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Matrix-based assessment of spatial correlations between marine uses and ecosystem service supply in German marine areas

Abstract

Marine ecosystems are highly dynamic and complex and contribute immensely to human well-being. Spatiotemporal overlaps of marine uses and human activities are constantly pressuring ecosystems, and that in turn impacts the supply quantity and quality of various ecosystem services (ES). This study is the first attempt to use the ES matrix to link marine uses and the capacity to supply ES. Combining expert- and literature-based evaluations, we assessed the relationships of twelve marine uses and five selected ecosystem services in the German North and Baltic Sea and mapped their spatial distribution. Despite a limited data availability and a higher need for simplification, the matrix approach proved to be applicable for the marine realm. Areas used for tourism and those that provide coastal safeguarding show high values of ES supply in comparison to areas used for sediment extraction and areas previously used as ammunition dumping areas. Nature conservation areas tend to have the highest capacity to supply ES. Differences in the ES supply pattern between the North Sea and Baltic Sea were identified. The results show the influence of anthropogenic activities on the spatial distribution of ES supply and can support future marine planning.

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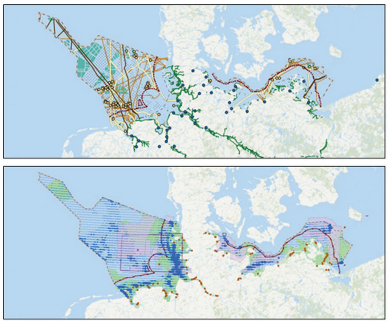
Graphical abstract

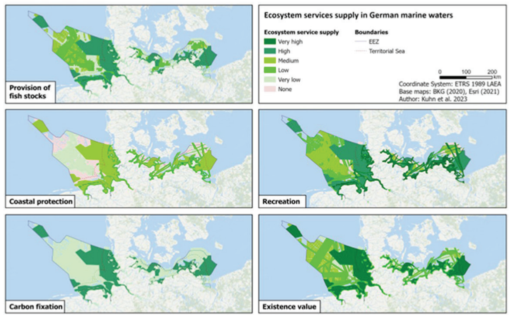
Spatial distribution of twelve marine uses → **Matrix of ecosystem services supply linked to marine uses** → **Maps presenting the supply of five ecosystem services**



Combined matrix

Twelve marine uses / Five ecosystem services	Provision of fish stocks	Coastal protection	Carbon fixation	Recreation	Existence value
Shipping	1.3	0.4	1.2	1.6	1.6
Platforms	2.3	0.2	0.9	2.1	2.8
Pipelines & submarine cables	1.3	0.1	0.7	0.6	1.1
Offshore wind turbines	2.7	0.1	1.0	2.4	2.8
Sediment extraction	0.6	2.8	0.2	0.3	0.5
Sediment placement	0.6	1.9	0.8	1.2	1.2
Military training areas	1.1	0.3	1.3	0.2	1.5
Former munitions dumping areas	0.8	0.1	0.7	0.3	0.7
Coastal safeguarding	2.0	3.9	2.4	3.6	2.7
Tourism	1.0	1.6	1.3	4.5	2.4
Fishery	1.7	0.6	0.9	2.5	0.7
*Nature conservation areas	4.1	3.3	3.9	4.0	4.9

Expert-based assessment
Literature-based assessment



1 Introduction

While marine ecosystems provide immense contributions to human health and well-being, anthropogenic activities affect the state of these ecosystems and thus their capacity to support society's demand for goods and services. The anthropogenic uses of marine waters are diverse and multiple sectors of often contradicting interests exist concurrently. To facilitate the sustainable use of marine resources and support environmental protection, multiple European Directives and policies have been established. Together, the EU Biodiversity Strategies 2020 and 2030 (European Commission 2011, 2019), the Marine Strategy Framework Directive (MSFD, 2008/56/EC) and the Maritime Spatial Planning Directive (MSPD, 2014/89/EU) build the foundation of European maritime policy, accompanied by regional efforts like the Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2030 (OSPAR 21/13/1) and the 2021 updated Baltic Sea Action Plan (HELCOM 2021) adopted by the Baltic Marine Environment Protection Commission (HELCOM). Responsible for the management of marine ecosystems are the littoral states of the North and Baltic Sea, members of OSPAR and HELCOM. Maritime spatial planning (MSP, 2014/89/EU) recommends that the spatial and temporal use of marine resources should combine environmental, economic, and social concerns in a sustainable manner, therefore ensuring sustainable development and the implementation of the aims set by the MSFD. All these policies apply the holistic ecosystem-based approach, thereby acknowledging the complexity of ecosystems and addressing the integrated management of human activities for healthy ecosystems and the sustainable use of ecosystem goods and services.

Our society depends heavily on the management of these ecosystems in order to assure a sustainable supply of ecosystem services (ES), the benefits people derive from nature (MA 2005). In more detail, ES are understood to be 'the contributions of ecosystem structure and function – in combination with other inputs – to human well-being' (Burkhard et al. 2012a, p.2). They are provided directly or indirectly to humans based on biophysical structures and processes that are the foundation of ecosystem functioning. The ecosystem state, however, is influenced by human activities that put pressure on the environment and therefore influence the capacity to supply ES. A popular method to spatially assess ES is the ES matrix approach, developed to link ecosystem or habitat types with ES supply and demand (Burkhard et al. 2009, 2012b, 2014). Matrix tables linking geospatial units and the capacity to supply ES are created, based on expert knowledge, measurement or modelling approaches. The initially comparably simple method allows the assessment of numerous ES at once and provides data that can be easily mapped. It has therefore become a popular and important method for the assessment and mapping of ES (Campagne et al. 2020).

Since its introduction, the ES matrix approach has been applied broadly and developed further for different applications and environments (e.g. Villoslada et al. 2018, Bicking et al. 2019, Sieber et al. 2021). Especially in data-scarce contexts, the assessment based on expert judgment has proven valuable and scientifically robust (Jacobs et al. 2015). Therefore, the matrix approach is considered to support transdisciplinary research by combining approaches from natural and social sciences and by involving stakeholders (Jacobs et al. 2015). The use of expert judgement presumes that education and experience provide specific knowledge on a given research subject. The popularity of the matrix approach is probably due to its efficient, comparably quick, and flexible application. The design of the ES matrix approach has the advantage that the level of detail and abstraction can range from very simple to very complex. In this way, the matrix method can be used to assess comparatively many ES (Campagne et al. 2020). These core strengths, however, hold risks in regard to the scientific reliability and repeatability (Hou et al. 2013, Jacobs et al. 2015). This criticism has been addressed, e.g. by calling for the explicit description of methodological approaches, the careful choice of the experts involved and the introduction of tests in regards to confidence, reliability and validation (Jacobs et al. 2015).

The application of the approach requires the adaptation of the matrix depending on the aim, the research question and space-specific peculiarities in regard to the study area (Campagne et al. 2020). While the matrix approach has predominantly been applied to terrestrial systems, comparably few applications in the marine realm have been conducted so far. One reason may be that marine ecosystems and their services are harder to map due to their three-dimensional, multi-layer (water surface, water column, sea bottom) and dynamic (flowing water, tide-affected systems) character. Most authors link specific habitats (Salomidi et al. 2012, Galparsoro et al. 2014, Depellegrin et al. 2017, Hattam et al. 2021) and/or species (Burdon et al. 2017, Culhane et al. 2018), or marine protected areas (Potts et al. 2014, Geange et al. 2019) and the supply of ES . Other authors combine the analysis of marine and terrestrial habitats (Müller et al. 2020, Schumacher et al. 2021) or connect ecosystem functions and the supply of ES (Armoškaitė et al. 2020).

Interrelations of land use and ES supply have been studied in terrestrial settings for over a decade, however, the connections in the marine realm are not as well-understood. Therefore, we aim to take a step towards closing this gap. This study provides the first known attempt to assess the direct relationships of anthropogenic marine uses and the supply of ES using the matrix approach in the marine context. It furthermore represents the first attempt to map multiple ES in the German marine waters of the North and Baltic Sea. We address two main research questions: (i) How can ES matrices be adapted to link marine uses and ES supply?, (ii) What is the influence of marine uses on the spatial distribution of ES supply? We applied the ES matrix approach, linking twelve prevalent marine uses and five selected ES of the German North Sea and Baltic Sea. The matrix was populated with values based on a combination of expert knowledge and evidence derived from scientific and grey literature. The resulting maps offer a visual representation of the spatial distribution and intensity of the ES supply.

2 Methods

2.1 Study site description

German marine waters consist of the North Sea in the north-west and the Baltic Sea in the north-east of the country. The North Sea is a relatively shallow marginal sea of the Northeast Atlantic and part of the Northeast European Shelf Sea. The coastal region is characterised by tidal dynamics. The extensive tidal flats, which dry out twice per day, contain diverse habitats, and are characterised by high biodiversity and high biomass productivity. The Baltic Sea is an inland sea and is one of the largest brackish waters on earth. The German Baltic Sea areas are located in the transitional zone between the central brackish waters and the Belt Sea, which is dominated by the North Sea. Tidal dynamics are only marginally present. More striking are the high salinity and the high level of nutrient input resulting in species-poor water communities. The case study area is delimited on the land side by the boundary of the base line. On the seaward side, the 12 nautical mile zone and the Exclusive Economic Zone (EEZ) form the border.

2.1.1 Marine uses

The German seas are shaped by diverse uses that are governed by the neighbouring federal states of Lower Saxony, Hamburg, Bremen, and Schleswig-Holstein (North Sea), and Schleswig-Holstein and Mecklenburg-Western Pomerania (Baltic Sea) (BLANO, 2018a, BLANO, 2018b). An overview of the twelve marine uses considered in this matrix application and their definitions can be found in Table 1. The spatial distribution of the marine uses is shown in Figure 1 (North Sea) and Figure 2 (Baltic Sea). The spatial uses of German marine waters are based on both natural conditions (e.g. water depth, sediment type) and administrative allocations (e.g. through spatial planning), thus overlap spatially and temporally. Since some of these uses are transboundary (e.g. military training areas, transnational submarine cables), a transitional area of 10 km beyond the EEZ and the base line was included.

2.1.2 Ecosystem services

The twelve marine uses are set in relation with five ES (whereof one provisioning ES (1), two regulating ES (2-3), two cultural ES (4-5)): 1) Provision of fish

Table 1. Description of the 12 marine uses under consideration. Their selection is based on Lange et al. (2010).

Marine Use	Description
Shipping	Transport of goods or people by means of different types of ships, predominantly, but not exclusively, on defined routes.
Platforms	Permanent construction in the sea for various purposes, e.g. transformer platform, research platform, oil platform, usually stationary.
Pipelines & submarine cables	Cables laid in the seabed for the purpose of cross-border electricity or data transmission, or pipelines for the purpose of transporting oil and gas.
Offshore wind turbines	Wind turbines permanently installed in the EEZ for electricity generation.
Sediment extraction	Extraction of sand and gravel for coastal protection measures, construction projects or industrial purposes.
Sediment placement	Dumping of sediments, e.g. dredged material; primarily in the coastal sea.
Military training areas	Restricted and warning areas that serve military use on, under and above water, e.g. for submarine travel, air combat exercises and firearms training.
Former munitions dumping areas	Areas where unusable ordnance and munitions waste have been dumped. Determining the exact location is problematic.
Coastal safeguarding	The totality of measures to protect the coasts (mainland, islands) from the destructive effects of the sea.
Tourism	Staying outside the usual working and living environment, e.g. for the purpose of day trips, short trips or holidays.
Fishery	Traditional form of exploitation in which fishery products are obtained. Only commercial fisheries are considered.
***Nature conservation areas**	Not a use in the narrower sense, but rather a guarantee of the claimed space, which has to be taken into account when being used by other marine uses. Therefore, marked with *.

Table 2. Description and categorisation in CICES of the five marine ES under consideration.

	Ecosystem service	Description	CICES 5.1
Provisioning ecosystem service	Provision of fish stocks	The provision of non-domesticated fish species and seafood caught for commercial purposes.	Wild animals (terrestrial and aquatic) used for nutritional purposes (Code 1.1.6.1) or for direct use or processing (excluding genetic materials) (Code 1.1.6.2).
Regulating and maintenance ecosystem service	Coastal protection	The regulation of water flow in coastal areas based on the physical characteristics of ecosystems that mitigate or prevent potential harm to human health and safety.	Hydrological cycle and water flow regulation (Including flood control, and coastal protection) (Code 2.2.1.3).
	Carbon fixation	Fixation of carbon in seagrass beds.	Regulation of chemical composition of atmosphere and oceans (Code 2.2.6.1).
Cultural ecosystem service	Recreation	The biophysical properties or qualities of species or ecosystems that are used or enjoyed in physical or cognitive ways (outdoor activities and tourism, including sports and recreation).	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions (Code 3.1.1.1) or through passive or observational interactions (3.1.1.2).
	Existence value	The biophysical properties or qualities of species or ecosystems (environments/landscapes/cultural areas) that people wish to preserve because of their non-utilitarian properties (beyond economic or human benefits).	Characteristics or features of living systems that have an existence value (Code 3.2.2.1) or an option or bequest value (Code 3.2.2.2).

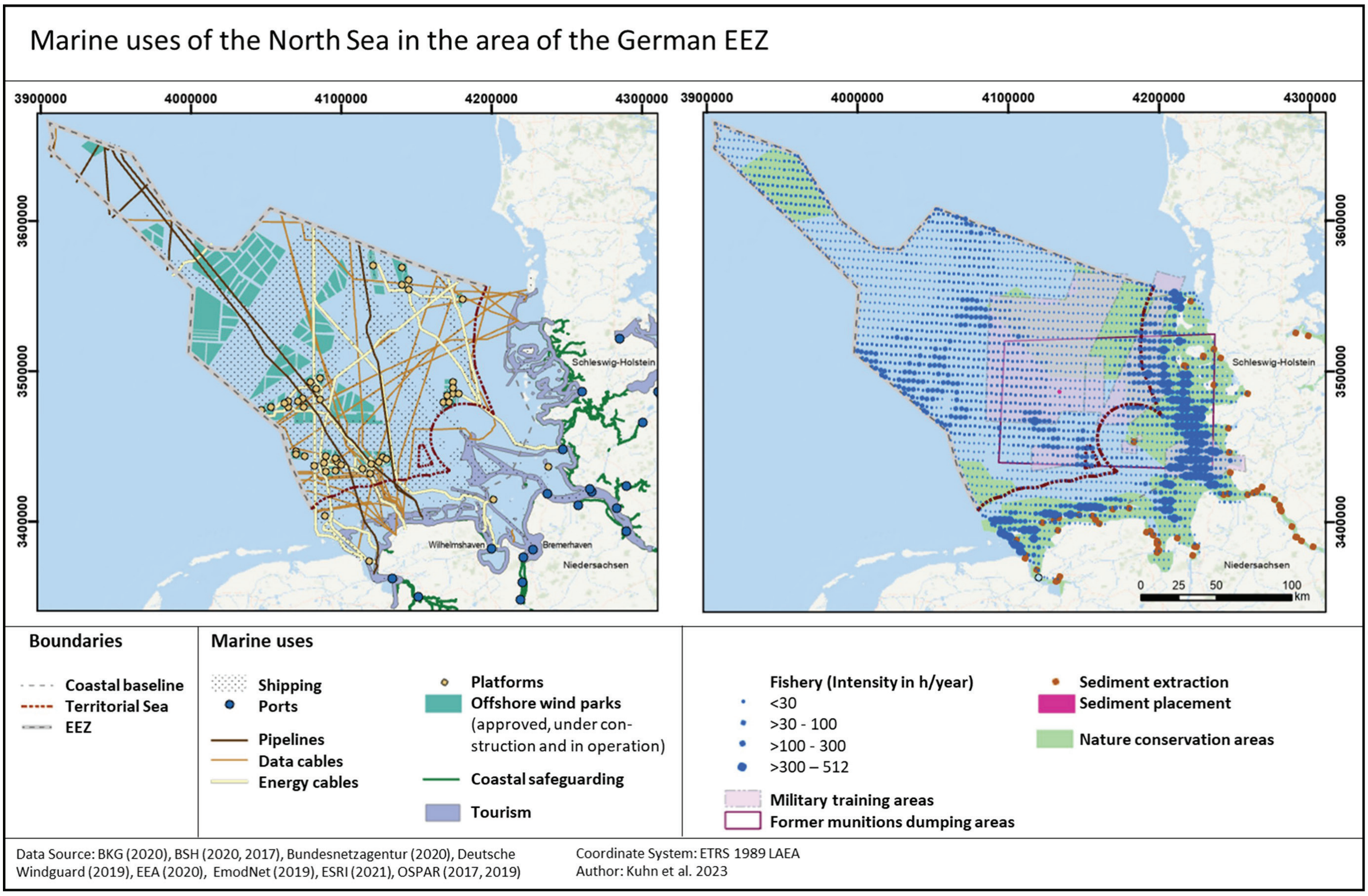


Figure 1. Marine uses in the German North Sea.

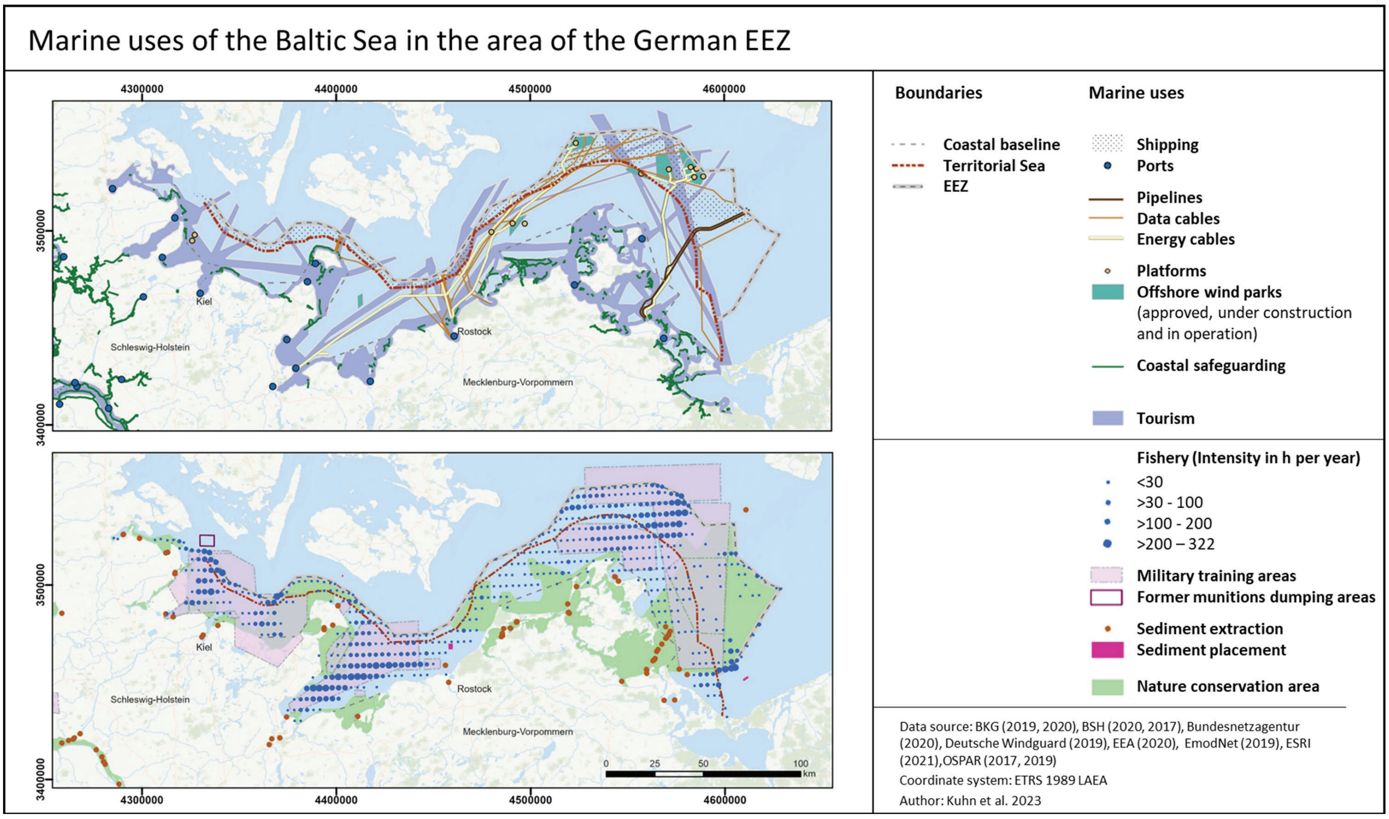


Figure 2. Marine uses in the German Baltic Sea.

("fisheries"); 2) Coastal protection; 3) Carbon fixation of sea grass meadows; 4) Recreation; 5) Existence value. Table 2 gives an overview of the ES and their assignment in the Common International Classification of Ecosystem Services (CICES 5.1) (Haines-Young and Potschin 2018). The choice of ES was predetermined by the project consortium.

2.2 Matrix approach

We developed an ES matrix to identify linkages between marine uses and the supply of ES in the German territorial waters and the EEZs of the North and Baltic Sea. To enhance the validity within the constraints of limited data availability, an integrated approach was employed, which incorporates expert-based and literature-based information. According to Roche and Campagne (2019), as well as Jacobs and Burkhard (2017), the values obtained with the help of expert-based evaluations tend to be qualitatively consistent with literature-based assessments.

The approach is based on a modification of the original ES matrix approach developed by Burkhard et al. (2009, 2012b, 2014) which describes the capacity of specific habitats, land cover types or other spatial units to supply ES. The geospatial units chosen for the assessment cover the areas occupied by current marine uses. Since seasonal aspects such as population fluctuations can have an impact on the supply of individual ES, all data are equivalent to an annual average. An empty matrix with the five ES as columns and the twelve marine uses as rows is used as the starting point (initial matrix) for both, the expert-based and the literature-based assessments. The value at each intersection indicates the ES capacity of a unit with the given marine use to supply an ES (see Table 3 for the description of values and colour schemes of the matrix). ES supply indicates the ES that are provided by the ecosystem irrespective from their actual use (Burkhard and Maes 2017). The assessment is made by assigning a value on an ordinal scale ranging from 0 (no supply) to 5 (very high/maximum supply). The colour assignment is used for the graphical representation and allows a quicker overview of the filled matrix. Additionally, a confidence value is given on an ordinal scale from 0 (no information available/ no statement possible) to 3 (high confidence). The confidence value indicates the certainty with which the value of the associated combination field was estimated. The whole matrix thus comprises 120 fields.

Table 3. Values and colour schemes of the ES matrix.

Ecosystem service value (0 - 5)		Colour assignment: Ecosystem services
5	Very high supply	4,5 - 5
4	High supply	3,5 - 4,4
3	Medium supply	2,5 - 3,4
2	Low supply	1,5 - 2,4
1	Very low supply	0,5 - 1,4
0	No supply	0,0 - 0,4
Confidence value (0 - 3)		**Colour assignment: Confidence value**
3	High confidence	2,5 - 3
2	Medium confidence	1,5 - 2,4
1	Low confidence	0,5 - 1,4
0	No statement possible	0 - 0,4

2.2.1 Literature searches

Literature-based ES value determination is the second most common method for matrix compilation, which is either based on already existing matrices or based on values derived from scientific and grey literature (Campagne et al. 2020). The literature-based matrix used in this study originates from a literature review of a set of publications identified by the authors based on their expert knowledge and forward snowballing. The available scientific and grey literature rarely establishes a direct link between a marine use and one of the ES under consideration. For example, the effect of a marine use on specific ecosystem structures and processes are described, but effects on the whole ecosystem or the supply of ES are usually not discussed. Therefore, a knowledge and/or value transfer is often required which is verified by using confidence values. A confidence value of 3 (high confidence) indicates a clear reference, a confidence value of 2 (medium confidence) indicates a transfer in the case of a clear information situation, and a confidence value of 1 (low confidence) indicates a patchy information situation. If no references could be found in the literature, the corresponding matrix fields remains empty. The sources are indicated for each row (see Tab. 5b).

2.2.2 Expert survey

The assessment through experts is considered a validated means to obtain scientifically sound results, especially for areas that have been insufficiently studied so far. This is advantageous for applications in the marine context. Expert knowledge represents a combination of subjective observations, objective sources of knowledge and mental models, and therefore particularly suitable for assessing and balancing between the tensions of complexity/ implicitness and accuracy/inaccuracy (Campagne and Roche 2018). The determination of values by experts followed the methods established by Campagne and Roche (2018). The expert survey was carried out online due to contact restrictions caused by the Corona pandemic in spring 2020. Online questionnaires have the advantage that they quickly reach a high number of experts at a comparatively low cost and effort.

The matrix was applied using the following four steps:

1. The initial matrix was designed as described in Section 2.2. A description of the intention of the approach and definitions of the study area, the marine uses and the ES according to CICES 5.1 (Haines-Young and Potschin 2018) was prepared.
2. The initially empty matrix was embedded in an online questionnaire, created according to the quality requirements for objectivity, reliability and validity by Moosbrugger and Kelava (2012) and Döring and Bortz (2016). The partially standardised questionnaire consisted of closed, semi-open and open questions that cover both factual information and opinions. The first four items of the questionnaire recorded information on socio-demographic (closed question) and professional background (semi-open questions), the following two items took note on the participant's familiarity with the ES approach in general and the ES matrix approach in particular. A four-point Likert scale, bypassing the neutral mean, was chosen for the response options. Item 7 was the empty initial matrix with 60 fields indicating the manifold relationships of marine uses and the supply of ES (matrix value M) and 60 fields for the corresponding confidence value (C). Item 8 recorded comments and criticism to be made by the participants via an open question.
3. Due to the selectivity of the group of experts, active sampling was chosen. Access information to the online questionnaire was emailed to selected experts based on pre-existing contacts to members of the project consortium. The experts were chosen based on their affiliation to the project as well as their professional affiliation with marine ecosystems or ES. In total, the questionnaire was emailed to 51 addresses, including three email distribution lists. Following the snowball procedure, the experts were asked to distribute the questionnaire to other suitable experts (Döring and Bortz 2016).
4. In a fourth step, the results of the survey were evaluated. The answers to items 1 to 6 and item 8 were listed and summarised. For item 7, the matrix, the weighted average (x_w) was calculated using Equation 1.

$$x_w = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} = \frac{w_1 x_1 + \cdots + w_n x_n}{w_1 + \cdots + w_n}$$

Equation 1. x_w, the weighted average of the matrix values is calculated based on the individual matrix values (x_i) and the confidence level (w_i) that weights them.

2.2.3 Matrix combination

To obtain the final matrix, the expert matrix and the literature-based matrix were combined. Following the recommendations of Burdon et al. (2017), we adapted a set of combination rules to calculate the

Table 4. Combination rules to obtain the final matrix values from the literature and expert matrix.

Combination rules	Literature matrix		Expert matrix		Combined matrix	
	M_{lit}	C_{lit}	M_{exp}	C_{exp}	$M_{combined}$	$C_{combined}$
Given the same confidence value (C_{lit}=C_{exp}), values of the combination fields are combined in equal parts.	1,5	2	3	2	2,3	2
Given the matrix value is equal, but the confidence values differ, their arithmetic mean is calculated.	2	2	2	3	2	2,5
	4,8	2	5	2,8	4,9	2,4
If only one value is available, it is taken over to the combined matrix.	-	-	1,4	2,5	1,4	2,5

individual and confidence values for the final matrix (Tab. 4). $M_{combined}$ was calculated from the ES values of the input matrices (M_{lit}, M_{exp}). $C_{combined}$, the confidence value used for weighting, was calculated from the confidence values C_{lit} and C_{exp}. The combined matrix led to the values rounded up to one decimal place.

2.2.4 Map compilation

The combined matrix was adapted for the application in ArcGis Pro 3.0 to present the information in a map format. Based on the allocation of the 12 marine uses (see Fig. 1 & 2) and the information provided by the combined matrix, maps of the spatial distribution of the ES supply were generated. Due to multiple spatial overlaps of marine uses in the case study area, the highest ES supply at the areas of overlapping uses is indicated in the maps. The fishery intensity that is indicated in Figure 1 and 2 is not included in the ES assessment.

3 Results

3.1 Expert-based matrix

Altogether 33 people initiated to participate in the survey. 13 persons fully and another three sufficiently completed the matrix. For a sufficient degree of validity, it is necessary that at least ten, preferably 15 to 20 experts participate in the value determination (Campagne et al. 2017). The comparison of the knowledge levels between those who only insufficiently filled in the survey (17 participants) and those who completed the matrix (16 participants) reveals the differences in their knowledge concerning the ES concept and the ES matrix approach. This might explain the relative high number of uncompleted surveys. The 16 people who completed the survey and filled in the matrix were considered the experts. 87.5% of experts indicated very good (56.25%) or good (31.25%) knowledge, while the remaining experts were familiar with the ES concept. Concerning the ES matrix, 81.25% of experts had a very good (12.5%), a good (42.75) or a basic understanding (25%) of the matrix approach. 18,75% had no previous experience with the ES matrix approach linking geospatial units and ES supply. Of the 16 respondents, respectively three (18.75%) work in geography and economics, two (12.5%) work in biology and two are employed in the field of ecology (landscape ecology, marine ecology), one person (6.25%) works in conservation. One respondent (6.25%) did not indicate his or her profession, and four (25%) of the respondents consider themselves to be active in other disciplines.

The expert-based matrix (see Table 5a) indicates no (0-0.4) or only a very low (0.5-1.4) to low capacity (1.5-2.4) to supply the selected ES for almost three-quarters (47/60) of all the combination fields. A medium capacity (2.5-3.4) was assessed for seven combination fields, and a high (3.5-4.4) or very high capacity (4.5-5) for three fields each. For the matrix value of the ES, in addition to the weighted arithmetic mean, the standard deviation (σ) was calculated. If the standard deviation of the assessment of the ES is $\sigma \geq 1.5$, the value is highlighted in red in the matrix. For the confidence values, the arithmetic means were calculated. Overall, the experts awarded their evaluations with a high level of confidence. The arithmetic means of the confidence values are between 1.8 and 2.8. An especially high consensus can be found among the experts for the ES recreation (no combination field with $\sigma \geq 1.5$).

3.2 Literature-based matrix

Table 5b shows the results of the literature-based matrix. The matrix is based on published peer-reviewed scientific journal articles and grey literature such as project reports or governmental publications. 48 fields and the corresponding confidence values were filled based on the literature review. For the remaining fields, no information was found in the literature. For 17 out of the 48 filled fields, ES supply under the given marine use was identified. A very low supply was assessed for ten fields, and low supply for three fields. Medium and high supply was expected for seven fields each and a very high provision for three combination fields. With regard to the type of use, little information could be found on sediment placement and military training areas, while a more extensive knowledge base was available specifically for nature conservation areas.

Table 5. **a)** Expert-based ES matrix (red fields: standard deviation ≥ 1.5); **b)** Literature-based ES matrix including references; **c)** Combined ES matrix. *Nature conservation areas do not depict a marine use in the classical meaning, but rather claim space not to be used, respectively to be used under specific conditions (see Table 1).

a) Expert-based matrix

Ecosystem services / Marine uses	Provision of fish stocks	Confidence value	Coastal protection	Confidence value	Carbon fixation	Confidence value	Recreation	Confidence value	Existence value	Confidence value
Shipping	1.4	2.5	0.4	2.7	1.3	2.3	1.9	2.5	1.4	2.4
Platforms	1.5	2.0	0.4	2.4	0.9	2.3	0.5	2.5	2.5	1.7
Pipelines & submarine cables	1.0	1.9	0.2	2.4	0.6	2.4	0.5	2.5	1.7	1.7
Offshore wind turbines	2.2	2.2	0.3	2.1	1.1	2.6	0.5	2.5	2.6	2,0
Sediment extraction	0.8	2.3	1.0	2.5	0.4	2.4	0.5	2.5	0.5	2.5
Sediment placement	0.6	2.2	2.7	2.2	0.8	2.0	1.2	2.3	1.2	2.0
Military training areas	1.1	2.2	0.3	2.3	1.3	2.1	0.2	2.5	1.5	2.0
Former munitions dumping areas	1.6	2.2	0.2	2.2	1.3	2.1	0.6	2.5	1.4	2.1
Coastal safeguarding	2.0	1.8	4.6	2.4	2.4	1.9	3.6	2.5	2.5	2.2
Tourism	1.4	2.3	1.8	2.3	0.9	2.1	4.7	2.5	1.7	2.2
Fishery	3.2	2.2	0.8	2.4	1.4	2.1	2.0	2.2	1.4	2.2
*Nature conservation areas	4.2	2.7	2.8	2.4	3.9	2.2	3.2	2.3	4.8	2.8

b) Literature-based matrix

Ecosystem services / Marine uses	Provision of fish stocks	Confidence value	Coastal protection	Confidence value	Carbon fixation	Confidence value	Recreation	Confidence value	Existence value	Confidence value	References
Shipping	1	1			1	2	1	1	2	1	[1], [2], [3]
Platforms	3	2	0	2	1	1	4	2	3	2	[1], [4]
Pipelines & submarine cables	2	1	0	2	1	1	1	1	0	1	[1], [4]
Offshore wind turbines	3	3	0	3	1	3	4	3	3	3	[3], [4], [5]
Sediment extraction	0	1	5	2	0	2	0	2			[3], [6], [7], [8]
Sediment placement			1	2							[9]
Military training areas	1	1									[2]
Former munitions dumping areas	0	2	0	2	0	2	0	2	0	2	[1], [10], [11]
Coastal safeguarding			3	2	2	1			3	1	[1], [6], [7], [12]
Tourism	0	1	1	1	2	1	4	1	4	1	[2], [3], [13]
Fishery	0	2	0	1	0	1	3	2	0	2	[1], [2], [3], [13], [14]
*Nature conservation areas	4	2	4	2	4	2	5	2	5	2	[15], [16], [17]

[1] de los Santos et al. 2019, [2] EEA 2019, [3] Rodrigues et al. 2017, [4] Vogel et al. 2018, [5] Gimpel et al. 2020, [6] ML-NDS 2017, [7] Ahlhorn and Meyerdirks 2017, [8] EEA 2020, [9] Kortekaas et al. 2010, [10] HELCOM 2013, [11] Böttcher et al. 2011, [12] NLWKN 2007, [13] Hasler et al. 2016, [14] Schmücker and Schmüdderich 2010, [15] BfN 2020b, [16] BfN 2017, [17] Schirpke et al. 2014

c) Combined matrix

Ecosystem services / Marine uses	Provision of fish stocks	Confidence value	Coastal protection	Confidence value	Carbon fixation	Confidence value	Recreation	Confidence value	Existence value	Confidence value	Value range
Shipping	1.3	1.8	0.4	2.7	1.2	2.2	1.6	1.8	1.6	1.7	1.2
Platforms	2.3	2.0	0.2	2.2	0.9	1.7	2.1	2.3	2.8	1.9	2.6
Pipelines & submarine cables	1.3	1.5	0.1	2.2	0.7	1.7	0.6	1.8	1.1	1.4	1.2
Offshore wind turbines	2.7	2.6	0.1	2.6	1.0	2.8	2.4	2.8	2.8	2.5	2.7
Sediment extraction	0.6	1.7	2.8	2.3	0.2	2.2	0.3	2.3	0.5	2,5	2.6
Sediment placement	0.6	2.2	1.9	2.1	0.8	2.0	1.2	2.3	1.2	2.0	1.3
Military training areas	1.1	1.6	0.3	2.3	1.3	2.1	0.2	2.5	1.5	2.0	1.3
Former munitions dumping areas	0.8	2.1	0.1	2.1	0.7	2.1	0.3	2.3	0.7	2.1	0.7
Coastal safeguarding	2.0	1.8	3.9	2.2	2.4	1.5	3.6	2.5	2.7	1.6	2.0
Tourism	1,0	1.7	1.6	1.7	1.3	1.6	4.5	1.8	2.4	1.6	3.5
Fishery	1.7	2.1	0.6	1.7	0.9	1.6	2.5	2.1	0.7	2.1	1.9
*Nature conservation areas	4.1	2.4	3.3	2.2	3.9	2.1	4.0	2.2	4.9	2.4	1.6
Value range	3.5		3.9		3.7		4.3		4.4		

Only one scientific publication was found that established a direct link between marine uses and ES supply. Vogel et al. (2018) analysed the relationships between marine ES supply and the energy industry sector in the North Sea. Based on their research it was possible to assess ES supply in relation to the marine uses “offshore wind turbines” with a high confidence (confidence value 3). Furthermore, for the marine uses “pipelines and submarine cables”, the ES supply could be derived with medium confidence (confidence value 2), as well as for the use “platforms” with low confidence (confidence value 1). For the marine uses “platforms, pipelines and submarine cables, former munitions dumping areas, tourism, fisheries” and for the “areas of nature reserves”, it was possible to infer a link to the supply of all five ES based on other publications, while for the other uses there was at least partially no evidence linking the marine uses to the supply of ES. The available derivations were classified with medium or low confidence, as no proven direct link could be found between the use and the provision of the ES. Often reverse conclusions were drawn based on the negative influence of a marine use on ES supply. For example, de los Santos et al. (2019) were able to show in a study on the decline of seagrass meadows that the construction of harbours and the removal of sediment have a negative impact on seagrass meadows that provide carbon fixation.

The information derived from Rodrigues et al. (2017) can be referred to as an example for the derivation. The authors reviewed literature on cultural marine and coastal ES. They indicate that tourism often takes place in particularly attractive places and that healthy ecosystems often serve as inspiration and opportunity for cultural experience (education, sense of existence). Based on these observations, it was derived that tourism is related to the ES recreation and existence value. As this connection requires a certain degree of interpretation, the respective value was assigned with a low confidence (confidence value 1).

3.3 Combined matrix and cartographic representation

The values of the expert-based matrix (see Section 3.1) and the literature-based matrix (see Section 3.2) were combined (Table 5c) according to the methodology described in Section 2.2. The observations made by Roche and Campagne (2019) and Jacobs and Burkhard (2017) can be mostly confirmed: the values determined by the experts are essentially consistent with the literature-based values. For 28 out of 48 fields (58,3%), the deviation in assessment is less than 1, resulting in no inevitable change of the matrix score. For an additional 15 fields (31,3%), the deviation in assessment is less than 2. In this case the matrix score changes by at least one category. Four combination fields (8,3%) stand out. The assessment of the combination field fishery (marine use) and the provision of fish stocks (ES) differs by the value of 3.2. The experts assessed a value of 3.2, while the literature values indicate no ES supply (value 0). The combination field coastal safeguarding (marine use) and sediment extraction (ES) shows the highest deviation with a value of 4. The experts provided a value of 1, while the literature matrix indicates a value of 5. The values for the combination fields between the marine uses platforms as well as offshore wind turbines and recreation (ES) both differ by the value of 3.5. The experts provided a value of 0.5 in each case, while the literature matrix indicates a value of 4.

Out of the 60 matrix fields, ten (16.7%) exhibit no capacity to supply ES under the given marine use. Twenty-four fields (40.0%) indicate a very low capacity (0.5-1.4), and thirteen fields (21.7%) indicate low capacity (1.5-2.4). Medium capacity (2.5-3.4) is indicated for seven fields (11.7%). High capacity (3.5-4.4) is indicated for five fields (8.3%) and a very high capacity (4.5-5) is indicated for one field (1.7%). The range of confidence values is between 1.4 and 2.8, which is substantially higher compared to the expert matrix. The highest confidence values are given for offshore wind turbines and range from 2.5 to 2.8. The lowest confidence values are given for tourism (1.6 - 1.8).

Every marine area examined offers at least one of the analysed ES to a low degree. In 55.4% of the marine territory, one or more of the assessed ES are provided to a very high degree. The highest provision of the respective ES could be identified in nature conservation areas. A very high supply of the ES recreation is indicated for areas of touristic use.

Furthermore, high ES supply was expected in areas characterised by coastal safeguarding. The lowest supply of the studied ES occurred in areas of the former munitions dumping areas and the military training areas as well as along the corridors of pipelines and submarine cables. These areas of very low capacity were mostly further away from the coast and with infrastructure like offshore wind turbines.

Assessing the range of values of marine use, we see that the lowest deviations are found in the areas of former munition disposal (0.7). The highest deviation is present in the areas of tourism (3.5). For the other marine uses the values range between 1.2 (shipping; pipelines and submarine cables) and 2.7 (offshore wind turbines). Furthermore, for each individual ES, a high deviation of the values can be seen. Here, the differences range from 3.5 (provision of fish stocks) to 4.4 (existence value). This means that the supply of the ES can differ greatly depending on the use of the area in which it is provided. Overall, a very low to medium supply is predominantly reported for the ES supply of fish stocks. However, since a high supply was expected in nature conservation areas, the value is 3.5. While for most uses no supply of coastal protection is indicated, the ES is supplied to a medium to high degree in areas assigned to coastal safeguarding, sediment extraction and nature conservation areas. Concerning the ES carbon fixation, the supply was assumed to be very low in almost all marine use areas, except for nature conservation areas. The ES recreation and existence value hold the greatest range of supply between the different marine use areas.

The map compilation was based on the values of the final ES matrix and the geospatial units, represented by the 12 marine uses (see Fig. 1-2). Five maps (Fig. 3) illustrate the ES supply of the five ES in the German North and Baltic Sea territorial waters and the EEZs.

3.3.1 Provision of fish stocks

The ES provision of fish is present throughout the study area. In the case study region, fishing quotas

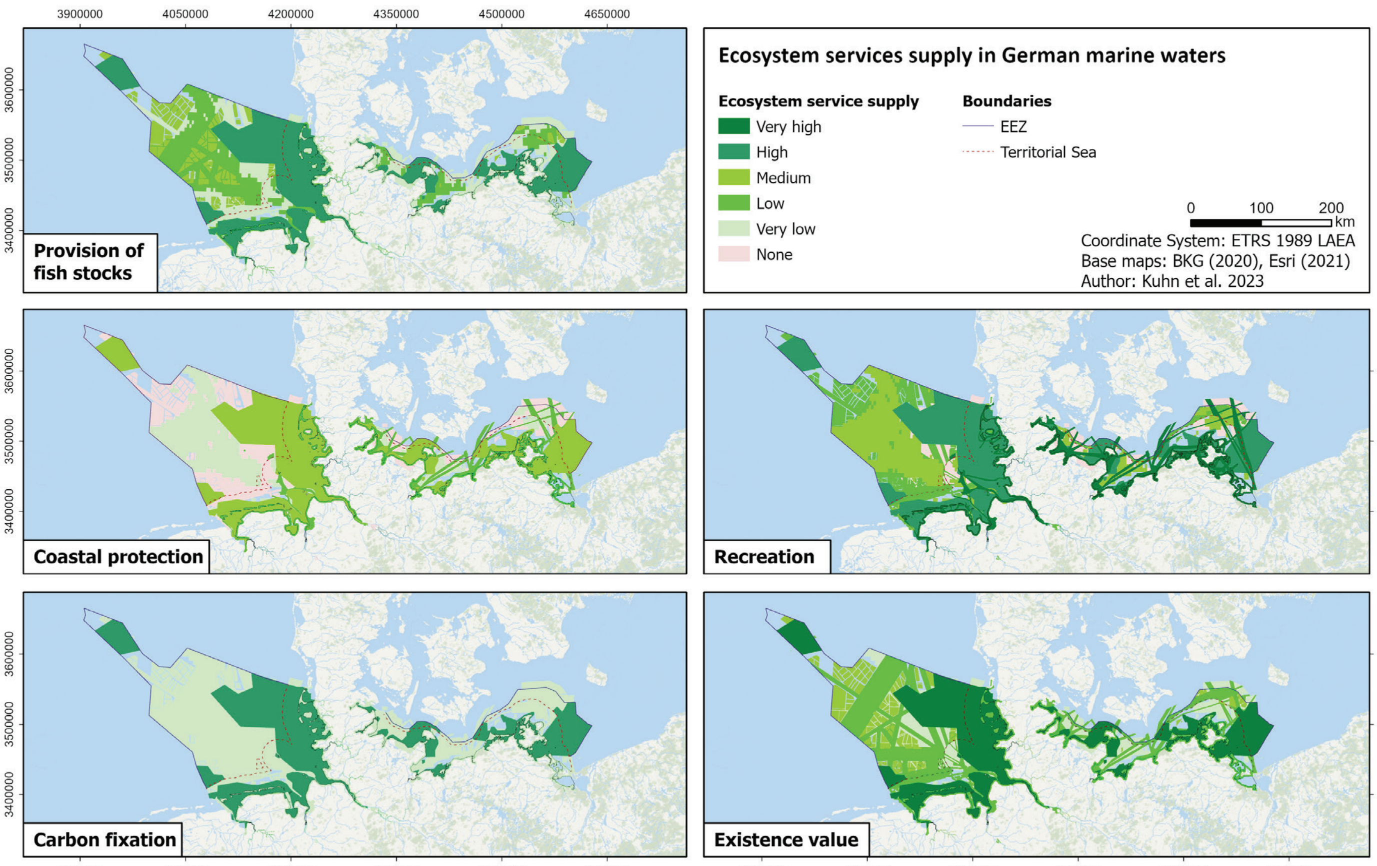


Figure 3. Maps of ES supply in the German North and Baltic Sea EEZs.

are established to regulate fishing. As commercial fishing is in principle allowed in all German territorial waters and the EZZ, no specific areas are designated for fishing in the marine spatial development plans and fishing interests have to be taken into consideration by other potentially opposing forms of use (AWZ Nordsee-ROV 2009, AWZ Ostsee-ROV 2009). While a very high provision of fish does not occur in the case study area, a high supply of the ES occurs in the nature conservation areas (approximately 2.7 million ha). A medium supply was assumed to occur in areas used for wind energy (approximately 610,000 ha). Low provision occurs in areas designated to fisheries, platforms, and coastal safeguarding (together about 2.6 million ha). For the remaining areas, a very low capacity to supply fish was expected (approximately 6.5 million ha in total). A high provision of fish occurs in about 5.99 million ha of the German marine waters (48.6%). This corresponds to 49.9% (about 4.5 million ha) of the North Sea and 45.1% (about 1.5 million ha) of the Baltic Sea. At least a very low provision of fish occurs on nearly 10 million ha of the German seas (81.8%). This corresponds to 79.1% of the North Sea (about 7.2 million ha) and 89.3% (about 2.9 million ha) of the Baltic Sea.

3.3.2 Coastal protection

No supply of coastal protection ES occurs in areas predominantly used for shipping, platforms, offshore wind turbines, pipelines and submarine cables, military training areas, and former munitions dumping areas (together about 5.6 million ha). A very low capacity occurs in fishing areas (2.5 million ha), while a low supply occurs in tourism and sediment placement areas. Medium supply occurs in nature conservation areas (2.7 million ha) and a high supply occurs in areas of marine use coastal safeguarding (about 72,000 ha).

At least a very low supply occurs in 53.8% (6.63 million ha) of the study area. 63.8% (5.8 million ha) of the North Sea and 26% (840,000 ha) of the Baltic Sea supply coastal protection. On large parts, however, the supply is significantly higher. In 50.3% (6.19 million ha) of the area of German marine uses, recreation is supplied at least to a high degree. Of this, about 4.7 million ha are in the North Sea (51.8%) and about 1.5 million ha in the Baltic Sea (46%).

3.3.3 Carbon fixation

Seagrass meadows are among the world's most significant carbon sinks, sequestering about 10-18% of the total fixed carbon annually in just under 0.1% of seafloor area (Fourqurean et al. 2012, Greiner et al. 2013). As European seagrass habitats are declining by 10% per decade due to anthropogenic stress, which leads to the release of stored carbon, these ecosystems are highly dependent on special consideration and protection (de los Santos et al. 2019, IPBES 2019). Apart from coastal protection, seagrass meadows supply numerous other ES like pH regulation, nutrient cycling, pollutant regulation, sediment retention, food for organisms, food web dynamics, habitat provision, resilience maintenance, and biodiversity enhancement (Geange et al. 2019, Heckwolf et al. 2021). For our study area, a high level of carbon fixation occurs on 50.3% of the area occupied by the marine uses (6.2 million ha). Of this, about 4.7 million ha are areas occupied by marine uses in the North Sea (51.8%) and just under 1.5 million ha in the Baltic Sea (46.2%). For the fixation of carbon, areas of nature conservation (2.7 million ha) are the most significant. Throughout the study area, at least a very low level of carbon fixation is expected (11.8 million ha, 95.6%). Proportionally, this corresponds to 96.5% of the study areas of the North Sea and 93.2% of the utilisation areas of the Baltic Sea. Exceptions are areas of coastal safeguarding (low provision, about 72,000 ha) and sediment extraction (no provision, about 460 ha).

3.3.4 Recreation

For the ES recreation, a very diverse capacity to supply ES is present throughout the study area. The areas of tourism activities supply these ES to a very high extent (about 1.37 million ha). Furthermore, nature conservation areas (about 2.7 million ha) and coastal safeguarding areas (about 72,000 ha) allow recreation to a high degree. The fishing areas have a medium potential for the ES recreation (about 2.5 million ha). Areas predominantly used for shipping, platforms, and wind energy, on the other hand, were rated with a low supply (about 2.5 million ha). A very low supply occurs along pipeline and submarine cable corridors, as well as in areas of sediment placement (approximately 50,000 ha combined). Areas of sediment extraction and areas of military exercises and former munitions dumping do not supply the ES recreation (about 3 million ha).

In total, at least a low supply of recreation ES occurs in 43.3% of the marine areas occupied by marine uses. This corresponds to about 5.3 million ha, of which about 4.78 million ha are in the North Sea (51.1%) and about 1.52 million ha in the Baltic Sea (21.4%). In 51.1% (6.3 million ha) of the study area, recreation is supplied at least to a high degree. This corresponds to approximately 52.7% (4.78 million ha) of the North Sea and 46.9% (1.52 million ha) in the Baltic Sea. In 22% of the used area of the German sea (approx. 2.7 million ha) a very high supply of recreation ES takes place. Of this, about 938,000 ha (10.3%) are in the North Sea and about 1.77 million ha (54.7%) in the Baltic Sea.

3.3.5 Existence value

In this study, the existence value is understood to be the value of nature and species per se, over and above economic or human benefits. It is supplied across the entire study area. A very low supply of this ES occurs in areas of former munitions dumping areas, fisheries, sediment extraction and placement as well as pipelines and submarine cables (in total approx. 4.2 million ha). A low level of supply is assumed for the areas of shipping, military training areas and tourism (approx. 5 million ha). Medium supply takes place in areas of offshore wind turbines and platforms as well as in areas of coastal safeguarding (approx. 700,000 ha in total). Very high supply takes place in nature conservation areas (approx. 2.7 million ha).

In total, 77.1% of the area of marine uses, corresponding to approximately 9.5 million ha, have at least a very low existence value. This corresponds to 82.7% of the North Sea (7.5 million ha) and 61.6% (1.99 million ha) of the Baltic Sea. A very high supply takes place on 6.2 million ha (50.3%) of the areas of marine uses, of which about. 4.7 million ha (51.8%) are in the North Sea and approximately 1.5 million ha (46%) in the Baltic Sea.

4 Discussion

The primary aim of this study was to link marine uses to ES supply, applying an ES matrix approach. Throughout our work, we showed the relationship of 12 selected marine uses and the spatial distribution of the supply of five ES. Marine areas of anthropogenic uses were established as spatial units equivalent to land use classes in a terrestrial setting. This approach fosters a direct link between human activities and the ES they impact. The study stands as an initial effort to map ES in the German North and Baltic Sea. The fusion of expert and literature-based information emerged as a valuable method, capable of working with limited data, while enhancing and validating the results through diversification. Confidence scores were added to reflect on the certainty of the available evidence and demonstrate the reliability of the individual scores (Campagne et al. 2017).

4.1 Marine ecosystem services supply in the German Baltic and North Sea EEZs

Our approach showed that the individual marine uses have an influence on the spatial distribution of the supply of the individual ES. Up until now, research concerning the interrelations between uses and the supply of ES in the marine context is insufficient. With regard to the case study area, Vogel et al. (2018) demonstrated the links of 23 ES to seven offshore energy sources in the wider North Sea region. The results reveal clear positive and negative interactions within the studied linkages. Potts et al. (2014) described the links between the supply of ES and the ecosystem components found within nature reserves, suggesting there are links between the types of use and the ES supply.

Each of the investigated areas of marine use supplies at least one of the considered ES at a low level. Between the different areas of marine use, the ES recreation and existence value display the greatest supply range. Our results suggest that nature conservation areas typically exhibit the highest ES supply. Areas of coastal safeguarding and tourism identified rather high supply values. In areas of sediment extraction and placement, pipeline and submarine cable corridors, areas with military exercise activities as well as the former munitions dumping areas, a rather low supply of the studied ES was found. Offshore wind turbines and platforms present a medium supply, potentially serving as an island function, comparable to flowering strips in agricultural landscapes.

The analysis indicates that, in comparison to the Baltic Sea, marine use areas in the North Sea demonstrate a higher ES supply in terms of fish stock provision, coastal protection, carbon fixation, and existence value. However, for recreation, the distribution shows the opposite trend. Here, the proportion of areas with very high supply potential is just under 10% in the North Sea, whereas in the Baltic Sea it is over 50%. This suggests that the Baltic Sea, associated with nature reserves, iconic landscapes, recreation, and typical animal and plant species, tends to be assigned a potentially higher supply of recreational ES. As a result, the landscape possesses increased recreational potential, which reflects the capacity of nature to contribute to human recreation and health through its psychological and physical effects, a value intrinsically tied to the characteristics of the landscape (Grunewald and Bastian 2013). Such recreational activities encompass tourism, sports, and activities in coastal areas like sunbathing, swimming, diving, as well as deeper water regions such as sailing and recreational fishing (Liquete et al. 2013, Hermes et al. 2018).

The case study region is characterised by an intense concentration of human activities. The twelve marine uses we examined represent only a subset, excluding activities such as aquaculture and wave-based renewable energy. Despite this, given the extensive overlap of marine uses in the case study region (Fig. 1 and 2), the need for space roughly doubles the available area. The availability of space is crucial, particularly for marine transport and shipping, as well as the positioning of wind power stations. Yet, like other abiotic structures and processes within ecosystems, current classifications do not explicitly identify space availability as an ES (van der Meulen et al. 2016).

4.2 Adopting marine uses as spatial units for the ES matrix approach

Previous research in the marine realm has primarily focused on benthic habitats as service-providing units (e.g. Galparsoro et al. 2014, Depellegrin et al. 2017, Culhane et al. 2018) or studied the interrelation between specific species and ES supply (Burdon et al. 2017). The approach presented here, with its emphasis on marine uses, highlights the impact of human interactions and societal needs on the supply of marine ES. It acknowledges the influence of human activities on ecosystems, underlining the dependencies between human action and the environment. The combined matrix draws mainly on expert knowledge and grey literature, with little evidence available from peer-reviewed scientific publications. Given the limited number of publications explicitly documenting ES supply in marine use areas, almost all the values in the literature matrix are based on interpretation, introducing a certain degree of subjectivity. Confidence values are assigned to explain the level of deduction. Despite an extensive body of literature on individual ES, the connection to marine uses has rarely been made. The prevalence of medium to low confidence values illustrates this situation.

The results established in the matrices before combination mainly corroborate the findings of Roche and Campagne (2019) and Jacobs and Burkhard (2017) that the expert matrix's values are compatible with the literature-based values. In the context of limited data availability, expert evaluations are an important aspect to support assessments where no scientific evidence is available. The combination of the expert and literature-based matrixes therefore depicts a valuable tool also for marine assessments. The discrepancy between the scoring of literature and expert opinion differs especially for four matrix field combinations (platforms-recreation; offshore wind turbines-recreation; sediment extraction-coastal protection; fishery-provision of fish stocks) and the respective reasons are likely multifaceted. One point might be that literature and expert knowledge address different scopes and levels of complexity. Expert knowledge encapsulates a broader spectrum of real-world experience, thus offering a multifaceted perspective, which may not always be reflected within academic literature. This expertise might also provide a more site-specific reflection. Furthermore, expert opinions can provide qualitative, experiential insights, which may diverge significantly from quantitative measures rather presented in the literature.

Also, there is a potential bias in the literature due to the prevalence of certain topics or specific aspects of the impact of marine uses on ES supply.

However, it is worth noting that despite the limitations encountered in this study, the approach holds promise for the application of case studies with high data resolution and accuracy as well as a pre-tested combinations of marine uses and ES. The confidence scores of the matrices can provide indications for the robustness of statements as well as the level of understanding the spatial dynamics and interactions between marine uses and the supply of ES. By employing marine uses as spatial units, the identification of trade-offs and synergies between different uses and their associated ES becomes possible. This spatially explicit analysis allows for the quantification and visualisation of overlapping or conflicting ES demands, which can be valuable for targeted management and decision making.

4.3 Limitations of the methodological approach

4.3.1 Uncertainties

A critical perspective is necessary when evaluating the validity and accuracy of the results concerning the assessed ES supply. The Baltic Sea and the North Sea exhibit distinct ecological characteristics, resulting from variations in environmental factors, nutrient inputs, salinity gradients, and species composition. The Baltic Sea, characterised by brackish water and lower species diversity, contrasts with the North Sea's greater biodiversity. Consequently, the implications for fishing practices, including target species, fishing methods, and management strategies, differ significantly between these two regions. Therefore, caution should be exercised when directly comparing the findings of both regions as their divergent natural conditions introduce notable variations in ecosystem dynamics and the associated supply of ES, especially for fisheries and the existence value.

Also, there are limitations to interpreting the findings of the remaining ES, carbon fixation, coastal protection, and recreation. The ES maps are based solely on the spatial distribution of marine uses, without considering specific habitats such as seagrass meadows. Therefore, it is essential to acknowledge that certain areas might not support seagrass beds, due to factors like water depths or other unsuitable conditions. Nevertheless, it is important to account for the discrepancy between the mapped carbon fixation and the actual presence of seagrass beds when interpreting the extent and impact of carbon sequestration in these regions.

Similarly, the assessment of the ES recreation should be approached critically. While the maps may indicate high levels of recreation in nature conservation areas, it is important to recognise that offshore locations, although showing recreational potential, might be challenging to access. Therefore, the practicality and feasibility of recreational activities in these areas should be thoroughly evaluated to understand the true extent and feasibility of this service.

Furthermore, the mapping of the ES coastal protection may present some limitations. The contrasting natural conditions between the North Sea and the Baltic Sea result in coastal protection being of significantly greater importance in the North Sea, where features such as dunes and coastal vegetation, including salt marshes, effectively reduce wave runup, mitigate erosion, and promote sediment deposition. The spatial distribution of the ES coastal protection appears to be contradictory in the maps (Fig. 3). Medium levels of coastal protection indicated far from the coast, such as at the Doggerbank, may raise questions regarding the actual impact of coastal protection in such remote areas. The distance from the coastline and the absence of significant coastal features may suggest that coastal protection effects are unlikely to occur in these particular regions.

These examples underscore the need to critically assess and interpret the spatial distribution of the ES supply as discrepancies between mapped values and actual presence are likely. In practice, this approach showed that the incorporation of an entire marine area does not yield accurate results for the assessment of the ES coastal protection. Hence, future studies should consider incorporating higher-resolution input data or supplementary information layers, such as habitat data, to enhance the precision of the assessment.

4.3.2 Specifics to the marine environment

The quantification of ES supply in terrestrial contexts, based on land use classes, represents a generalisation (Ellis and Ramankutty 2008). Due to the three-dimensional nature and the high interconnectivity of the water body, the degree of simplification is further increased in the marine context. The inherent complexity of marine ecosystems, for example the seasonal movements of specific fish species and the temporary exclusion of fishing in certain areas, presents a challenge for accurately capturing data. Marine uses are determined by both natural conditions (e.g. water depth, sediment type) and administrative allocations (e.g., through spatial planning, EEZ delineation). While spatial overlaps are inherent for marine systems, there may also be a mismatch between areas where ES are provided and where they are utilised (Drakou et al. 2017b). The lack of clear spatial delineation in the marine context impedes the differentiation and therefore the comparative assessment for specific marine uses (e.g. sediment extraction), depending on their specific location such as nearshore versus offshore.

Another relevant specification of marine environments is the temporal dimension (Fernandez et al. 2017). Within a time sequence of a few hours, the same hectare of sea can provide several forms of use. Also, seasonal impacts and differences should not be neglected in marine ecosystems, e.g. location of spawning, mating and hunting grounds of specific fish populations throughout the year. For a large part of the uses, this temporal dimension can be captured well, e.g. for shipping, fishing (intensity by h) or offshore wind energy (area data and information on regular maintenance by operators). For other uses, however, this information is insufficient or not publicly available (e.g. deployment and exercise plan of the German Navy). Due to the level of generalisation needed for the application of the ES matrix under the given circumstances, no specific point in time for the assessment was chosen. For future studies, however, we recommend handling this differently.

The great temporal and spatial diversity exhibited by marine ecosystems often results in limited data availability. For instance, datasets for fishery activities are typically limited to key species, such as cod and herring (Teal 2011, Kruse and Kruse 2018). Even though the Baltic Sea and North Sea are recognised as well-studied marine environments (Emeis et al. 2015), the availability of data concerning the study area ranges from very good to poor, depending on the type of use. Especially regarding the military exercise areas and the munitions dumping areas, knowledge gaps exist that hold a higher level of uncertainty and limit the analysis. The spatial delineation of marine use areas also includes uncertainties as the extensions of and borders between the different uses are not always as clear as they appear in maps or geographic information systems. The accessibility and quality of data may present complications for the approach, particularly for less-explored marine uses or specific services.

The specific natural conditions caused by the spatial and temporal overlap of the marine subsystems (e.g. sea floor, water column, water surface) pose difficulties concerning the analysis and cartographical representation. Two-dimensional static maps do not always suitably represent three-dimensional dynamic natural systems (Drakou et al. 2017a). They are in general not able to illustrate the temporal and spatial overlaps of marine uses without losing specific layers of information. Therefore, although maps are an effective communication tool, not all input values and matrix outcomes are spatially clear enough to be presented graphically without losing accuracy. This point always needs to be considered when conducting future analyses, as cumulative effects and biases may occur. More dynamic, animated three-dimensional graphical representations may help to better capture these complexities.

5 Conclusions

The combined ES matrix approach was able to demonstrate certain relationships between individual marine uses and the supply of selected ES. To our knowledge, this is one of the first studies to assess and map marine ES supply related to marine uses. Unlike most of the previously published studies, a wide variety of marine uses and ES were taken into account and their interrelationships could be qualified.

To identify spatial correlations and differentiate the supply of five ES across twelve selected marine uses, an approach utilising an ES matrix was employed, combining literature-based assessment with expert-based evaluations. This approach, equivalent to approaches for land use classes in terrestrial settings, proved to be applicable for spatially analysing anthropogenic uses of marine space.

However, where terrestrial land use classes already represent a simplification of real conditions, in the marine context the degree of generalisation had to be increased even more. The highly dynamic nature of marine ecosystems, the spatial and temporal overlap of marine uses, insufficient data availability and the three-dimensionality of water bodies impede respective ES assessments.

Our study showed that the application of the ES matrix approach in a marine context is possible, although seemingly more complicated than applications in a terrestrial context. Especially the graphical representation of marine ES constitutes a major challenge that the terrestrial context does not display in the same manner. The results showed that the application of a combined ES matrix approach depicts a promising tool for the mapping of marine ES. Due to the temporal and spatial conditions of the marine environment and thus the higher level of complexity, the limiting factor is the availability of appropriate data. Therefore, a high degree of generalisation is necessary that needs to be considered when building on the results. Nevertheless, our work showed that analysing the relationships between current marine uses and ES supply provides a comparatively simple but feasible approach to identify the spatial distribution of ES supply patterns.

This study indicated differences in the capacity to supply the studied ES between the German marine waters of the North Sea and the Baltic Sea. In the North Sea, the supply of fish, coastal protection; carbon fixation of sea grass meadows and the existence value of biodiversity dominate, while in the Baltic Sea the supply of recreational services is predominant. The analysis of the spatial correlations between human activities and the marine ES supply specifically showed the spatial influences of anthropogenic activities and can therefore illustrate the impacts of current and future marine uses on marine ecosystems and their services. The spatially differentiated representation of the selected ES in the German North Sea and Baltic Sea regions can contribute to improved management and protection. As current conservation efforts seem to be insufficient to prevent the unsustainable exploitation of marine resources, better knowledge of the impact of anthropogenic uses on biodiversity and ES supply can help to implement more rigorous and targeted protection and restoration strategies.

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Conflicts of Interest

There are no conflicts of interest.

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