study area exhibit the most drastic state changes from high to low overall profitability and ACP values. Moreover, while climate change effects seem to influence the SES as a whole, spatial restrictions due to the installation of OWFs and MPAs appear to have a much more localised impact on specific areas.

We further evaluated the beliefs (posterior probability distributions) assigned to each state of the target nodes across the tested scenarios to assess the probability distribution over all possible outcomes and the associated level of uncertainty. This analysis allows for an improved assessment of potential consequences and trade-offs associated with certain management targets. When comparing the beliefs of most probable states for nine key nodes (fishing effort, landings and revenues of plaice, sole, and Nephrops, profitability, ACP) and how they change under the spatial scenarios similar patterns are evident for all nodes (Fig. 5). Except for the node profitability, the lowest state increases in probability across all spatial scenarios with the highest increment under scenario *MSP2040* (up to a factor 26, e.g., for fishing effort and plaice landings). In all other (higher) states the probability is reduced. For the node profitability, the upsurge is found in the second lowest rather than the lowest state but otherwise, the same structure can be found. These outcomes again corroborate the strong influence spatial fishery closures have on the plaice-related fisheries SES of the southern North Sea and its fate in the future.

3.3. Analysis of hotspots of ACP

Our analysis of the ACP hotspots under the different scenarios (Fig. 6) revealed that the most significant state changes (up to −3) occurred under the *MSP2040* scenario. The maps further highlight that the most pronounced changes were concentrated in the southern part of the study area, particularly visible in *MSP2025* and *MSP2030* scenarios, indicating sensitive areas that require effective management. It was also noticeable that overall, there were very few increases towards higher ACP states (indicated in blue), while most changes showed a loss in ACP (except for the management scenario), hinting at a general decrease in the capacity of the SES to adapt to future changes. The observable increase in ACP near the fishing closure areas in the *MSP2040* scenario could be attributed to an increase in fishing effort resulting from assumed fishing effort displacement. The absence of state changes between 2030 and the economic scenario (*MSP2030_prices*) is indicated by the white area encompassing the entire plaice-related fishing grounds. The state changes in the climate change scenario (*MSP2030_PLE*) were less severe compared to the *MSP2040* scenario but more widely distributed, hinting at the need for different management strategies to address the effects of climate change than space loss due to fishing restrictions.

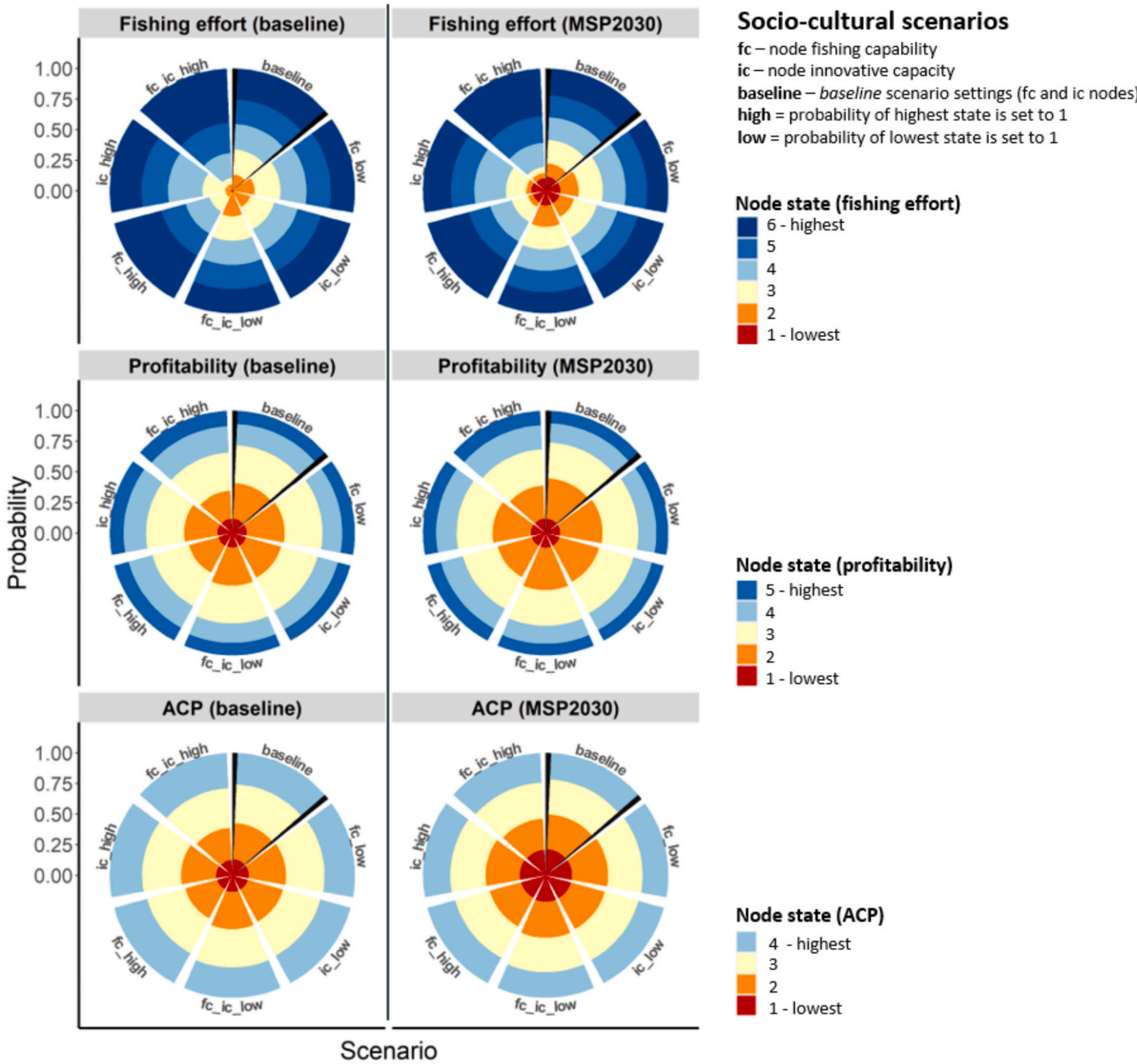

Fig. 7. Posterior probabilities (beliefs) of the three nodes fishing effort, profitability, and adaptive capacity potential (ACP) under two scenarios: *baseline* (left) and *MSP2030* (right) showing the influence of the states of the socio-cultural nodes fishing_capability (fc) and innovative_capacity (ic). The states of the *baseline* scenario, which were also used in all other scenarios, are outlined in black.

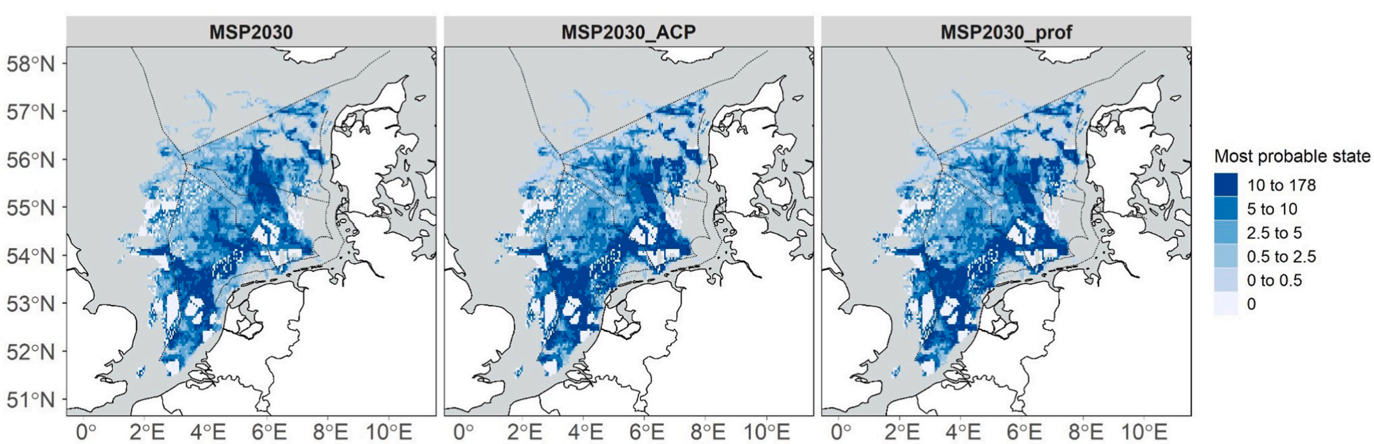

Fig. 8. Most probable states of the node **fishing effort** of the German plaice-related fisheries in the southern North Sea across management scenarios in 2030. The scenarios simulate different management targets: maintaining a medium adaptive capacity potential (*MSP2030_ACP*) and maintaining a medium level of profitability (*MSP2030_prof*) and are compared to the spatial scenario *MSP2030*.

3.4. Socio-cultural scenarios

The socio-cultural scenarios revealed that while fishing capability and innovative capacity had the strongest influence on fishing effort, which aligns with the network structure, there was also a visible influence on ACP, while the least impact was on profitability (Fig. 7). The latter were generally more affected by landings and revenues, highlighting the importance of considering a range of factors when assessing the potential fates of a fisheries SES. Additionally, our findings suggest that the socio-cultural factors had a comparable effect under both the *baseline* and *MSP2030* scenarios, indicating the absence of any combined or synergistic effects of socio-cultural and spatial constraints.

3.5. Management strategy scenarios

The two management scenarios (*MSP2030_ACP* and *MSP2030_prof*) simulating potential management strategies or targets to stabilise the SES in 2030 showed no differences in predicted fishing effort (Fig. 8). Both strategies indicate that fishing effort should be best maintained to more or less equal parts in all fishing effort states to support a sustainable SES. Compared to the predicted non-managed fishing effort in 2030 (*MSP2030*), this entails balancing the effort between lower states while simultaneously significantly increasing fishing effort in the highest state by almost 10 %. The specific areas where intensifying fishing effort is suggested by the BN are located in the southern part of the study area and closer to the coastline (Fig. 8).

4. Discussion

In this study, we present an integrated and spatial-explicit assessment of both the adaptive capacity and profitability of the German plaice-related SES in the North Sea region. Here, adaptive capacity entails the accessibility of fishing grounds that can provide sufficient catches given the costs and landed values in the past. This capacity plays a crucial role in the SES's ability to respond to spatial fishing restrictions, climate change effects, as well as economic fluctuations, and can be decisive for whether the SES can adjust to these future changes.

By incorporating spatially explicit ecological, economic, and socio-cultural data into a probabilistic Bayesian Network (BN) approach, we not only assess potential trajectories of the SES's adaptive capacity and profitability but also provide spatially resolved information on these factors. Furthermore, our study demonstrates how vulnerabilities and complexities of fisheries contribute to the inherent dynamics of fisheries SES in which they are embedded. Previous approaches to fisheries SES typically encompass environmental and economic considerations and rarely include essential socio-cultural considerations, but see for example Naranjo-Madrigal et al. (2015) or van Putten et al. (2012).

Spatial information plays a vital role in effective management by identifying areas of high relevance and vulnerability to human impacts or climate change (Lorenzen et al., 2010; Yates et al., 2015). Maps generated by the BN can thus inform MSP processes or other ecosystem-based management approaches. These maps can enable decision-makers to pinpoint regions with high adaptive capacity potential (ACP), i.e. areas that substantially contribute to the overall adaptive capacity of the SES, enhancing its resilience to future changes. For the German plaice-related fisheries such hotspots of ACP primarily exist in the southern part of the study area (Fig. 6). MSP can leverage this information to sustain SES's adaptive capacity by locating other activities, such as renewable energy deployment, outside these hotspots. Presently, MSP processes in the study area do not consider the adaptive capacity of fisheries SES, resulting in socio-economic impacts of MSP measures being addressed through ad-hoc mitigation measures (Bonsu et al., 2024). Consequently, the planned installation of OWFs in the southern North Sea, located within many ACP hotspot areas, could significantly reduce profitability and the SES's ability to adjust to future challenges as indicated by the BN. Our findings align with previous studies emphasising the importance of spatial closures in determining the adaptive capacity of future fisheries SES (Campbell et al., 2014; Gimpel et al., 2013; Püts et al., 2023; Sguotti et al., 2022). While a fishing ban in these areas may increase fishing pressure on surrounding areas, well-defined closures could also provide refuges for target stocks, contributing to long-term fisheries benefits (Campbell et al., 2014; Püts et al., 2023).

Spatial planning, however, is a multi-layered process and spatial allocations are seldom straightforward as they have to satisfy (opposing) objectives of various stakeholders (Zaucha and Gee, 2019; Zuercher et al., 2022). The successful implementation of an ecosystem-based approach to MSP centres on the comprehensive consideration of all key sectors and their spatial requirements. This process entails finding suitable compromises (Christie et al., 2014; Stelzenmüller et al., 2021b; Trouillet and Jay, 2021), which may involve co-locating activities, such as fisheries within offshore wind farms (OWFs) or conservation areas (MPAs) (Rossiter and Levine, 2014). Our spatially explicit assessments enable effective communication during the planning process and facilitate the dialogue among stakeholders by visualising consequences of potential planning activities in an easily understandable way and assist in finding the most suitable compromise.

In addition, as the identified hotspot areas of the German plaice-related fisheries SES extend across administrative borders, our findings stress the significance of international collaboration and aligned national management measures for sustainable demersal fisheries in the North Sea area. As yet, European fisheries SES are governed by the EU Common Fisheries Policy in relation to quota and harvest control rules (CFP; EU, 2013; 2019) and national area-based management measures do not consider coherent transboundary management objectives on a spatial level (Elliott et al., 2023; ICES, 2021). Hence, formulating clear fisheries management objectives becomes critical to develop effective spatially explicit management strategies (Stephenson et al., 2019). Ensuring ecological, economic and socio-cultural factors are considered in such strategies (Letschert et al., 2023) will help to enable resilient fisheries SES.

With the obligatory implementation of the EU biodiversity strategy to protect 30 % of national waters, of which 10 % will be strictly protected, some of the fishing grounds will likely be closed to demersal fisheries in the near future. In our scenarios, we simulated 5.5 % of the study area (30 % of all MPAs) as no-take zones (scenarios *MSP2025*, *MSP2030* and *MSP2040*), cutting the proportions of areas with high profitability almost by half. Implementing the EU biodiversity strategy will therefore possibly further reduce the adaptive capacity of the SES and accelerate the transformation of the fishing sector. To increase the fishery's adaptive capacity, a shift towards a different management system and more effective policies including fisheries viability policy objectives at an EU scale and active participation of the fishers in EU fisheries might be needed (Cormier et al., 2019; Rindorf et al., 2017). Furthermore, sector development processes in which spatial and temporal restrictions play a bigger role than quotas may be required (Stephenson et al., 2019).

In addition to spatial fishing restrictions, we identified climate change as a critical factor for the persistence of German plaice-related fisheries, which may be compounded by the already challenging economic environment. These economic challenges could further reduce the adaptive capacity of the fishery in the next decade. The potential adverse effects of climate change on fisheries are well described, with most fisheries projected to experience a shift in the distribution of resources by 2050, and some facing significant decline (Cheung et al., 2013). Plaice stocks, for instance, might shift further north and offshore to deeper water due to climate change-induced rise in water temperature (Engelhard et al., 2011). However, German fleets targeting plaice, do not have the technical capacity to access the new resource distribution and are confined by SES boundaries, potentially reducing plaice landings and consequently the ACP. Moreover, the magnitude and timing of these climate-change-induced alterations remain uncertain

(Goto et al., 2022), making it challenging to predict their consequences for a more distant future. Due to these uncertainties, climate change effects are difficult to plan for and require additional strategies other than spatial use allocations in the context of MSP. Hence, adaptive management approaches such as MSP, require not only flexibility in governance structures or in coping with increased uncertainty under changing environmental conditions (Månsson et al., 2022) but also suitable management tools. In this context, our approach offers a further benefit by allowing for a diagnostic (mixed reasoning) rather than a predictive application: By using the BN as a mixed reasoning tool results can illustrate how the fisheries SES could be managed under climate change scenarios to remain viable.

While it is critical for successful fisheries management, fishers' behaviour is often poorly understood (van Putten et al., 2012, 2013). Our analysis of socio-cultural scenarios underscores the significance of considering a wide range of factors including fishers' options and their decisions regarding their livelihood when analysing complex fisheries SES. Specifically, we found that fishing capability, which encompasses the capability to operate a fishing vessel and sustain this activity over time, exerts a strong influence on fishing effort. This influence can have cascading effects on other factors of the system, even if they might only marginally impact profitability and ACP. In contrast, innovative capacity, which reflects the ability of fishers to explore various avenues, in fishing, marketing strategies or technology adoption, to adapt to changing circumstances, seems to play a less decisive but still relevant role. Our scenario analysis further illustrates that these socio-cultural factors may enhance the profitability and ACP of the SES, even when subjected to increased spatial restrictions (*MSP2030* scenario).

The results of our management strategy scenarios suggest that achieving potential management goals, such as maintaining a medium level of adaptive capacity and profitability of the described SES, would entail a substantial increase in the overall fishing effort. This effort would be more evenly distributed among the different states (i.e., fishing effort intensities) compared to the baseline scenario. Interestingly, the predicted maps reveal that fishing effort would not be evenly distributed throughout the study area but rather locally concentrated. From a practical perspective, our findings indicate that maintaining the current SES requires a local intensification of fishing effort, including the increased deployment of trawled gear in specific areas. This contradicts the future needs of conservation and improvement of the environmental status.

The identified spatial heterogeneity, however, also opens interesting pathways for MSP in fisheries. These pathways may include planning installations of OWFs outside the most profitable fishing areas, offering recommendations for installation designs (Gimpel et al., 2023) that enhance fisheries' benefits or providing options for less invasive fishing practices (Stelzenmüller et al., 2021b) to potentially mitigate use conflicts among sectors.

With an error rate of 39 %, model validity is satisfactory, considering the complexity of the modelled SES, and aligns with findings from similar environmental system studies (Karimi et al., 2021). We therefore assume that the BN accurately captures the relationships among SES components, providing reliable predictions of profitability, fishing effort, and adaptive capacity. However, in the case of (discretized) continuous variables (nodes), the BN cannot make predictions outside its nodes' state range. In other words, it is not possible to simulate scenarios where, e.g., economic fluctuations exceed the range of historical data (used to train the BN). Our empirical dataset, spanning from 2012 to 2019, lacks recent crises such as the COVID-19 pandemic, Brexit, or the Russian-Ukrainian war, which could significantly impact economic factors. Fuel prices, once less critical, gained importance as a consequence of the Ukrainian war. Brexit, involving high-yield fishing grounds in British waters, has introduced uncertainties critical to fisheries (STECF, 2022). Furthermore, due to a lack of empirical data, crude displacement estimates were employed for fishing effort (see Annex 2) when simulating spatial fishing restrictions, not accounting for local fish stock depletion due to displaced fishing effort or the influence of international fishing fleets, which was not considered here. Future incorporation of agent-based models may enhance accuracy.

5. Conclusions

In this study, we have explored the intricate dynamics of fisheries SES in the North Sea region, focusing on the adaptive capacity and profitability of the German plaice-related fisheries as a representative case. Our spatially explicit Bayesian Network approach has proven useful to illuminate the connections between ecological, economic, and societal factors of complex fisheries SES, offering practical insights for decision-makers to achieve spatial management objectives under uncertain future conditions. By providing a comprehensive system's perspective and clear spatial predictions regarding the adaptive capacity potential of marine areas, our BN has the potential to enhance an ecosystem approach to MSP. This is particularly important given the critical role adaptive capacity plays for fisheries SES to withstand the multitude of future challenges.

Our study identified potential key areas (ACP hotspots) primarily in the southern part of the study area, emphasising the importance of aligning international MSP measures to enable sustainable fisheries management in this area. Additionally, our results support the formulation of localised management recommendations such as co-locating fisheries and OWFs. We further believe our findings provide a transparent means to communicate trade-offs and implications of current and future MSP measures to stakeholders.

In summary, our study highlights that the spatial restrictions coupled with unforeseen climate change impacts, will ultimately determine the adaptive capacity of existing fisheries SES and thus their ability to withstand future changes. Untangling key factors and their interdependencies that determine the adaptive capacity of a fisheries SES operating in a transboundary context is complex, requiring transdisciplinary approaches and strong cross-border collaboration.

CRediT authorship contribution statement

M. Kruse: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **J. Letschert:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. **R. Cormier:** Conceptualization, Methodology, Writing – review & editing, Formal analysis, Investigation. **H. Rambo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **K. Gee:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **A. Kannen:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **J. Schaper:** Conceptualization, Methodology, Writing – review & editing, Data curation, Investigation. **C. Möllmann:** Conceptualization, Methodology, Writing – review & editing. **V. Stelzenmüller:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

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

The authors do not have permission to share data.

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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.2024.120685.

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