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Investigating the influence of tourism on the Wadden Sea using a multi-layer social-ecological network

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ABSTRACT

Coastal zones are the epicentre of significant social, cultural, and economic development worldwide. A human activity with increasing importance for coastal ecosystems is the expanding tourism sector, a core economic activity, one of the fastest-growing sectors worldwide and included in the list of cultural ecosystem services. The World Heritage Site of the Wadden Sea, located in the south-eastern North Sea, belongs to the coastal ecosystems of outstanding value and is a highly attractive area for tourism. Given the complexity of potential ecological, social, and socio-economic relationships involved in tourism, single-discipline studies fall short in capturing the full range of interactions between tourism's economic value and its ecological influences. To bridge the gap between these social and ecological aspects, a comprehensive approach utilising Social-Ecological Systems (SES) has been suggested by different authors and employed to study human-nature linkages. Social-ecological networks (SENs) provide a suitable tool to study SES, utilising language, methods, and models common in both natural and social sciences. Hence, we used a SEN approach to study tourism's ecological, and socio-economic relations in the Wadden Sea with the aim to provide a holistic picture of the relationships between tourism and ecological nodes, socio-economic nodes, other ecosystem services, and threats that might influence the area's natural value. We constructed a multi-layer social-ecological network with 30 nodes and 147 edges representing to our knowledge the first SEN approach in the Wadden Sea. With a total degree of 37, tourism was the most connected node in the SEN, with numerous direct and indirect relationships to nodes from the same and other layers indicating a huge potential for cascade effects. Furthermore, we identified 12 loops in the network related to tourism that could result in positive or negative feedbacks. Furthermore, critical data and knowledge gaps were revealed to fully capture the complexity of tourism interaction in the Wadden Sea. By highlighting the interconnectedness of tourism, ecosystem services, and anthropogenic threats, this study provides guidance for sustainable management practices that can preserve the Wadden Sea for future generations.

1. Introduction

Coastal ecosystems are the interface between land and sea and biologically highly productive areas (Burke et al., 2001). These ecosystems play a vital role in supporting human well-being by producing goods and services essential for livelihoods (Zaucha et al., 2016). Coastal zones are the epicentre of significant social, cultural, and economic development worldwide. With more than half of the global population residing in coastal areas and increasing rates of population growth, urbanisation, and economic advancement, pressures from human activities exert significant impacts on coastal ecosystems and their contribution to human wellbeing (Patterson and Hardy, 2008; Neumann et al., 2015).

The expanding tourism sector is a human activity with increasing importance for coastal ecosystems. It is a core economic activity, one of the fastest-growing sectors worldwide (UNWTO, 2019), and included in the list of cultural ecosystem services (Millennium Assessment Board, 2005). Tourism adds further tension to already existing pressures such as climate change effects (Gössling, 2002; Scott, 2021) or pollution (Zhang et al., 2020; Liu et al., 2022) in coastal areas. It demands for high resources and generates multiple environmental and social impacts

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(Büscher and Fletcher, 2017) by directly and indirectly interacting with various components of the coastal zone.

Given the complexity of potential ecological, social, and socio-economic relationships involved regarding tourism, single-discipline studies fall short in capturing the full range of interactions between tourism's economic value and its ecological influences. To bridge the gap between these social and ecological aspects, a comprehensive approach utilising Social-Ecological Systems (SES) has been suggested and employed to study human-nature linkages (Glaser et al., 2012; Heslinga et al., 2017; Haraldsson et al., 2020) such as tourism. Over the past two decades, several social-ecological approaches and frameworks have been developed (Berkes, 2003; Liu et al., 2007; Ostrom, 2009; Binder et al., 2013) to comprehend the links between social and natural components, and their role in shaping the functioning of SES (Glaser, 2006; Haines-Young and Potschin, 2010; Reyers et al., 2013; Bruley et al., 2021; Jin et al., 2024). However, integrating natural and social science to study SES remains challenging. Social and natural sciences often exhibit different scientific approaches, as well as divergent social and political positions of research (Glaser, 2006; Mooney et al., 2013; Milanez, 2015; Stojanovic et al., 2016; Barthel and Seidl, 2017). In this context, network approaches provide a valuable framework for examining social-ecological relationships (Kluger et al., 2020). Traditionally, network research has focused on either social or ecological networks and their implications for environmental management. In recent years, various human-environment research communities have increasingly used network concepts and methods to advance integrative research approaches (Sayles et al., 2019). The use of social-ecological networks (SENs) as a tool for studying SES was introduced more than a decade ago by Janssen et al. (2006), Cumming and Norberg (2008) and Cumming et al. (2010). In SENs, each component (be it social or ecological) can be described as a node within the network, with connections between the different nodes depicted by directed or undirected edges (Dee et al., 2017; Sijtsma et al., 2019). SENs emerged as a valuable tool for holistically assessing SES and exploring interactions between social and ecological subsystems (Jacob et al., 2020) as well as ecosystem services, which represent the interface between social and ecological systems and the benefits people receive from nature (Manez et al., 2014; Díaz et al., 2015; Bodin, 2017; Dee et al., 2017; Felipe-Lucia et al., 2021). SENs have been applied to investigate teleconnections and ecosystem services (Liu et al., 2016; Wang et al., 2022), the impacts of human natural resource use on ecological systems (Baird et al., 2009; Villasante et al., 2016), ressource exchange (Baggio et al., 2016), collective action for water management (Lubell et al., 2014), and governance of the food-energy-water nexus (Giampietro et al., 2009).

Kluger et al. (2019) applied the SEN approach to investigate fishing impacts in Sechura Bay, Peru. Their findings revealed that high specialisation towards a specific target species leads to the vulnerability of fishermen to external disturbances such as El Niño. In Indonesia, Eider et al. (2023) employed a SEN to examine the governance of the SCUBA tourism sector, revealing the existence of a densely interconnected social cooperation network and underscoring the necessity for diversification of diving locations. Furthermore, Haraldsson et al. (2020) explored the impacts of an offshore wind farm in the English Channel on the local society and the ecosystem through the lens of a SEN approach. Despite their differing problem orientations, these studies demonstrate the value of SENs in providing insights into the vulnerabilities, governance challenges and interdependencies across diverse social-ecological system settings. This approach is therefore applicable across a range of contexts and geographies. Under this umbrella, network approaches use language, methods, and models common in both natural and social sciences (Janssen et al., 2006; Quintessence Consortium, 2016; Bodin, 2017; Dee et al., 2017; Turnbull et al., 2018). They offer a pathway to foster the cross-disciplinary collaboration essential for addressing complex environmental challenges (Barnes et al., 2019). Therefore, SENs present an ideal approach to further explore the complex interactions of the tourism ecosystem service in coastal zones.

The World Heritage Site of the Wadden Sea, located in the southeastern North Sea, belongs to the coastal ecosystems of outstanding value (CWSS, 2014) and is a highly attractive area for tourism. The Wadden Sea stretches along the coastline of Denmark, Germany and the Netherlands, and is the world's largest wetland characterized by an unbroken belt of tidal flats. It provides a habitat for a diverse range of benthic flora and fauna (Wolff, 2013). The Wadden Sea holds both ecological and economic significance for coastal communities, providing a range of ecosystem services essential for human well-being (Giebels et al., 2013). The unique landscape attracts a growing number of tourists supporting an essential economic branch of the coastal society (Sijtsma et al., 2019). The Wadden Sea receives approximately 8.5[1] million tourists per year generating an annual turnover of 6.7 billion€ (Hartman et al., 2022). Its designation as a World Heritage Site has promoted tourism, particularly ecotourism, a rapidly growing sector of the tourism enterprise. Ecotourism is understood as a natural resources-based tourism that is supposed to preserve environmental sustainability and to develop human well-being (Rahman et al., 2022). However, critical tourism literature argues that there is an "ecotourism bubble", which refers to the detachment of ecotourists from the context of their visit (Carrier and Macleod, 2005; Hounnaklang, 2016; Postma and Schmuecker, 2017; Sobhani et al., 2023), often overlooking the necessary infrastructure required to allow visitors to arrive at a destination. Therefore, it is necessary to examine the environmental implications of tourism, including ecotourism, in valuable and fragile World Heritage Sites such as the Wadden Sea (Landorf, 2009; Yang et al., 2013). This is timely, since tourism is of enormous importance for the Wadden Sea economy, but could simultaneously exert multiple influences, both negative and positive on the ecosystem and the local Wadden Sea communities.

While Heslinga et al. (2017) already highlighted the need to investigate the Wadden Sea tourism with an SES approach, it has not been explored with a SEN, yet. A comprehensive network perspective could provide further insights into potential synergies of tourism in the Wadden Sea area, but also into potential conflicts of interest. In this study, we used a SEN to study tourism's ecological, and socio-economic relations in the Wadden Sea. We aimed to provide a first holistic picture of the relationships between tourism and ecological nodes, socio-economic nodes, other ecosystem services, and threats that might influence the area's natural value.

We examined 1) a multi-layer SEN of the Wadden Sea with ecological and socio-economic components, anthropogenic threats and ecosystem services including tourism, 2) direct and indirect interactions between tourism and other system components, 3) feedback loops that could fortify or impede tourism.

2. Material and methods

2.1. Network construction

In order to investigate the impacts of tourism on ecological and socio-economic components in the Wadden Sea, their interactions with each other, ecosystem services and additional threats, we built a qualitative multi-layer SEN based on Jacob et al. (2020), who defined a multi-layer network approach in which each layer consists of a different network that is connected to other networks at different layers. We focused on four interrelated layers that were conceptualised as different networks (Fig. 1): socio-economic network, ecological network,

[1] This data does not include Denmark. The delineation of tourist destinations in Denmark, has been changed in recent years. The previously called South West Jutland, which encompassed the four municipalities of Wadden Sea, has been divided in three distinct destinations, with two of them comprising areas that extend beyond the Wadden Sea. Consequently, the collection of tourist data of the Danish Wadden Sea has become more complicated.

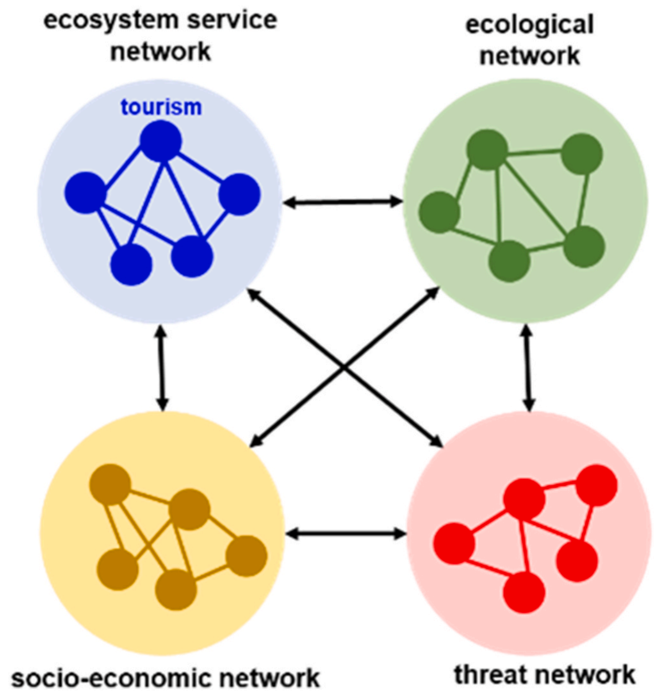

Fig. 1. Conceptual framework of the multi-layer SEN with tourism being part of the ecosystem service layer.

ecosystem services network, and threat network. The included networks were composed of nodes that were based on the available literature on coastal areas and the Wadden Sea. A qualitative literature review was carried out to identify and select relevant research papers, official documents, reports and communications dealing with ecological, socio-economic, ecosystem service and threat networks in the Wadden Sea. We searched in academic databases such as Scopus, PubMed, Google Scholar and JSTOR. We used keywords like "coastal ecosystems", "economic activities", "tourism", "human impact", "Wadden Sea", and "ecosystem services". In addition, a snowballing technique was used, where references from these initial sources were used to find further relevant literature, ensuring a comprehensive and thorough selection of nodes.

The ecological network referred to the biotic components of the Wadden Sea as described in Baird et al. (2004) and de la Vega et al. (2018). We aggregated the relevant species and functional groups to six major ecological nodes (i.e., marine plants, invertebrates in the water column, invertebrates in the sediment, fish, coastal birds, marine mammals; Table 1). The socio-economic network consisted of nodes related to social and economic activities in the Wadden Sea. We identified seven important nodes for the Wadden Sea area representing energy production, fishing, the service sector, industry, coastal infrastructure and harbours, marine transport, and sand extraction (Table 1). The threat network alluded to the most damaging changes to coastal ecosystems. We identified four major threats impacting the Wadden Sea which are changes in dissolved nutrient concentrations (eutrophication or de-eutrophication) (Peñuelas et al., 2013; Wiltshire et al., 2015; Meunier et al., 2016; Rick et al., 2022), temperature (global warming) (Wiltshire et al., 2015; Behrenfeld et al., 2016; Rick et al., 2022), pH (acidification) (Aberle et al., 2013; Flynn et al., 2015; Rick et al., 2022), and plastic pollution (Fleet et al., 2017). The ecosystem service network addressed the benefits for human well-being derived from ecosystems, including tourism. The initial list was based on the ecosystem services as described by the Millennium Assessment Board (2005). However, the selection of ecosystem services included in the SEN was adapted in accordance with section 2.2.

Edges between the nodes indicate a relationship of one node with another (directed edge), classified as positive, negative or unspecified as defined in Appendix 1.

During the node and edge definition process, we identified a severe lack of knowledge with regard to the importance of the Wadden Sea for specific ecosystem services including tourism, and relationships between tourism and other system components. To gain more insight into the Wadden Sea ecosystem services and specifically the relationships between tourism and other nodes, we conducted a stakeholder survey as described in section 2.2.

2.2. Survey data

To complement available information on edges involving the tourism node (es19) and other ecosystem services, a stakeholder survey was conducted over a six-week period, from January 2022 to February 2022. A survey template is provided in Appendix 2.

We identified key stakeholders linked to the Wadden Sea World Heritage Site, through document analysis. We reviewed existing documents, reports, and organizational charts to identify key stakeholders, their roles, and their relationships to the Wadden Sea. In addition, we observed the participants of the 15th International Scientific Wadden Sea Symposium that took place from November 30th to December 2nd, 2021 and where more than 200 natural and social scientists from Denmark, Germany and the Netherlands presented and discussed the latest scientific findings on the status of the Wadden Sea. The list of participants complemented our stakeholder list.

Stakeholders were selected on the basis of their expertise in coastal management, tourism studies and the Wadden Sea, and included experts from German, Dutch and Danish universities and research centres, technical officers from protected areas within the Wadden Sea, active members of Wadden Sea trilateral institutions (such as the Wadden Sea Board, the Wadden Sea Forum and the Common Wadden Sea Secretariat), regional and local technical officers from Wadden Sea municipalities or regions, fishermen, farmers, civic and environmental organisations working in the area, and tourism businesses operating in the region. The snowball method was used to identify other relevant stakeholders. Initially, the survey was sent to 171 mail addresses belonging to seven stakeholder groups (Table 2). However, respondents were invited to circulate the survey further to expand its reach. When possible, personal email addresses were utilised for contacting respondents. In cases involving stakeholder groups such as ministries and politicians, tourism agencies, or fisheries and farmer organisations, collective email addresses of their respective organisations were used due to unavailability of personal contact information. The survey could be answered online and it was accessible in English.

All survey and interview participants gave informed consent. The Ethics Committee reviewed the study and determined that a full assessment was not required due to the low ethical risks involved. The analysis of the survey data was always aggregated and all identifying information was removed from the analysis to ensure anonymity.

The survey was comprised by four major parts. Firstly, demographic characteristics of the respondents, including age, gender, area of operation, and main expertise, were collected (Van Riper and Kyle, 2014). Secondly, in the "Natural contributions and benefits"-section, respondents were asked to identify and value the importance of the Wadden Sea for the ecosystem services using Likert's scale in Questions 1 (Q1) (i.e. highly important, important, less important, unimportant, no answer). In Question 2 (Q2), the influence of tourism on these ecosystem services have been assessed, also based on Likert's scale (i.e. severe negative impact, remarkable negative impact, marginal negative impact, no impact, marginal positive impact, remarkable positive impact, severe positive impact, I do not know).

After identifying relevant ecosystem services, the survey focused on the relationship between socio-economic and ecological components to tourism activities. Respondents were asked to assess the influence of ecological and socio-economic nodes on tourism (Question (Q) 3) and

Table 1
Overview of the four different layers included in the multi-layer SEN, the respective nodes and the nodes' definition.

Layer	Node	Node Description	Definition	Reference
ecological	e1	Marine plants	Primary producers including phytoplankton, microphytobenthos, and macrophytes	Baird et al. (2004), de la Vega et al. (2018), Jung et al. (2020)
	e2	Invertebrates in the water column	zooplankton, shrimps, and other small organisms living in the pelagic zone	Baird et al. (2004), de la Vega et al. (2018), Jung et al. (2020)
	e3	Invertebrates in the sediment	Benthic organisms (e.g. worms, clams, snails, crabs etc.)	Baird et al. (2004), de la Vega et al. (2018), Jung et al. (2020)
	e4	Fish	Pelagic and demersal fish species	Baird et al. (2004), de la Vega et al. (2018), Jung et al. (2020)
	e5	Coastal Birds	Waders and waterfowl	Baird et al. (2004), de la Vega et al. (2018), Jung et al. (2020)
	e6	Marine mammals	seals and harbour porpoises	Baird et al. (2004), de la Vega et al. (2018), Jung et al. (2020)
socio-economic	se1	Energy production	Extraction of energy products in a useable form from natural sources	Kloepper et al. (2017), Schep (2021)
	se2	Fishing	Economic activity of commercially catching fish and shellfish	Kloepper et al. (2017), Schep (2021)
	se3	Service sector	Economic sector that produces intangible goods and services	Kloepper et al. (2017), Schep (2021)
	se4	Industry	Economic sector in charge of manufacturing goods for sale	Kloepper et al. (2017), Schep (2021)
	se5	Coastal infrastructure and harbours	Structures, harbours, and facilities built along coastlines	Schroor., Kloepper et al. (2017), Schep (2021)
	se6	Marine transport	Means of transport where goods (or people) are transported via sea routes	Kloepper et al. (2017), Schep (2021)
	se7	Sand extraction	Extraction of sand for building purposes and for the extraction of heavy minerals such as rutile and zircon	Kloepper et al. (2017), Schep (2021)
threats	t1	Changing nutrient concentrations	Nutrient inputs (e.g. nitrogen and phosphorous) into water bodies	Peñuelas et al. (2013), Wiltshire et al. (2015), Meunier et al. (2016), Rick et al. (2022)
	t2	Temperature increase	Rise of global temperature	Wiltshire et al. (2015), Behrenfeld et al. (2016), Rick et al. (2022)
	t3	Ocean acidification	Global decrease of seawater pH	Aberle et al. (2013), Flynn et al. (2015), Rick et al. (2022)
	t4	Plastic pollution	Accumulation of synthetic plastic in the environment	Fleet et al. (2017)
ecosystem service	es1	Provision of food	Provision of biomass for human consumption and the conditions to grow it (e.g. fisheries, aquaculture, plant production, hunting)	Millennium Assessment Board (2005); CICES (2023) [a]
	es2	Provision of fibre	Fibres and other materials from plants, algae and animals for direct use or processing	Millennium Assessment Board (2005); CICES (2023) [a]
	es3	Provision of biological material used for as an energy source	Provision of biomass or biotic elements for non-food purposes	Millennium Assessment Board (2005); CICES (2023) [a]
	es4	Provision of mineral material used for as an energy source	Provision of primary production extractable as raw materials (e.g. fuel)	Millennium Assessment Board (2005); CICES (2023) [a]
	es5	Production of wind energy	Construction of wind farms	Millennium Assessment Board (2005); CICES (2023) [a]
	es6	Maintenance of genetic diversity of animals and plants	Genetic variety of species populations	Millennium Assessment Board (2005); CICES (2023) [a]
	es7	Fresh water provision	Ground and surface water for non-drinking and drinking proposes	Millennium Assessment Board (2005); CICES (2023) [a]
	es8	Air quality maintenance	Regulation of air pollutants concentration in the lower atmosphere	Millennium Assessment Board (2005); CICES (2023) [a]
	es9	Climate regulation	Regulation of greenhouse and climate active gases (e.g. carbon sequestration)	Millennium Assessment Board, 2005; CICES (2023)[a]
	es10	Water regulation	Regulation of hydrological flows, Prevention of floods, river runoff, etc.	Millennium Assessment Board (2005); CICES (2023) [a]
	es11	Erosion control	Soil retention and the prevention of landslides	Millennium Assessment Board (2005); CICES (2023) [a]
	es12	Water quality regulation	Biochemical and physicochemical processes involved in the removal of wastes and pollutants from the water	Millennium Assessment Board (2005); CICES (2023) [a]
	es13	Storm protection	Protection against floods, droughts, hurricanes and other extreme events. It also refers to erosion protection in the coast	Millennium Assessment Board (2005); CICES (2023) [a]
	es14	Cultural value of the Wadden sea	Elements linked to nature that people identify with the culture or history of the Wadden Sea (e.g. fishing practices)	Millennium Assessment Board (2005); CICES (2023) [a]
	es15	Education and knowledge	Use of natural environments for knowledge, education or research proposes	Millennium Assessment Board (2005); CICES (2023) [a]
	es16	Inspiration	Use of natural environments for inspiration	Millennium Assessment Board (2005); CICES (2023) [a]
	es17	Aesthetic value of the environment	Aesthetic enjoyment of the natural landscapes and landmarks	Millennium Assessment Board (2005); CICES (2023) [a]
	es18	Influence on coastal society, their culture and self-identification	Ecosystem elements that have symbolic meaning linked to regional culture and identity. Biophysical characteristics, qualities of ecosystems, landscapes, species that are considered by people as important for their cultural meaning and are used as signifiers of some type	Millennium Assessment Board (2005); CICES (2023) [a]
	es19	Tourism	Opportunities that the natural environment provide for recreation and leisure	Millennium Assessment Board (2005); CICES (2023) [a]

[a] https://cices.eu/.

Table 2
Overview of included stakeholder addresses for initial contact.

Stakeholder group	Number of initial contacts
Researchers (natural and social science)	68
Ministries and Politics	12
Regional and local managers	24
Fishermen and Farmers	17
Social and environmental organisations	23
Tourism and marketing organisations	13
Trilateral organisations	14
Total	**171**

vice versa (Question (Q) 4) using Likert's scale (i.e. severe negative impact, remarkable negative impact, marginal negative impact, no impact, marginal positive impact, remarkable positive impact severe positive impact, I do not know). Lastly, respondents were requested to identify the impacts of additional anthropogenic drivers on tourism (Question (Q) 5) again through Likert's scale (i.e. severe negative impact, remarkable negative impact, marginal negative impact, no impact, marginal positive impact, remarkable positive impact severe positive impact, I do not know). The anthropogenic drivers included socio-economic and the threat layer nodes (Table 1).

2.3. Network analysis and statistics

All analyses were conducted using R statistics version 4.0.1 (R core team 2022).

To analyse the survey data, descriptive statistics were used to understand the respondents' general background including age, gender, and area of occupation. Furthermore, we tested the survey data for significant differences between responses to include or exclude nodes and edges. To facilitate statistical analyses, response options with low numbers of responses were grouped. In Q1, we asked for the importance of the Wadden Sea area for specific ecosystem services, the response options "highly important" and "important" were combined into "important", while "less important" and "unimportant" were grouped as "unimportant". In Q2-5, which focussed on identification of relationships between the different nodes, the response options "severe negative influence" and "remarkable negative influence" were grouped as "negative influence". Similarly, "severe positive influence" and "remarkable positive influence" were combined into "positive influence", while "marginal positive influence", "marginal negative influence", and "no influence" were grouped as "marginal influence".

Normal distribution of data in each group was tested using a Shapiro Wilk test. Subsequently, the Wilcoxon rank test was applied in Q1 and Kruskal-Wallis test was used in Q2-5 to test for differences between the response groups. Dunn's test was further applied to determine significant differences between response options.

For Q1, we only kept the ecosystem services in our SEN if stakeholders perceived them as significantly important in the Wadden Sea. For Q2-5, we included an edge in the multi-layer SEN, if a relationship between two nodes was statistically significant according to the Kruskal-Wallis test. Additionally, edges were included for cases where Dunn's test failed to distinguish between marginal and positive or marginal and negative relationships. We then categorised an influence as marginal/positive or marginal/negative if Dunn's test did not reveal a significant difference. Relationships deemed of marginal importance were included as an unspecified edge.

For network analysis, we used the R package igraph (Csardi, 2013). We identified ingoing, outgoing and total degrees of each node using degree analysis. Furthermore, we tested direct and indirect connection between the tourism node and any other node by using shortest pathway analysis. Lastly, feedback loops related to tourism were identified using an adjacency matrix.

3. Results

Using a multi-layer social-ecological network (SEN) approach after Jacob et al. (2020), we investigated the relationships between tourism and other system components in the Wadden Sea. The complex SEN revealed multiple direct and indirect relationships of tourism with other nodes, and several feedback loops.

3.1. Data collection using surveys

Literature on ecosystem services and especially tourism effects in the Wadden Sea was insufficient to construct a tourism-focused SEN. Therefore, we complemented our data base using a stakeholder survey. The survey data were used to define edges related to tourism within the SEN and to complement existing literature. An overview of the survey participants can be found in Appendix 3.

3.1.1. Identification of ecosystem services

The survey results were used to identify the significance of the Wadden Sea for various ecosystem services. Findings of the survey revealed that the Wadden Sea was perceived to play a vital role in preserving genetic diversity (es6), regulating air (es8) and climate quality (es9), managing water resources (es10), controlling erosion (es11), water quality regulation (es12), providing storm protection (es13), fostering cultural values (es14), facilitating education and knowledge (es15), serving as an inspiration (es16) due to its aesthetic value (es17), influencing coastal society and culture (es18), and supporting tourism (es19) (Appendix 4). However, the Wadden Sea was considered unimportant in terms of providing fibre (es2) and biological material for energy generation (es2). The assessment of ecosystem services related to food provision (es1), mineral material (es4), wind energy (es5), and freshwater provision (es7) lacked clear consensus.

Only ecosystem services that were perceived as "important" were kept as nodes in the SEN for further analyses, resulting in 13 nodes in the ecosystem service layer.

3.1.2. Identification of edges related to tourism

The perceived influence of tourism on the Wadden Sea ecosystem services was examined using the Kruskal-Wallis test. Of the 19 ecosystem services initially considered, tourism was perceived to have an impact on 15 services ($p < 0.05$). Overall, the influence of tourism on ecosystem services was perceived to be low, with slight tendencies towards non-significant positive or negative influences. The influence of tourism was perceived to be marginal for es2, es3, es8, es10, es11, and es12. For es1, es14, es15, and es16, the influence of tourism was perceived to be marginal/positive (Appendix 5). In contrast, tourism was perceived as having a marginal/negative influence on es4, es5, es7, es9, and es13 (Appendix 4). No statistically significant influence of tourism on the ecosystem service was determined for es6, es17, es18, and es19, according to the survey respondents.

The survey also explored the influence of the social-ecological nodes of Table 1 on tourism (Appendix 5). Birds (e5) and mammals (e6) were perceived to positively influence tourism. The other ecological nodes (e1-e4) as well as some nodes of the socio-economic layer (se2, se3, se5, se6) were assessed as having a marginal/positive influence (Appendix 5). In contrast, energy production (se1) and industry (se4) were perceived as having a marginal/negative influence, while sand extraction (se7) did not show a significant influence.

Furthermore, the survey revealed the perceived positive and negative influences of tourism on other social-ecological nodes. The service sector (se2) was perceived to be positively influenced by tourism. However, for all other system components (e1-6, se1, se3, se4, se7) the influence of tourism was perceived as marginal showing slight, non-significant trends to negative impacts on ecological components (Appendix 5). No relationship was observed for coastal infrastructure and harbours (se5).

Regarding the influence of anthropogenic threats on tourism (Q5, Appendix 6), nutrient changes (t1) and plastic pollution (t4) were perceived as having a negative impact on tourism. However, no trend was found for temperature increase (t2) and energy production (se1). The remaining potential threats were perceived to influence tourism only marginally with a slight, mostly non-significant trend towards positive or negative impacts. Specifically, ocean acidification (t3), the service sector (se2), fishing (se3) and sand extraction (se7) were perceived as having a marginal/negative influence, while industry (se4) and marine transport (se6) were perceived as having a marginal/positive influence.

In total 21 edges were included in the SEN based on the survey results and cross-checked with existing literature.

3.2. Multi-layer SEN of the Wadden sea

3.2.1. General structure

Based on the results of the qualitative literature review and the survey output, we constructed a multi-layer SEN of the Wadden Sea consisting of 30 nodes and 147 edges (Appendix 1), with 100 inter-layer edges and 47 intra-layer edges (Fig. 2). Positive influence was observed in 51 % of the edges, while 37 % represented negative relationships, and 12 % of the edges were unspecified (Appendix 1).

The ecological layer showed the highest number of edges, 67 in total, predominantly characterised by positive relationships (Fig. 3). Negative relationships were relatively few, primarily associated with predator-prey dynamics. The socio-economic layer comprised 46 edges, with 25 positive edges, 20 negative edges and one unspecified relationship (Fig. 3). Intra-layer edges predominantly represented positive influences among socio-economic nodes. The threat layer revealed the fewest edges, with a total of 22 edges. None of these relationships were positive, with 15 representing negative influences and 7 unspecified edges (Fig. 3). The ecosystem service layer included 22 edges, with 8 unspecified edges, the highest among the layers.

The degree analysis revealed that the nodes with the highest and the lowest total degree both belonged to the ecosystem service layer. Node es19 (tourism) was the most connected, with the highest values for in degree (15), out degree (22) and total degree (37) (Table 3). The lowest total degree was found for es15 (education and knowledge) with just 1 in degree connection. In the ecological layer, e3 (Invertebrates in the sediment) showed the highest values for in degree (14), out degree (12) and total degree (26). The lowest in degree and total degree values were found for e1 (Marine plants), the lowest out degree for e4 and e6. In the socio-economic layer, se2 (fishing) revealed the highest in degree (8) and total degree (15) values, whereas se5 showed the highest out degree (12). The lowest values were found for se7 (sand extraction) with 1 in degree, 2 out degree, and 3 total degree. The threat layer generally showed low degree values for all four nodes.

3.2.2. Relationships with tourism

Out of the total 147 edges in the SEN, 37 were related to tourism (es19). These tourism related edges demonstrated the influence of tourism on other nodes (22 edges) and the influence of other nodes on tourism (15 edges) (Appendix 1).

Tourism was directly, positively influenced by all nodes from the ecological layer. In the socio-economic layer, four nodes (se2, se3, se5, and se6) had a direct, positive influence on tourism, while se1 and se4 negatively influenced tourism. Nodes from the threat layer also had a negative impact on tourism (t1, t3, t4). No intra-layer edges were identified to directly influence tourism.

The shortest pathway analysis revealed that tourism was connected directly or indirectly to all other nodes except for se5 (coastal infrastructure and harbours). However, shortest pathway lengths differed across the nodes. Most nodes (22) were directly connected to tourism, thus with a direct edge from tourism to the other node. Tourism directly influenced all components of the ecological layer negatively. In the socio-economic layer, nodes were either positively influenced by tourism (se2, se3, se6) with a direct edge or showed an unspecified relationship (se1, se4, se7). The threat layer revealed a direct, positive influence of tourism on t4 (plastic pollution). Intra-layer interactions showed a mix of direct positive (es14, es15, es16) and direct negative (es9) influences on specific ecosystem service nodes, while some remained unspecified (es8, es10, es11, es12, es13).

Tourism was indirectly connected to six more nodes (Fig. 4). Four were connected to tourism with one node in between, and two nodes with two and three nodes in between, respectively.

Loop analysis showed 12 tourism-related loops in the SEN (Fig. 5). Tourism influenced all ecological nodes negatively, but at the same time, the ecological nodes had a positive influence on tourism. Three nodes of the socio-economic layer showed a positive feedback loop with tourism. Tourism positively influenced the nodes fishing (se3), service sector (se2), and marine transport (se6) which also positively influenced tourism. In the threat layer, tourism has a positive influence on plastic pollution (t4), but plastic pollution negatively influenced tourism.

Unspecified effects of tourism were found for energy production (se1) and industry (se4), which showed a negative effect on tourism.

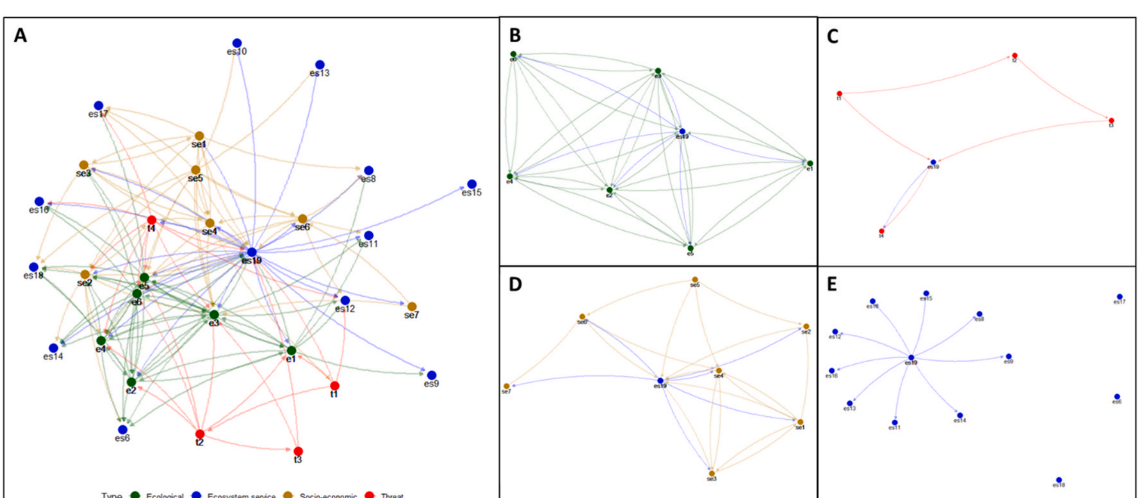

Fig. 2. Multi-layer SEN of the Wadden Sea and the interactions between the different nodes. Node labels refer to abbreviations in Table 1, A) Representation of the entire SEN, B) sub-network of the ecological layer and tourism (es19), c) sub-network of the threat layer and tourism (es19), D) sub-network of the socio-economic layer and tourism (es19), E) sub-network of the ecosystem layer including tourism (es19).

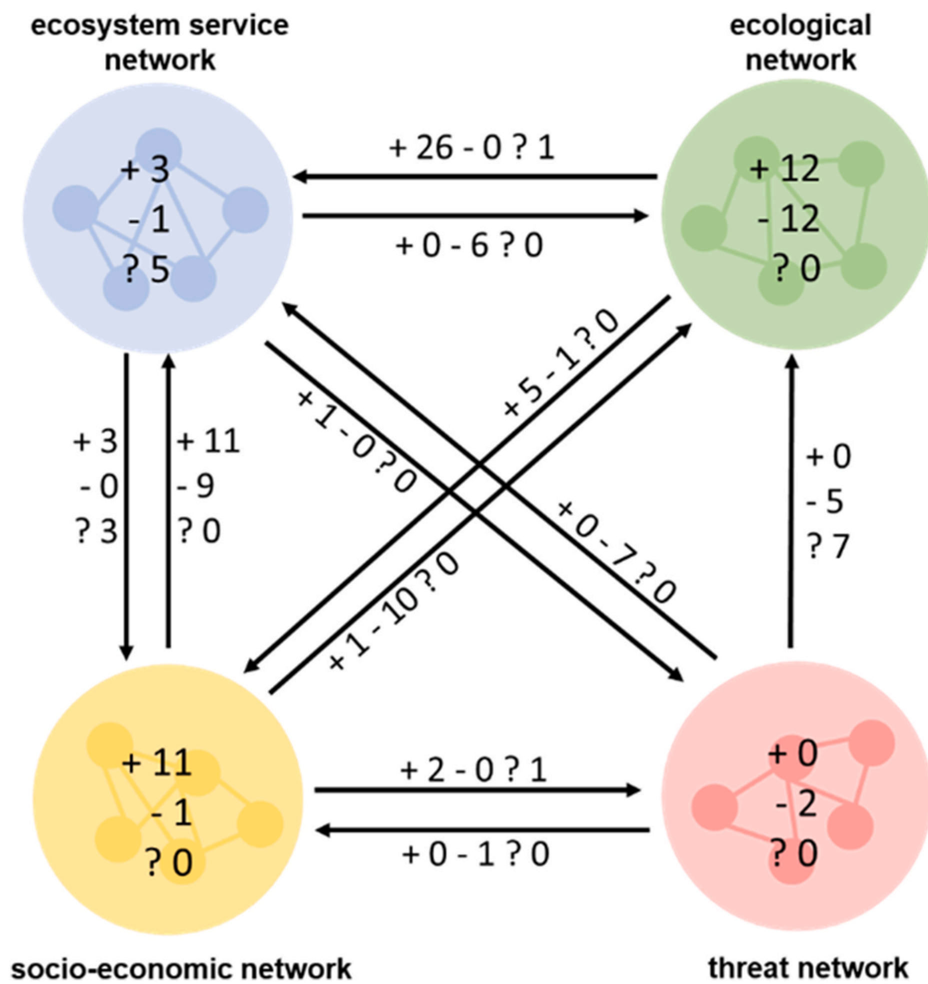

Fig. 3. Summary of intra- and inter-layer edges and their characterisation as positive influences (+), negative influences (−) and unspecified influences (?).

4. Discussion

4.1. The multi-layer SEN of the Wadden sea

In order to investigate the relationships of tourism in the Wadden Sea, we constructed a multi-layer social-ecological network with 30 nodes and 147 edges. To our knowledge, this represents the first SEN approach in this area. With a total degree of 37, tourism was the most connected node in the SEN, with numerous direct and indirect relationships to nodes from the same and other layers indicating a considerable potential for cascade effects. Certainly, tourism's high total degree is also related to the theme-specific stakeholder survey. Presumably, additional links in the SEN could be identified with more node-specific surveys. Furthermore, we identified 12 loops in the network related to tourism that could result in positive or negative feedbacks.

4.2. Direct and indirect relationships of tourism

In our SEN, we included tourism in the ecosystem service layer alongside with other ecosystem services (ES) that were highlighted to be important in the Wadden Sea. The identification and prioritisation of ES stressed the Wadden Sea's pivotal role in maintaining ecological balance vis á vis supporting human activities. It is noteworthy that services related to genetic diversity, climate regulation, water management, and cultural values were identified as being of vital importance.

Tourism plays a pivotal role in the Wadden Sea area (Hartman et al., 2022) as shown by the high degree values attached to it. Despite that we had a topical focus in our survey on tourism, a large amount of the edges going from tourism to other nodes were classified as marginal or unspecified. This indicates that there are further interdisciplinary research efforts required to deepen our understanding of the interconnectedness of our SEN. Nevertheless, outgoing edges from tourism influenced directly or indirectly all other nodes in the network, except for the node se5 (coastal infrastructure and harbours). While se5 appears to positively influence the tourism node, the missing connection from tourism to se5 could indicate that the planning and construction of coastal infrastructure and harbours works independently from the tourism sector. Potentially, se5 is more reliant on other aspects, such as the importance of a specific site for economic development or coastal protection.

Tourism was majorly supported by nodes from the ecological and the socio-economic layer. The positive influence of birds, mammals, and the service sector on tourism underlines the importance of the unique environment and the supporting local economy. For example, activities such as bird watching, intertidal tours, and seal tours have become popular tourist attractions along the Wadden Sea coast (Gätje, 2004; CWSS, 2022). Despite the favourable stance of the ecological layer towards tourism, all nodes within this layer were subjected to detrimental effects resulting from disturbances related to tourism (Andersen et al., 2012; van der Kolk et al., 2022). The direct negative influences of tourism on the ecological layer could be further intensified via indirect positive influences of tourism on the threat layer nodes such as pollution (Wolff and Zijlstra, 1980) which results in further negative repercussions on the ecological nodes. In order to address these issues, the Common Wadden Sea Secretariat (CWSS) has constituted a stakeholder forum with the objective of promoting the integration of nature

Table 3
Results of the degree analysis for the 30 nodes included in the SEN analysis.

Layer	Node	Node description	in degree	out degree	total degree
ecological layer	e1	Marine plants	6	9	15
	e2	Invertebrates in the water column	7	9	16
	e3	Invertebrates in the sediment	14	12	26
	e4	Fish	9	8	17
	e5	Coastal Birds	9	11	20
	e6	Marine mammals	8	8	16
socio-economic layer	se1	Energy production	3	7	10
	se2	Fishing	8	7	15
	se3	Service sector	5	4	9
	se4	Industry	5	8	13
	se5	Coastal infrastructure and harbours	0	12	12
	se6	Marine transport	3	6	9
	se7	Sand extraction	1	2	3
threat layer	t1	Changing nutrient concentrations	1	4	5
	t2	Temperature increase	1	7	8
	t3	Ocean acidification	1	2	3
	t4	Plastic pollution	3	9	12
ecosystem service layer	es6	Maintenance of genetic diversity of animals and plants	6	0	6
	es8	Air quality maintenance	4	0	4
	es9	Climate regulation	2	0	2
	es10	Water regulation	2	0	2
	es11	Erosion control	4	0	4
	es12	Water quality regulation	6	0	6
	es13	Storm protection	2	0	2
	es14	Cultural value of the Wadden sea	5	0	5
	es15	Education and knowledge	1	0	1
	es16	Inspiration	4	0	4
	es17	Aesthetic value of the environment	5	0	5
	es18	Influence on coastal society, their culture and self-identification	7	0	7
	es19	Tourism	15	22	37

conservation and tourism development in the sense of a "protection by use" approach. This is on the basis of the recognition that these two objectives can potentially coexist within the World Heritage Site (CWSS, 2014).

Our work revealed further socio-economic activities, such as energy production and industry, that may exert negative impacts on tourism, thereby indicating potential areas of conflict. Visual impacts of power plants, wind farms and large factories could affect cultural ES such as tourism (Sæþórsdóttir, 2012; Frantál and Urbánková, 2017; Voltaire et al., 2017). For instance, Gee and Burkhard (2010) demonstrated that the visual impacts of wind farms could impair the cultural ES, e.g. sense of vastness of the ocean, provided by the Wadden Sea area. These insights emphasize the need for balanced management strategies that support tourism while minimizing its negative effects on other critical system components. Our SEN approach serves as a valuable tool to constructive discourses across different, potentially conflicting, interest groups.

However, positive effects of tourism on other ecosystem services were noted on cultural values, education, and inspiration, aligning with ecotourism goals. This is consistent with the objective of tourism, particularly ecotourism, to foster an appreciation of local culture in the Wadden Sea region. Negative impacts of tourism on local identities, as previously documented in other studies (Saarinen, 2004; Daly et al., 2021), do no longer appear to be prevalent in the Wadden Sea region. Rather, negative impacts were seen in water and climate regulation, and storm protection. Water demands of tourists for purposes such as irrigation, hotel amenities, food production, and infrastructure development contribute significantly to freshwater consumption (Gössling, 2001; Chapagain and Hoekstra, 2008; Yang et al., 2011; Gössling et al., 2012; Becken, 2014; Yoon et al., 2018). Similarly, the energy consumption associated with tourism, which is primarily sourced from fossil fuels, has the effect of increasing carbon emissions and affecting climate regulation (Dwyer et al., 2009). Consequently, tourism is responsible for 8 % of global greenhouse gas emissions, predominantly CO_2 (Rico et al., 2019). Thus, tourism industry is a significant contributor to the deterioration of freshwater provision and climate regulation. In our case however, edges from tourism on other ecosystem services were mostly identified as marginal with slight positive or negative tendencies implying that the effects are not perceived as substantial enough to cause major disruptions on other Wadden Sea ES. Indeed, a considerable number of interactions between edges pertaining to ecosystem services remain unspecified. These SEN findings highlight the necessity for future research to further examine in more detail both positive and negative relations between ES, as well as their interdependencies with ecological and socio-economic nodes.

Interestingly, the relationship of tourism with nodes from the threat layer was mostly via indirect pathways of different lengths. Plastic pollution was the only threat node that was directly influenced by tourism. The indirect influence of tourism on the other threats through the industry node appeared to be reasonable. Tourism effects and demands could cause a change in the industry of an area with further implication on threats such as temperature increase due to increased industrial CO_2 emissions or changes in nutrients by industrial water discharge. While nutrient concentrations in the Wadden Sea have constantly decreased since the 1980s, high concentrations in coastal

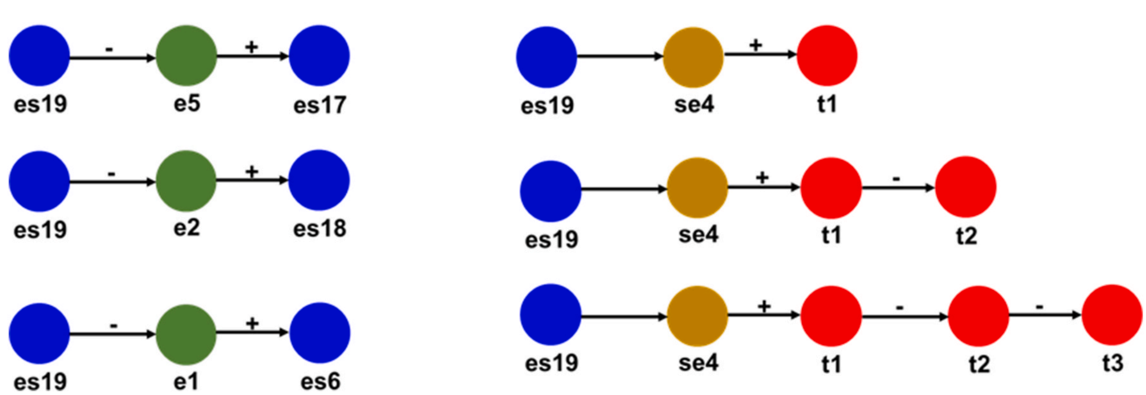

Fig. 4. Indirect connections via the shortest pathway as identified with the shortest path analysis. Node names refer to Table 1. Edges between the nodes represent a positive (+) or negative (−) influence, or an unspecified relationship (blank edge).

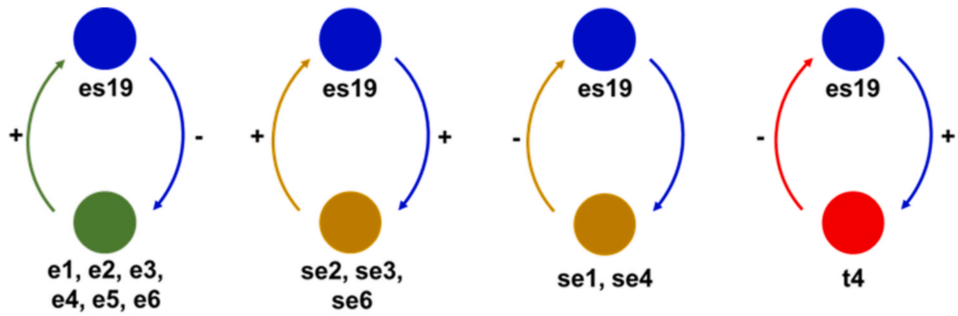

Fig. 5. Feedback loops in the SEN related to tourism. Node names refer to Table 1. Edges between the nodes represent a positive (+) or negative (−) influence, or an unspecified relationship (blank edge).

waters are frequently associated with eutrophication and algal blooms and can result in a deterioration of water quality (Van Beusekom et al., 2019), which may ultimately deter tourists. However, the edge from tourism to the industry was unspecified and identified in the survey output. To avoid future intensification of tourism cascading effects on the threat nodes, a more precise investigation of the relationship with the industry is crucial. Vice versa, the threat node of ocean acidification was the only one that directly impacted tourism. This edge was derived exclusively from the survey responses of the stakeholders involved. Further research is required in order to gain a deeper understanding of the implications of this relationship. It seems reasonable to suggest that ocean acidification could lead to changes in biodiversity and ecosystem functioning within the Wadden Sea, with the potential to impact tourism.

By and large, the growing impact of human-induced threats on coastal ecosystems has the potential to impair essential ecosystem services (Solé Figueras et al., 2024), including those related to recreation and tourism. In our case study, we identified nutrient changes and plastic pollution as significant negative influences, underscoring the necessity to address environmental pollution in order to sustain tourism. In light of these findings, it is imperative to implement proactive measures to mitigate pollution and manage anthropogenic pressures in order to preserve the Wadden Sea's appeal as a tourist destination.

4.3. Fortifying and impeding feedback loops

Feedback loops in a network appear when two nodes influence one another directly. We identified feedback loops in relation to tourism with nodes from ecologic layer, the socio-economic layer, and the threat layer. Tourism negatively influences all nodes from the ecologic layer, while at the same time being positively influenced by these nodes. These loops underline the dependency of tourism on an attractive environment while tourism itself usually cause disturbances and deteriorations on the very ecosystem it is targeted to (Andersen et al., 2012; Kabat et al., 2012; Kloepper et al., 2017; van der Kolk et al., 2022). A well-balanced management is therefore crucial to guarantee ecosystem health and to keep an area attractive for touristic activities on a long-term basis (CWSS, 2014).

Positive feedback loops were identified for tourism relationships with the service sector, marine transport, and fishing. These findings mirror earlier research that these economic sectors benefit from an increase in tourism due to the supply and demand chain (Murphy et al., 2000; Jovanoviä and Ivana, 2016).

Similar to findings by (Fleet et al., 2017), our SEN identified plastic pollution harbouring a feedback loop in which tourism both exacerbates and is harmed by plastic pollution. Furthermore, the increased prevalence of plastic pollution has a deleterious impact on birds and marine mammals, which are integral components of the ecosystem and provide support to the tourism industry.

4.4. Lessons learned

It is important to acknowledge that SENs have limitations like any other methodology. The construction of a focused SEN provides a common language for addressing complex social-ecological questions, but requires the input of experts from a range of disciplines. Researchers must be willing to transcend their own discipline and broaden their perspectives in order to fully utilise the potential of this approach. The construction of a multi-layer SEN requires a substantial corpus of data, comprising information on nodes and edges. Even with the four layers included in our presented Wadden Sea SEN, the acquisition of primary data proved challenging, particularly the identification of peer-reviewed publications for edges related to the socio-economic and ecosystem service nodes. In order to enhance comprehension of the relationships of tourism, a survey was conducted utilising the expert elicitation method, with the objective of eliciting stakeholder perceptions regarding the influence of tourism. The survey identified 21 edges, 15 of which were solely based on the survey results, reflecting only the stakeholders' perceptions and do not necessarily correspond to actual relationships as we could not find further literature support. These edges require further investigations and a grounded theory approach. This is particularly true for edges that were only found to be "marginal" in the statistical assessment without a positive or negative tendency as these edges might have suffered from edge-overestimation due to response grouping. Furthermore, stakeholders' perception could differ from information found in the literature. For example, while survey participants indicated that the impact of tourism on coastal storm protection was of a marginal negative nature, literature has described this impact as positive (Folmer et al., 2016). As a result, this edge has been marked as 'unspecified' in our SEN an requires further investigations. While surveys are an effective method for gathering data on specific SEN components, it is essential to be aware of potential biases or missing information. Our survey was sent initially to a wide range of stakeholders with different perceptions. However, the response rate was higher for scientists than for the other stakeholder groups which could have led to a bias in edge identification. The SEN could be further refined in future with including the knowledge of currently underrepresented groups in a more straightforward way. For instance, for a SEN addressing fisheries question, a workshop with coastal fishermen could provide the necessary basis for the identification of all relevant nodes and edges. Also, further layers might be required for future questions. The SEN could be extended with a network representing social values or governmental bodies.

In the current SEN, several nodes were represented at a high level of aggregation, which impeded the clear assessment of positive or negative relationships. While this was sufficient for the investigation of tourism influences, subsequent research could concentrate on particular motifs within the Wadden Sea SEN (Bodin et al., 2019; Eider et al., 2023) that necessitate higher resolution to address specific questions to more tailored problem-foci.

4.5. Recommendations for management

The value of nature is perceived in diverse ways by a range of stakeholders (Arias-Arévalo et al., 2017; Díaz et al., 2018; Zafra-Calvo et al., 2020). Some stakeholders ascribe an intrinsic value to fish species in the Wadden Sea, viewing them as a valuable component of the ecosystem. Others regard these species as instrumental resources for economic purposes, particularly in the context of fishing and sustaining local livelihoods and local identities. The existence of disparate world-views and values associated with ecosystem services gives rise to a multitude of perspectives on conservation, land use, and sustainability goals that are, at times, in conflict with one another (Pascual et al., 2017). It is regrettable that decision-making processes frequently fail to take account of this plurality of norms, identities and values (Pascual et al., 2017; Zafra-Calvo et al., 2020; Topp et al., 2021). In order to promote sustainability and strengthen social justice, it is imperative that decision makers gain a deeper understanding of the diverse perceptions, world-views and values held by different stakeholders with regard to the natural world (Pascual et al., 2017; Díaz et al., 2018). Pascual et al. (2022) posited that the incorporation of value plurality into decision-making processes is a crucial step towards a transformative future which necessitates an examination of the intricate dynamics of social-ecological systems, encompassing their implications for ecosystem services and the impact of threats on diverse components. In this regard, SENs can serve as a valuable tool to create novel insights into the interlinked nature of our world.

Our Wadden Sea SEN represents an inaugural descriptive approach, exemplifying the relationship between a flourishing ecological system, tourism, and the economic benefits derived from tourism. The comprehensive management programme for the Wadden Sea, developed in collaboration with various stakeholders, seeks to achieve a balance between the benefits of tourism for coastal communities and the sustainable capacity of the ecosystem (CWSS, 2014). We could demonstrate that the collective negative impact of tourism on ecological nodes, coupled with the influence of socio-economic nodes, and the threat layer, hosts the potential of indirect and probable negative cascading effects.

As tourism is further increasing in the Wadden Sea, SENs provide a basis for managing thresholds of potential concern (TPC) or limits of acceptable change (LAC) as they combine social and ecological components representing a SES (Biggs et al., 2011; Werners et al., 2013; Dragovich and Bajpai, 2022). Indeed, as Biggs et al. (2011) already highlighted, TPCs should not be considered in isolation, but rather in a broader, system-wide perspective. Hence, SENs can be used to develop mitigation options if TPC or LAC are reached by identifying affected nodes and edges. The identification of key nodes and edges and definition of their LAC and TPC is therefore essential for the implementation of targeted interventions that can enhance positive interactions and mitigate negative impacts. The current equilibrium between constructive and destructive influences within the SEN indicates that sustainable tourism practices can be integrated without significantly compromising ecosystem health. Policies designed to achieve a balance between tourism development and environmental conservation can leverage the positive synergies identified in the SEN, thereby ensuring that negative impacts in the Wadden Sea SES are minimised, also under climate change conditions.

Thus, we recommend to include SENs in future management decision processes. However, to provide valuable outcome, data acquisition needs be adapted to node and edge identification as a basis for these complex networks. Best practices for SEN construction and analyses for management purposes are a necessary next step and need to be based on comprehensive transdisciplinary studies.

5. Conclusion

We developed the first multi-layer SEN for the Wadden Sea region to study the direct and indirect relationships of tourism with various social-ecological system components. As a data base, we used a combination of literature and survey data to construct the multi-layer SEN. In conclusion, the approach has proven effective in elucidating the complex relationships between tourism and ecosystem services in the Wadden Sea. Tourism directly or indirectly influenced almost all included nodes in the SEN. Furthermore, we revealed important feedback loops in the network. Nevertheless, critical data and knowledge gaps were found. By highlighting the interconnectedness of tourism, ecosystem services, and anthropogenic threats, this study provides guidance for sustainable management practices that can preserve the Wadden Sea for future generations.

CRediT authorship contribution statement

Sabine Horn: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Cédric L. Meunier:** Writing – review & editing, Conceptualization. **Gesche Krause:** Writing – review & editing. **Liliana Solé:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Application of AI

During the preparation of this work SH used ChatGPT in order to improve R coding. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107686.

Data availability

The data for constructing the SEN is shared in the attachement. Data gained in the stakeholder survey is confidential and cannot be shared freely.

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