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# Assessment of Ecosystem Services across the Land–Sea Interface in Baltic Case Studies

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**Abstract:** Spatial assessments of ecosystem services (ES) are needed to fulfil EU policy requirements and to support practical applications of the ES concept in policy implementation. So far, ES assessments have largely focused on terrestrial systems. A joint approach for land and sea is especially lacking. To overcome this gap, we present a novel spatial habitat typology and ES classification for an assessment across the land–sea interface. We build upon existing approaches and common spatial definitions, like CORINE land cover (CLC) types, water bodies of the Water Framework Directive (WFD), and habitat types according to the Habitats Directive (HD). We show applications of the resulting ES matrix for an expert-based assessment of ES potentials in three Baltic study sites (Schlei, Greifswald Bay and Curonian Lagoon). A complementary indicator-based approach to assess ES flows is introduced and applied. It enables a quantification of ES potentials and flows and ensures comparability among case study sites. Comparisons between the results for ES potentials and flows show that development capacities exist in particular for provisioning ES for marine habitats. Our approaches are spatially expandable and transferrable and could be applied to support environmental policy implementation. Further, we discuss their practical relevance, current limitations, and future research perspectives.

**Keywords:** Water Framework Directive; Biodiversity Strategy; habitats directives; ecosystem service potential; ecosystem service flow; matrix; experts; coastal and marine management



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## 1. Introduction

In the last decade, considerable attention in science and policy has been paid to ecosystem services (ES). The ES concept links the state of ecosystems to human well-being [1,2] and is considered beneficial for supporting sustainable policy- and decision-making. As such, it has been included in environmental policies from the global to the sub-national scale.

The need to integrate the ES concept into policies is also increasingly being acknowledged in the European Union (EU) [3]. With a shift from sectoral towards holistic policies, which focus on the management of ecosystems rather than single activities or pressures [4], the implementation of EU directives has become more challenging, causing delays and leaving policy objectives unmet, as shown for instance for the Water Framework Directive (2000/60/EC) (WFD) [5] and the Marine Strategy Framework Directive (2008/56/EC) (MSFD) [6]. Major impediments for policy implementation include the lack of a holistic view and low acceptance of environmental measures among stakeholder groups. An integration of the ES concept can be beneficial for emphasizing social and economic benefits of protecting, managing, and restoring different ecosystems, and thus enhance acceptance of environmental measures [3].

Since the adoption of the EU Biodiversity Strategy in 2011, much research on approaches to map and assess ES has been conducted on an EU, national and regional level [7]. However, so far, spatial ES assessments have largely focused on terrestrial systems. Approaches for marine systems lag behind and are often restricted to a small number of ES [8,9]. Particularities, such as knowledge and data gaps, as well as the three-dimensional character of aquatic systems, pose challenges and have hampered ES assessments of marine systems [10].

Joint approaches to map and assess ES at land and sea are particularly rare [9]. However, activities taken at land also affect the coastal and marine environment and need to be regarded holistically. For instance, fertilization of agricultural fields is a major source for coastal eutrophication and the increasing strive towards a climate-neutral continent will lead to an increase in offshore renewable energy, causing competition for space and impacts on the seascape as well as on marine habitats and life. Hence, a holistic and integrated assessment of ES across terrestrial, coastal, and marine ecosystems is urgently needed. Furthermore, EU environmental policies are often not restricted to one side of the shoreline. For instance, the Habitats Directive (92/43/EEC) (HD) aims to protect a wide range of terrestrial, coastal, and marine species and habitats [11], the WFD promotes the protection of inland surface, transitional, coastal, and groundwater [12], and the Maritime Spatial Planning (MSP) Directive (2014/89/EU) requires member states to take into account land–sea interactions [13]. Thus, a joint spatial assessment approach for land and sea is inevitable for supporting the practical application of the ES concept in EU policy implementation. Few examples of joint assessments exist, but they are often conducted on a global or European scale (e.g., [14]) or focus on a small number of ES. In order to support EU environmental policy implementation, joint approaches for the national and sub-national scale are needed that cover a variety of ES.

The ES matrix approach [15], which links geospatial units (e.g., biotope or land-use/land-cover types) with ES, has been widely applied to map and assess ES in a large variety of case studies all around the globe, ranging from the local to the continental scale [16]. Even though the approach bears many uncertainties [17,18], a major advantage is that the scoring process used to assess ES can integrate a variety of data sources (e.g., statistical data, model outputs, or expert scoring) and allows an easy and comparably quick application and is thus recommended in case sufficient information or data for more precise assessments are lacking [19,20]. Even though the initial ES matrix was highly focused on terrestrial areas, it has more recently also been applied to marine areas (e.g., [21–23]). Hence, it has the potential to serve as a suitable approach for a joint ES assessment of land and sea.

In a recent paper by Müller et al. [18], a first joint ES potential matrix for terrestrial, coastal, and marine ecosystem types of Northern Germany is presented. The terrestrial ecosystem types were adapted from previous works (e.g., [24,25]) and include the CORINE land cover (CLC) types found in Northern Germany. They are complemented by several coastal infrastructural elements, like coastal protection structures. Furthermore, a marine part was added. It consists of three main subsystems covering key habitat and community types, sediment types, and water body types according to the WFD. The study by Müller et al. [18] is a major step towards an assessment of ES across land and sea. Furthermore, it has the advantage that it is not case study specific, but applicable to a wider geographical region. However, it has several key limitations: First, the study is mostly limited to the development of the ES potential matrix. Concrete case study applications to show its applicability are missing. Second, spatially explicit units for the marine part are lacking and hamper the spatial mapping of ES across land and sea. Third, the matrix is limited to values for ES potentials. The ES potential refers to the capacity of an ecosystem to provide an ES [26] and is defined as 'the hypothetical yield of selected ecosystem services' [24]. Alone, ES potentials do not provide any information on the actual ES provision. They can be used for hypothetical comparisons between habitats, as shown by Müller et al. [18], or serve as baselines for subsequent assessments. In order to support sustainable policies or decision-making, a comparison of ES potentials with the ES demand or flow, that is, the actual use of an ES, is needed [26].

In this study, we address these limitations in order to advance joint ES assessments across land and sea for supporting policy implementation. First, we present a spatial habitat typology and ES classification for a spatial ES assessment across the land–sea interface that builds upon existing approaches and common spatial definitions. Second, we prove its applicability for assessing ES potentials in three Southern Baltic case studies using an expert-based approach. Third, we conduct a complementary indicator-based assessment of the ES flow in comparison to the ES potential. Finally, we discuss strength and weaknesses of the approaches, as well as their transferability to other regions and suitability for supporting policy implementation.

Our exemplary applications are focused on three systems along the Southern Baltic coast, that represent rural river basin–coastal water–sea transects with varying ratios of land, coast, and sea areas. The land-dominated system Schlei and the balanced system Greifswald Bay are located in Northern Germany, for which the original matrix by Müller et al. [18] was developed. The Curonian Lagoon in Lithuania represents the sea-dominated system and is further used to assess the transferability of our approach. Each case study site (CSS) includes the lagoon and adjacent municipalities and water bodies. Furthermore, all sites are designated Natura 2000 sites and popular tourist destinations.

## 2. Materials and Methods

### 2.1. Spatial Habitat Typology for Land and Sea

To enable a joint spatial ES assessment across land and sea, we developed a spatially explicit typology for coastal and marine systems, which can complement the CLC classification that is based on satellite images and most commonly used in matrix-based assessments [16,27]. Our typology builds upon spatial units of the WFD and the HD, since they are commonly accepted and applied across Europe. The WFD typology subdivides coastal and marine waters into comparable water bodies, based on factors such as latitude, longitude, tidal range, depth, current velocity, residence time, and salinity. Therefore, water bodies, the management units of the WFD, which belong to the same surface water type, share many abiotic and biotic similarities. To reflect the three-dimensional character of aquatic systems, we added sediment and benthic habitat characteristics, based on the HD, which includes a list of habitat types and species of community interest. It is closely related to the EUNIS classification [28], which provides a hierarchical framework for coastal waters and marine habitats and formed the basis for an EU-wide assessment of the distribution of marine ES [21].

We used the WFD typology of surface water types in German coastal waters of the Baltic, namely oligohaline inner coastal waters (B1), mesohaline inner coastal waters (B2), mesohaline open coastal waters (B3), and mesopolyhaline open coastal waters, seasonally stratified (B4). This typology covers only coastal waters up to one nautical mile off the national baseline (a simplified coastline). We extended the WFD approach to marine surface waters so that all German territorial waters up to 12 nautical miles are covered. In line with the WFD classification, we separate coastal and marine surface waters by the 15 m isobaths. According to this distinction, coastal waters comprise the shallow, light-penetrated, and wave-influenced waters up to 15 m depth. Marine waters are deeper than 15 m. Therefore, they have a reduced vertical exchange and are potentially seasonally stratified, bearing the risk of hypoxia. Hence, all marine waters are included in the WFD surface water type B4. Water body types B1 to B3 were further subdivided according to selected benthic habitat types, which were based on HD and HELCOM underwater habitat and biotope types (HELCOM HUB). This includes different sediment types, mud- and sand flats, vegetation, and reefs. In total, 10 marine habitat types were included in the matrix structure of the Baltic Ecosystem Service Potential Matrix (Baltic ESP Matrix).

For the terrestrial areas, we included all CLC types (CLC 2018), which are present in the German Baltic Sea Region, which comprises the federal states Schleswig-Holstein and

Mecklenburg-Western Pomerania. This covers 28 CLC types, which form the terrestrial ecosystem types of the Baltic ESP Matrix. Coastal ecosystem types, which are partly covered by the CLC classification, were redefined according to the HD and HELCOM coastal habitat types (e.g., 'sea dunes', 'sea cliffs, shingle, and stony beaches', and 'salt marshes and salt meadows') and resulted in four coastal ecosystem types.

Different geodata served as a base for the derivation of ecosystem types. Relevant information and data sets were obtained from geoportals and national and regional authorities. They were processed and, if applicable, transformed individually for the three zones, terrestrial, coastal, and marine. Afterwards, the data sets were merged in order to come up with one integral spatial layer. As overlaps between the different data sets occurred, they have been assigned different priorities based upon their spatial resolution, accuracy, and relevance for the assessment. Highest priority has been assigned to the coastal data set, followed by the data on the ecosystems in the marine areas. The terrestrial information based upon the CLC10 data sets has been set with the lowest priority. For data processing and spatial analyses, ArcMap 10.8.1 and QGIS 2.18.24 have been used.

### 2.2. Expert-Based Ecosystem Service Potential Assessment

For the expert-based ES potential assessment, the initial 'ES potential matrix for terrestrial, coastal and marine ecosystem types of Northern Germany', presented by Müller et al. [18] was adjusted and resulted in the new 'Baltic German ES Potential Matrix' (Baltic ESP Matrix). The development of the initial matrix is described in detail by Müller et al. [18]. Thus, we focus here on the changes conducted. A comparison of both matrices is presented in Table 1.

**Table 1.** Comparison of the initial ecosystem services potential matrix by Müller et al. (2020) [18] and the Baltic ESP Matrix, with number of included habitats and ecosystem services indicated in brackets.

| | ES Potential Matrix by Müller et al. (2020) | Baltic ESP Matrix |
|---|---|---|
| **Terrestrial ecosystems** | CORINE CLC types 2012 (28) | CORINE CLC types 2018 (27) |
| **Coastal ecosystems** | Coastal infrastructure (9) and coastal ecosystem types (6) | Only coastal ecosystem types (based on HD and HELCOM habitat and biotope types) (4) |
| **Marine ecosystems** | 3 Marine system blocks, incl. water body types (4), key community types (8) and sediment types (6) with weighting factors | Spatially explicit typology for inner and outer coastal waters based on WFD and HD and HELCOM habitat and biotope types (10) |
| **Ecosystem services (ES)** | **Ecosystem integrity attributes (6):** Abiotic heterogeneity, Biodiversity, Biotic water flows, Exergy capture, Reduction of nutrient loss, Storage capacity; **Provisioning ES (14):** Crops (human nutrition), Biomass for energy, Crops (fodder), Livestock, Timber, Fibers, Wood fuel, Wild food, Fish and seafood, Beach wrack/flotsam, Ornamentals, Drinking water, Abiotic energy, Minerals; **Regulating and maintenance ES (11):** Groundwater recharge, water flow, Local climate regulation, Global climate regulation, Flood protection, Air quality regulation, Erosion regulation (wind), Erosion regulation (water), Nutrient regulation, Water purification, Pest and disease control, Pollination; **Cultural ES (6):** Recreation and tourism, Landscape aesthetics, Knowledge systems, Cultural heritage, Regional identity, Natural heritage | |

In the first step, the matrix structure was modified. The initial habitat types, shown on the horizontal axis of the matrix, were replaced by the habitat types included in our new typology (cf. Section 2.1). The ES classification, which forms the vertical axis of the matrix, was directly taken over from Müller et al. [18]. Included ES are based on the Common International Classification of Ecosystem Services (CICES), which distinguishes between three ES sections (i.e., provisioning, regulating and maintenance, and cultural ES) [29], but are partly adjusted as a result of experiences gained during previous practical applications (e.g., [30,31]). In total, the ES classification covers 14 provisioning ES, 11 regulating and maintenance ES, and 6 cultural ES. In addition, 6 integrity indicators were included, which provide information on the ecological state and quality of the ecosystem service types.

In the second step, the expert-based values for ES potentials had to be adjusted to the revised coastal and marine ecosystem types. The initial ES potential values were generated using an expert-based scoring approach. For this, a preliminary matrix was filled by an internal expert working group and was then sent to more than 100 external experts. A scoring range between 0 and 100 (highest potential capacity of a habitat to provide an ecosystem service) was used to score the relative ES potential for each habitat-ecosystem service combination. However, in the initial matrix only values between 10 (very low ES potential) and 90 (very high ES potential) were proposed. The score 5 was used when an ES provision could be logically excluded (e.g., provision of fish and seafood in broad-leaved forests). Allowing only scores between 10 and 90 can be considered artificial but was chosen with regard to the inherent uncertainties of the approach. The value 5 was chosen to leave a minimal probability. External experts reviewed and commented on the given values and proposed alternatives where necessary. All comments were taken into account in the preparation of the final matrix. We directly adopted the ES potential values for terrestrial habitats from the initial matrix by Müller et al. [18]. Based on the values for coastal ecosystems and the marine subsystems included in the initial matrix, we determined values for coastal and marine habitats in an internal expert group. The resulting Baltic ESP Matrix is provided as Supplementary Materials (Table S1).

### 2.3. Indicator-Based Ecosystem Service Flow Assessment

For a subset of ES, a complementary ES flow assessment was conducted to allow for subsequent comparisons of ES potential and flow. A shortcoming of the matrix-based assessment by Müller et al. [18] and previous matrix-based applications is the lack of reference points. For instance, the habitat type 'non-irrigated arable land' is considered to be the one with the highest potential for the ES 'crops (for human nutrition)' and has thus an ES potential value of 90. However, no information is provided on what a potential of 90 would correspond to in an absolute value. This hampers direct comparisons of ES potential and flow, as they remain mostly hypothetical.

The initial ecosystem service potential matrix presented by Müller et al. (2020), and subsequent Baltic ESP Matrix, was developed to fit the conditions of Northern German ecosystem complexes. Similar conditions exist for the same ecosystem types within the same climatic zone, which is the Cfb-climate zone (Warm temperate-fully humid-warm summer), according to an updated map of the Köppen-Geiger climate classification, representing the time period between 2001 to 2025 [32]. As background for our indicator-based ES flow assessment we assume that the highest ES potential represented in the Baltic ESP Matrix reflects the highest ES flow that exists within the Cfb-climate zone. The assessment then consisted of four main steps:

In the first step, we selected suitable ES and indicators. Selected ES should equally cover provisioning, regulating and maintenance, and cultural ES. Furthermore, they needed to be applicable for both land and sea. In total, 10 ES were selected for the ES flow assessment. For each ES, we identified indicators to assess the ES flow in terrestrial (incl. coastal) and marine ecosystem types. Selection criteria were: (a) applicability in all study sites, (b) policy relevance, and (c) data availability. Additional quality criteria for ES indicators as defined by Hattem et al. [33] were taken into account in the indicator selection. These include precision, sensitivity, specificity, scalability, and transferability. Previous mappings and assessments of ES [25,34], as well as the structured indicator pool for marine ES assessments by von Thenen et al. [35], served as sources for the indicator selection. An overview of the selected ES and their corresponding flow indicators is provided in Table 2 (Section 3.3).

**Table 2.** Overview of the provisioning (P), regulating and maintenance (RM), and cultural (C) ecosystem services and corresponding indicators for terrestrial (T) and marine (M) areas, used in the ES flow assessment. In addition, results for the maximal flow value and the case study site flows are shown. Case study site flows are indicated as absolute values (bold) and proportionally to the maximal flow (in brackets).

| Ecosystem Service | Indicator (Unit) | Max. Flow | Schlei | GWB | CL |
|---|---|---|---|---|---|
| **P1: Crops** | T: Harvested crops (average yield of (winter) wheat (t/ha) | 10.5 | 8.7 (0.83) | 7.5 (0.71) | 0 (0.0) |
| | M: Harvest from marine aquaculture production (seaweed) (t/km coastline) | 0.07 | 0 (0.0) | 0 (0.0) | 0 (0.0) |
| **P2: Livestock** | T: Livestock (dairy cows) biomass per ha agricultural land (t/ha UAA) | 4 | 1.2 (0.30) | 0.7 (0.17) | 0 (0.0) |
| | M: Marine aquacultures production (fin fish and mussels) (t/km coastline) | 100 | 0 (0.0) | 0 (0.0) | 0 (0.0) |
| **P3: Wild food** | T: Hunting yield (deer and wild boar) (t/km2) | 1 | 0.2 (0.20) | 0.7 (0.70) | 0.2 (0.20) |
| | M: Fishing yield (t/km2) | 19 | 2.93 (0.15) | 0.78 (0.04) | 2.43 (0.13) |
| **P4: Abiotic energy production** | T: Wind and solar energy capacity (KW/ha) | 19 | 0.65 (0.03) | 0.46 (0.02) | 0 (0.0) |
| | M: Wind and solar energy capacity (KW/ha) | 19 | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| **RM1: Local climate regulation** | T: Evapotranspiration (mm/year)<br>M: Evaporation (mm/months) | 800<br>40 | 500 (0.48)<br>20 (0.50) | 550 (0.50)<br>20 (0.50) | 505 (0.63)<br>20 (0.50) |
| **RM2: Nutrient regulation** | T: Nitrogen cleaning (nitrogen surplus) (kg N ha$^{-1}$ yr$^{-1}$) (*reversed*) | 213 | 115 (0.46) | 60 (0.72) | 15 (0.93) |
| | M: Nitrogen cleaning (denitrification, estimated based on TN) (kg N ha$^{-1}$ yr$^{-1}$) | −266 | −120 (0.45) | −51 (0.19) | −101 (0.38) |
| **RM3: Pest and disease control** | T/M: Presence of pathogenic bacteria (in lakes (T) and coastal waters (M)) | 4 | 4 (1.00)<br>3.63 (0.91) | /<br>3.05 (0.76) | /<br>3.82 (0.95) |
| | T: Micro algae biomass chl-a concentration (µg/l)—terrestrial: lakes | 54 | 10.8 (0.20) | / | / |
| | M: Micro algae biomass chl-a concentration (µg/l)—marine: coastal water bodies | 48 | 32.5 (0.68) | 10.5 (0.22) | 113.2 (2.36) |
| **C1: Recreation and tourism** | T/M: Ratio of local residents to tourists (tourists/1000 inhabitants) | 61,000 | 13,780 (0.23) | 16,667 (0.27) | 13,571 (0.22) |
| **C2: Landscape aesthetics and inspiration** | T/M: Habitat diversity based on Simpson's Index | 1 | 0.85 (0.85) | 0.93 (0.93) | 0.88 (0.88) |
| | T/M: Naturalness based on Hemeroby Index | 1/2 | 1/4.13 (0.48) | 1/2.8 (0.71) | 1/2.1 (0.96) |
| **C3: Natural heritage** | T/M: Proportion of area that is protected (Natura 2000) (%) | 100 | 7 (0.07)<br>74 (0.74) | 14 (0.14)<br>95 (0.95) | 77 (0.77)<br>56 (0.56) |

In the second step, a maximal flow value for each indicator was defined. We searched for the highest flow value within the Cfb-climate zone, which ranged from Ireland to the coast of Lithuania and from Denmark to France (excluding the Alps region). First, the country with the highest flow value on the national level (NUTS 1 level) was identified, using international geoportals and databases, such as EMODnet [36], Eurostat [37], or the FAO databases [38,39]. Afterwards, geo- and statistical portals and reports from national and regional authorities were reviewed to obtain more precise values for the regional or county level (NUTS 2 or 3 level) for the respective country. This approach was used for the majority of indicators. Yet, for single indicators (e.g., the Simpson's and Hemeroby indices, used for the ES 'Landscape aesthetics and inspiration') it was not applicable and therefore adjusted. A detailed description of the methods and data sources used to derive the maximal flow value for each indicator is provided as Supplementary Materials (File S2).

In the third step of the flow assessment, the ES flow indicators were applied to the three CSS. To score the indicators, data on the smallest possible scale was used, that is the municipal level for indicators for terrestrial areas and the WFD water body level for indicators for marine areas. Data sources included regional and local statistics, geoportals, and scientific literature. Furthermore, experts were consulted in case no other data sources were available or to validate data-based values.

In the final step, the ES flow values and the Baltic ESP Matrix were combined to derive an ES flow matrix for each CSS. Hereby, the maximal flow value was equated to the highest potential value found in the Baltic ESP Matrix (i.e., 80 or 90, indicator-dependent). For each case study site, a flow value relative to the maximal flow of the climate zone was calculated, and then multiplied with the values in the Baltic ESP Matrix.

*2.4. Case Study Sites*

Three Baltic CSS were assessed in this study. Their location in the Baltic Sea Region and main CLC types are shown in Figure 1.

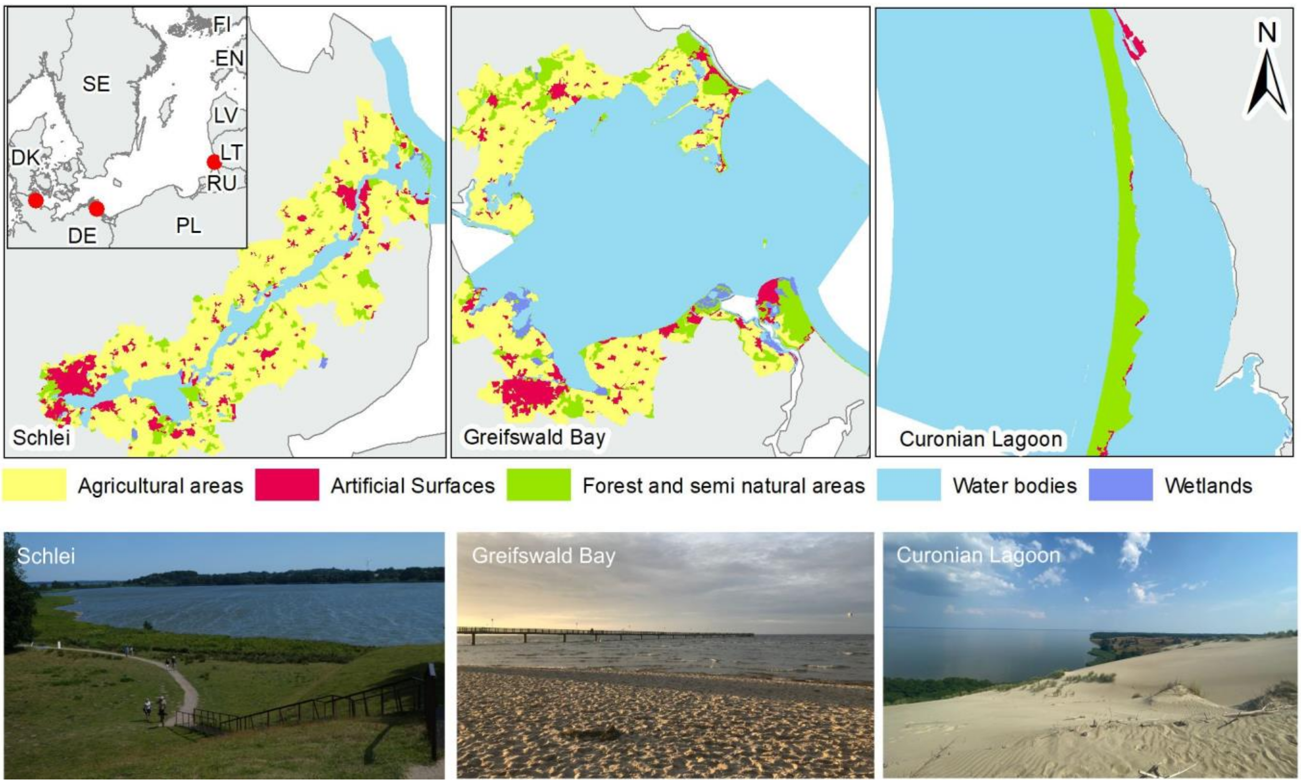


**Figure 1.** Location of the three case study sites (CSS) Schlei (land-dominated system), Greifswald Bay (balanced system) and Curonian Lagoon (sea-dominated system) (from west to east) in the Baltic Sea. CSS maps show the dominating land cover types.

The Schlei is located in northern Germany and represents the land-dominated CSS. It comprises the 43 km long water inlet Schlei with a surface area of 54 km$^2$ and its adjacent municipalities with a total population of 60,000 inhabitants which are concentrated mainly in the cities Schleswig and Kappeln [40]. The landscape was formed during the Weichselian glaciation and is characterized by a gently hilly landscape [35]. The Schlei is a brackish and shallow water body with a strong salinity variation range between a few to 20 PSU [41] and an average depth of 2.5 to 3 m [42]. The CSS Schlei has total area of 398 km$^2$, which is dominated by agricultural areas (61%). Other land-cover types include artificial surfaces

(9%), and forests and semi-natural areas make up 7%. 23% of the area is covered by water, which includes the water bodies of the Schlei and adjacent water bodies of the Baltic Sea. The Schlei region is a popular tourist destination with around 82,700 overnight stays in 2019 [43] and many additional day visitors. Popular tourism activities in the area include hiking, cycling, sailing, canoeing, and angling. Another tourist attraction is the Viking Age trading site Haithabu close to Schleswig, which was included in the World Heritage list in May 2018.

The CSS Greifswald Bay is located in the north east of Germany and represents the balanced system. The CCS has a total area of 1139 km$^2$, of which 66% (748 km$^2$) are water bodies. The marine area includes Greifswald Bay with a total surface area of 514 km$^2$ and adjacent water bodies. Greifswald Bay is shallow with a mean depth of 5.8 m and a salinity range between 5 and 7 PSU [44]. The terrestrial area is dominated by agricultural land (22% of the total CCS area). Artificial areas make up 4% of the area and include the Hanseatic city of Greifswald and several smaller towns and seaside resorts. The northern part of the CSS is situated on the island of Rügen and characterized by rolling hills and heathland. In contrast, the southern part of the CSS is characterized by lowlands and includes long sandy beaches, but also wetland areas. Forests and semi natural areas make up 6% of the total CSS area and wetlands 2%. The CSS has a total population of around 84,000 inhabitants, which are mainly concentrated in Greifswald (ca. 59,000) and Putbus (ca. 4400) [45]. Tourism is the main economic driver in the area, with around 460,000 tourists and 2.5 mio. overnight stays, which are mostly concentrated in the municipalities at the outer coast, such as Baabe, Göhren, and Mönchgut (ca. 240,000 tourists and 1,4 mio. overnight stays). Popular tourism activities include water sports like sailing and (kite-) surfing. As the main spawning ground for Baltic Herring, Greifswald Bay [46] is also a popular destination for angling tourists, as well as an important catch area for inland and coastal fisheries.

The CSS Curonian Lagoon represents the sea-dominated system in this study and is located in the most western part of Lithuania. It comprises Neringa municipality on the Curonian Spit (a narrow peninsula) and adjacent water bodies, that is the Curonian lagoon on the eastern side and the Baltic Sea on the western side. It has a total area of 1590 km$^2$, of which 93% is water bodies. The terrestrial part of the CCS is dominated by forest and semi natural areas (mostly sea dunes and coniferous forest) which comprise 6% of the total CSS area. Artificial areas (0.5%), agricultural land, and wetlands can also be found in the study area, but are spatially negligible. All settlement areas are located on the lagoon coast. The CSS has a total population of approximately 3500 inhabitants, which are mostly concentrated in Nida (ca. 1200) and Juodkrantė (ca. 700). In 2000, the Curonian Spit was inscribed on the UNESCO World Heritage List [47]. It is among Lithuania's most popular destination for domestic, but also international, tourists. In 2017, approximately 23,600 tourists were accommodated in hotels in Neringa municipality and accounted for 47,500 overnights [48]. In addition, an estimated number of 400,000 day tourists visit the area per year [49].

## 3. Results

### *3.1. Application of the Spatial Habitat Typology*

The application of the spatial habitat typology in the three CSS showed that it was generally applicable in Germany as well as Lithuania. Geodata for CLC types, WFD water body types, and HD habitats were easily accessible from European and national geoportals, but the years from which data was available differed between CSS. To obtain data on marine sediments and vegetation, which were needed for the spatial definition of the inner and outer coastal waters, was more difficult. While they are mostly available for open coastal waters, information on the spatial distribution of sediments in shallow inner coastal waters is often hampered by sampling and interpolation methods [50]. Therefore, geodata for sediments and vegetation cover for inner coastal waters were obtained through direct contact with persons from regional authorities and research institutes. Geospatial information on emergent vegetation (reed belts) and sandy beaches had to be mapped manually from satellite images.

For the application of the spatial habitat typology to the Lithuanian CSS, the German water body classification had to be applied to the Lithuanian water bodies. As it is based on environmental parameters, such as depths and salinity, it was easily transferable. Transitional waters (LIT-004 to LIT-006) and the heavily modified waterbody Klaipeda Strait (LIT-001) were included in the inner coastal waters, and coastal waters (LIT-002 and LIT-003) were classified as open coastal waters. Almost all CLC types that were found in the terrestrial part of our CSS were covered by the spatial habitat typology. Only the CLC type 'Land principally occupied by agriculture' (243) had to be transferred to the more general type 'Heterogeneous agricultural areas' (240).

Out of the 41 habitats included in the spatial habitat typology and following Baltic ESP Matrix, 38 were found in the three CSS. Since this study is focused on the development of a spatial ES assessment approach for land and sea that can support coastal and marine policy, our focus is on natural and semi-natural areas. Consequently, for the purpose of this study, we grouped settlement related CLC types into one category (i.e., artificial surfaces), which will not be further considered in the following ES assessments. Figure 2 lists the remaining 29 habitats and shows their spatial distribution in the CSS. In addition to the 29 distinct habitats, we added three general habitat types called 'Beach, dunes, sands (other) (3110)', 'Coastal lagoons and estuaries (other) (5210)', and 'Open coastal waters (other) (5230)'. They were used in case no further differentiation of the CLC types was possible. Together, they make up less than 1% of the studied area and are mostly negligible. The Lithuanian CSS forms an exception, as around 7% of the terrestrial area was classified as 'Beach, dunes, sands (other)'.

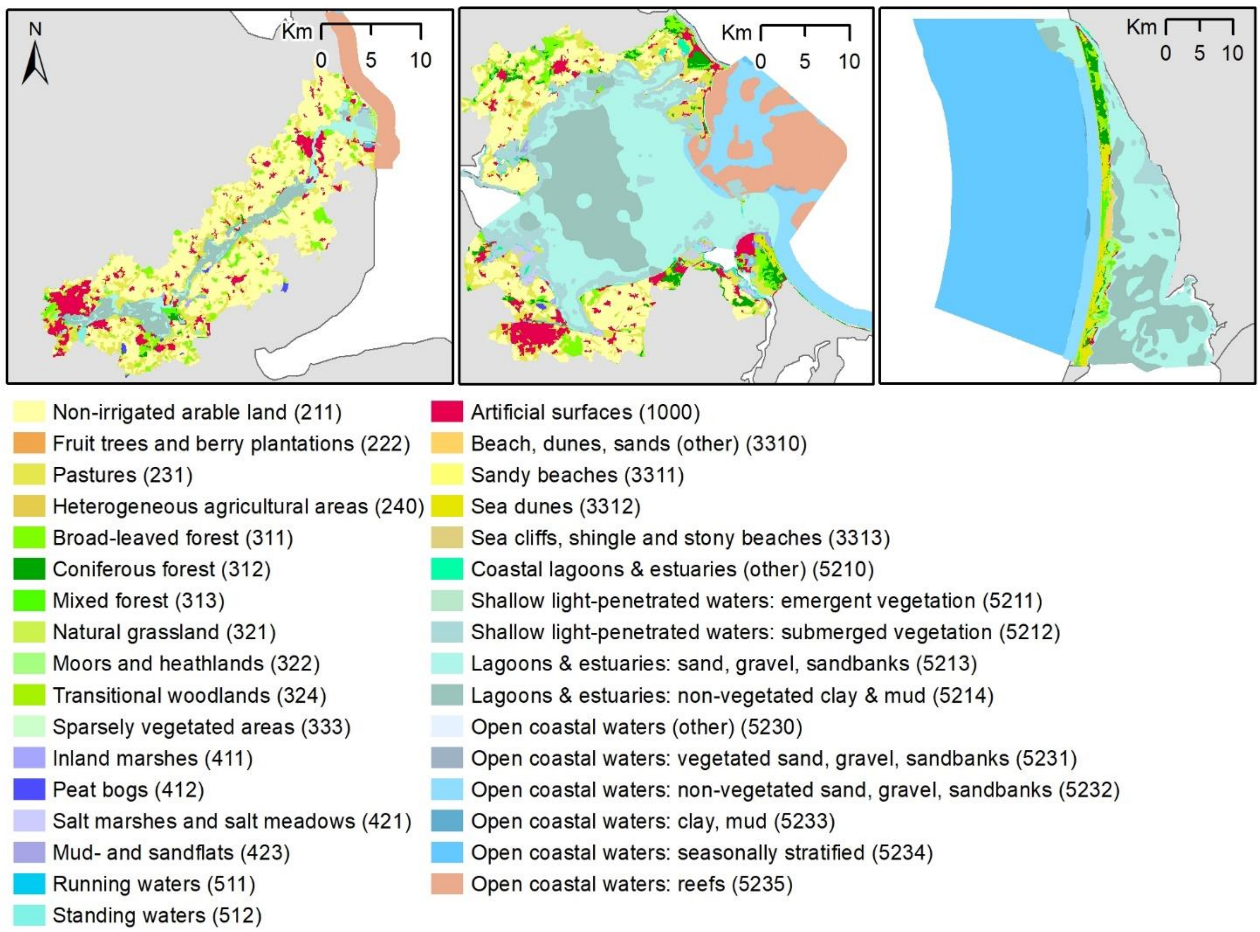


**Figure 2.** Spatial distribution of ecosystem types in the study areas Schlei, Greifswald Bay, and Curonian Lagoon (left to right).

### 3.2. Ecosystem Services Potentials

Resulting maps for ES potentials, based on the expert-based Baltic ESP Matrix (Table S1), are shown in Figure 3. ES potentials are shown on an aggregated level for each ES section. In addition, an overall habitat-weighted ES potential value was determined. It takes into account the proportional contribution of each habitat to the total area of each CSS. Besides the habitat-weighted ES potentials on an overall level (O), habitat-weighted ES potentials were also calculated separately for the terrestrial and marine area of each CSS. The habitat-weighted ES potential for terrestrial areas (T) is based on the proportional contribution of each terrestrial habitat to total terrestrial area of a CSS. Likewise, the habitat-weighted ES potential for marine areas (M) was calculated for each CSS.

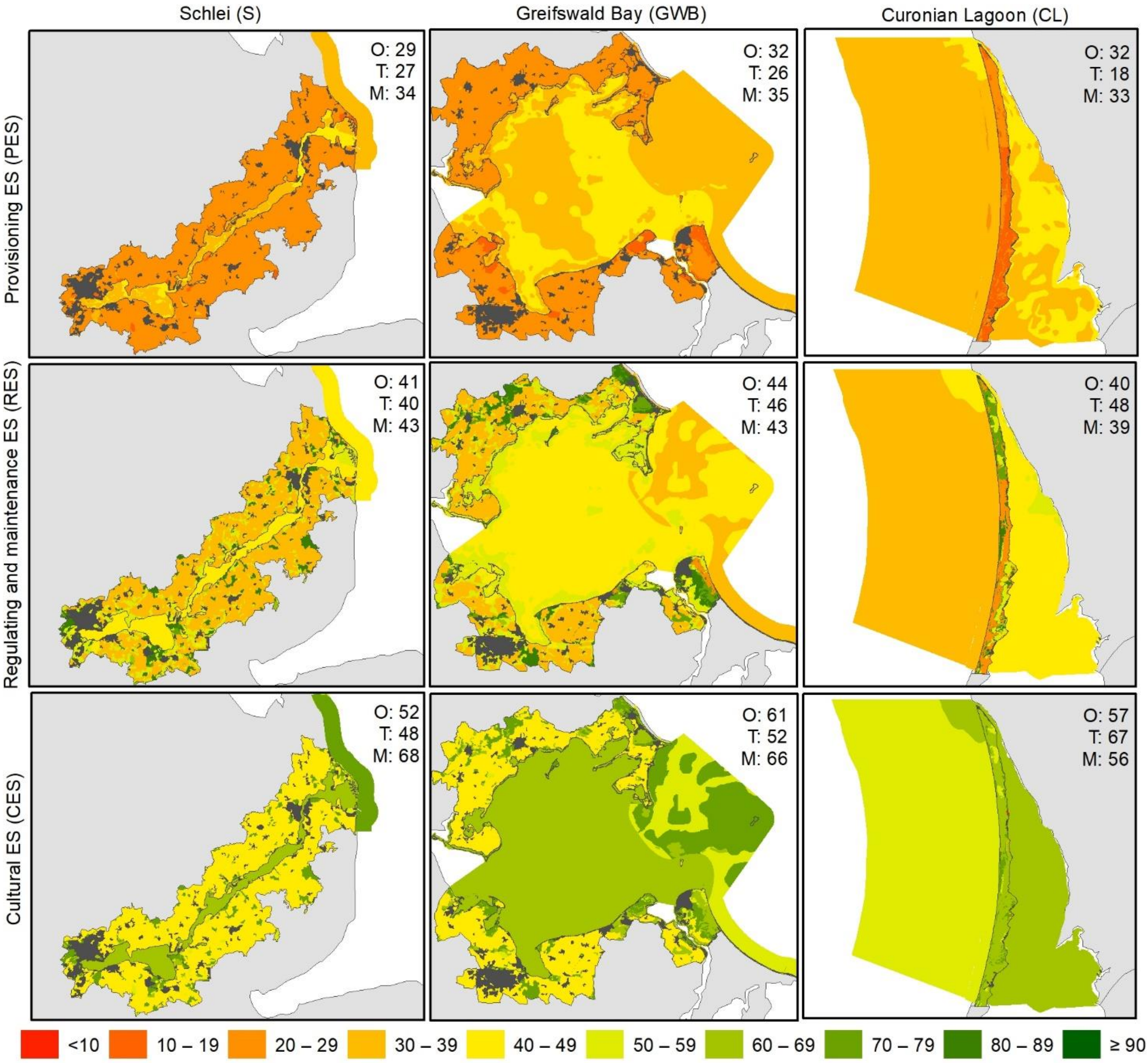


**Figure 3.** Ecosystem services (ES) potentials shown on an aggregated (averaged) level for provisioning, regulating and maintenance, and cultural ES. Lowest ES potentials are shown in red (<10) and highest potentials are shown in dark green (>90). Habitat-weighted ES potentials are indicated for each site for the overall areas (O), and for terrestrial (T) and marine (M) areas separately.

General differences among the three ES sections can be observed, with increasing potentials from provisioning (PES O: 29 to 32), to regulating and maintenance (RES O: 40 to 44), to cultural ES (CES O: 52 to 61). This trend is shown for terrestrial as well as marine areas. However, differences in the relative increase between ES sections exist between land and sea. For terrestrial areas, the relative increase from provisioning to regulating ES is higher than the increase from regulating to cultural ES. In contrast, for marine areas it is reversed.

This general trend can be explained by the inherent characteristics of the three ES sections. While provisioning ES, such as timber or crops, are often habitat-specific and spatially mutually exclusive, single habitats can have high potentials for multiple regulating ES. An example is the habitat type 'broad-leaved forest' (and other forest ecosystem types), which has very high potentials in the Baltic ESP Matrix (90) for the majority of regulating and maintenance ES, like groundwater recharge, and regulation of climate, air quality, erosion, and nutrients. Values for cultural ES potentials are often positively correlated. Natural habitats, such as coastal sandy beaches, reefs, rivers, lakes, and broad-leaved forests are considered to have high potentials for regional identity and natural heritage, which can also make them a hotspot for tourism and recreation.

Differences between land and sea can be attributed to different characteristics of terrestrial and aquatic systems and their habitats. On land, ownerships are well defined, and the habitat types included in the CORINE classification largely reflect dominating land uses. Marine habitats are usually more natural and do not directly reflect human uses, as these are more variable in space and time. In addition, the three-dimensionality of aquatic systems enables a spatial and temporal co-existence of multiple uses. As a consequence, aggregated potentials for provisioning ES for marine areas are generally higher in comparison to terrestrial areas. Higher aggregated potentials for cultural ES can be ascribed to their higher degree of naturalness.

Besides the general trends, differences among the three CSS can be observed. Indicated values for habitat-weighted ES potentials for provisioning ES are similar for the land-dominated system Schlei (PES-S O: 29; T: 27; M: 34) and the balanced system Greifswald Bay (PES-GWB O: 32; T: 26; M: 35). In comparison, the potential for provisioning ES for the terrestrial area of the sea-dominated system Curonian Lagoon, is much lower (PES-CL T: 18). In contrast, potentials for cultural ES are higher for the CSS Curonian Lagoon (CES-CL T: 67) compared to Schlei (CES-S T: 48) and Greifswald Bay (CES-GWB T: 52). These differences can be ascribed to the dominance of natural habitats in the terrestrial area of the CSS Curonian Lagoon compared to Schlei and Greifswald Bay, which are dominated by agroecosystem types. Furthermore, ES potentials for the marine area of the CSS Curonian Lagoon are lower in comparison to the CSS Schlei and Greifswald Bay, as it is dominated by open coastal waters that are potentially seasonally stratified. Compared to the shallower coastal waters, this habitat type has received lower ES potentials on an aggregated level in the Baltic ESP Matrix.

### *3.3. Ecosystem Services Flow*

An overview of selected ES, chosen indicators and resulting maximal flow values used for the ES flow assessment is shown in Table 2. A detailed description for each indicator and the background for the maximal flow calculation is provided as Supplementary Materials (File S2). In addition, for each indicator the absolute and relative (proportional to the maximal flow) flow values for each CSS are shown.

As shown in Table 2, four provisioning ES represented by eight indicators were included in the flow assessment. For the ES 'crops' (P1), 'livestock' (P2), and 'wild food' (P3), different indicators for terrestrial and marine areas had to be chosen, due to the different types of cultured plants and domesticated or hunted animal species. We chose complementary indicators for land and sea. Yet, the flow values for P1 and P2 are not directly comparable due to different units used. Only for 'abiotic energy' (P4) could a common indicator and maximal flow value be applied for terrestrial and marine areas.

Results for the CSS show that the ES flow of provisioning ES occurs mostly in terrestrial areas. Only for 'wild food' (P4) is an ES flow shown for terrestrial and marine areas. Here, the absolute flow values are higher for the marine areas of all CSS. Yet, in proportion to the maximal flow values, which differ strongly between land (1 t/km$^2$) and sea (19 t/km$^2$), the relative flow for 'wild food' is higher for terrestrial areas. Hence, our results show that the flow of provisioning ES is dominated by flows from terrestrial areas.

'Local climate regulation' (RM1), 'nutrient regulation' (RM2), and 'pest and disease control' (PM3) were the selected regulating and maintenance ES. The same indicators could be applied for terrestrial and marine areas. However, the approaches for defining maximal flow values and data sources differed between terrestrial and marine areas. 'Local climate regulation' (RM1) is assessed based on the indicator evapotranspiration. Nitrogen cleaning was used as an indicator for 'nutrient regulation' (RM2). For 'pest and disease control' (RM3) two indicators were applied, namely presence of pathogenic bacteria and of micro algae biomass, which were chosen based on their relevance for EU directives, namely the EU Bathing Water Quality Directive (BWD) and the WFD. For RM3, ES flows are assessed based values for coastal waters for marine areas and based on values for lakes for terrestrial areas. A disadvantage of the approach is that it is not applicable in areas without lakes, or only lakes for which BWD and/or WFD monitoring is not required. This was the case for the CSS Greifwald Bay and Curonian Lagoon. Relative flow values for RM1 and RM2 are largely equal for the CSS Schlei and Greifswald Bay. The CSS Curonian Lagoon forms an exception, with a much higher value for nitrogen cleaning for terrestrial areas compared to the other sites, but also in comparison to the relative flow indicated for marine areas of the CSS Curonian Lagoon.

Three cultural ES were selected for the flow assessment. For 'recreation and tourism' (C1) the ratio between residents and tourists was used as an indicator. 'Landscape aesthetics and inspiration' (C2) was assessed based on two indicators, namely habitat diversity and naturalness. Indicators and maximal flow values for C1 and C2 are equally applied for terrestrial and marine areas. Natural heritage (C3) is assessed based on the proportion of protected areas. It is applied to both terrestrial and marine areas and the same maximal flow value is used, but the flow values for terrestrial and marine areas were assessed separately in each CSS. Flow values for 'recreation and tourism' (C3) were similar for all CSS. All CSS got high scores for habitat diversity (C2a), but the strong differences are show for naturalness (C2b). CSS Curonian Lagoon reached a relative flow score of 0.96 (compared to CSS Schlei: 0.48 and Greifswald Bay: 0.71). Thus, the total relative flow for C2 (mean value of C2a and C2b) was found to be highest for the CCS Curonian Lagoon. Differences between land and sea can only be assessed based on the ES 'natural heritage' (C3). For the German CSS, the proportion of protected areas, and thus the ES flow value, is higher for marine areas (Schlei: 0.07 terrestrial vs. 0.74 marine; GWB: 0.14 terrestrial vs. 0.95 marine). In contrast, the ES flow is higher for marine areas for the CSS Curonian Lagoon (0.77 terrestrial vs. 0.56 marine). All CSS cover coastal lagoons, which are included in the list of specific habitats that are of European interest in accordance with the HD. As such, they targeted for conservation and included in the Natura 2000 network. The marine area of the sea-dominated CSS Curonian lagoon has a large share of open coastal waters, which are often not designated as protected areas. Hence, the flow is lower in comparison to the land-dominated CSS Schlei and the balanced CSS Greifswald Bay.

To generate ES flow maps, the relative flow values for the selected ES were multiplied with the corresponding ES potentials across all habitats. Resulting maps for ES flows, based on the CSS-specific flow matrices, are shown in Figure 4.

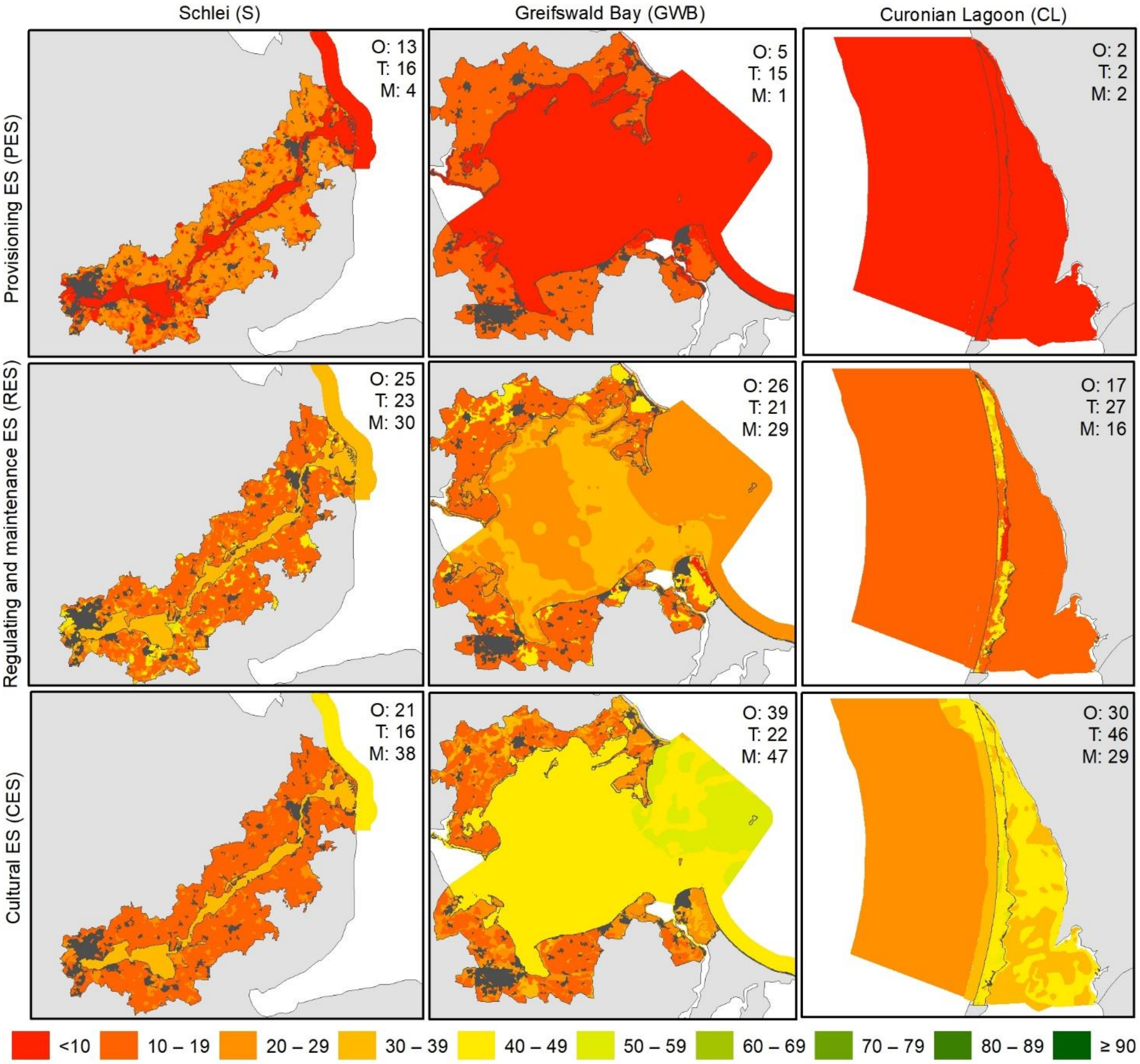


**Figure 4.** Ecosystem services (ES) flows shown on an aggregated (averaged) level for provisioning, regulating, and maintenance, and cultural ES. Lowest ES flows are shown in red (<10) and highest ES flows are shown in dark green (>90). Habitat-weighted ES flows are indicated for each site for the overall areas (O), and for terrestrial (T) and marine (M) areas separately.

A generally increasing trend from lower provisioning ES to higher cultural ES is also shown for ES flows, with the exception of CSS Schlei. Here, the habitat-weighted flow values for the overall area and the terrestrial area are higher for regulating ES than for cultural ES. Differences in aggregated ES flows across land and sea are shown between the CSS. On an aggregated level, low ES flows are shown in all CSS. In contrast to the other CSS, there is no difference between the habitat-weighted flow values for terrestrial and marine areas. The habitat-weighted flow of regulating and maintenance ES is very similar for the German CSS (RES-S: O:25, T:23, M:30 vs. RES-GWB: O:26, T:21, M:16). In contrast, the overall habitat-weighted flow is lower in the Lithuanian CSS and higher for terrestrial the terrestrial area compared to the marine area (RES-CL: O:17, T: 27, M:16). The habitat-weighted ES flow is highest for Greifswald Bay (CES-GWB: O:39, T:22, M:47) and Curonian Lagoon (CES-CL: O:30, T:46, M:29). Additionally, in this case, the higher contribution of terrestrial areas in the CSS Curonian Lagoon in comparison to Greifswald Bay is directly visible in the spatial maps.

The maps presented in Figure 4 allow a general comparison of ES flow across land and sea and among CSS. However, for a better interpretation a comparison of ES potentials and flows is needed, as low ES flows indicated in the maps can both be a result of low case study flow values (cf. Table 2) or a result of low ES potentials values in the expert-based Baltic ESP Matrix.

### 3.4. Comparison of Ecosystem Service Potential and Flow

Figure 5 combines the results of the previous sections. 'Development capacities' were calculated as the difference between ES potential and ES flows for the ten ES that were included in the flow assessment and are shown on an aggregated level for the three ES sections. Moderate to high development capacities for provisioning ES are shown for the marine areas of all CSS. The development capacities for terrestrial areas are comparably low (15 to 22) and indicate that the ES potential at land in all CSS has been mostly exhausted in comparison to the sea. For the German CSS, in which agricultural areas are dominating, this could be explained by the relatively high flow values for 'crops' (P1) and 'wild food' (P3) (for CSS Greifswald Bay). In the Lithuanian CSS, the low development capacity for provisioning ES is also a result of the dominance of natural habitats which have a generally low ES potential for provisioning ES. Development capacity for regulating and maintenance ES is visible especially for the Lithuanian CSS and in particular for its marine area, as well as the forest and natural areas within the CSS Greifswald Bay. Development capacities for cultural ES are highest for CSS Schlei. In general, habitat-weighted development capacities are highest for the marine area of the CSS. Yet, in the terrestrial area high development capacities for cultural ES are also shown for forest habitats. The maps in Figure 5 are useful for comparisons across land and sea and between CSS. They can be used to visualize gaps between ES potentials and flows and thereby support decision-making for future development.

On an aggregated level, differences between CSS become attenuated. Thus, a closer look at the results for single ES is needed, to assess differences between the land-dominated, balanced, and sea-dominated CSS. We chose one ES from each section to analyze differences. Furthermore, we point out some of the specificities of our approach that shall be addressed in the subsequent discussion.

Figure 6 shows the spatial distribution of development capacities for each ES across the CSS. For 'wild food' (P3), strong differences between land and sea are shown for all CSS. The difference in development capacities between land and sea is most pronounced for the CSS Greifswald Bay (P3-GWB: T:9, M:85). At first glance, this might be surprising, because Greifswald Bay is among the areas with the highest commercial fisheries catches in the German Baltic Sea area [51]. In contrast, the area is popular for hunting wild boar and red deer, but it is not among the most intensively used hunting areas in Germany [52]. In Section 3.3, the differences in the maximal flow values were already addressed. It was shown that the absolute flow values for 'wild food' (P3) were lower for terrestrial areas compared to marine areas in all CSS (cf. Table 2). Yet, in order to understand why there is a high development capacity for marine areas, but not for terrestrial areas, a closer look at the approaches to determine the maximal flow values is needed. As hunting data is largely lacking or not harmonized across Europe [53], the maximal value flow for hunting yield was based on statistical data from Germany. It is likely that the indicated maximal flow is underestimated, as for instance hunting yield on a regional level in Poland is likely to be higher. Furthermore, the data for Germany showed that the hunting yield of deer and wild boar species is currently at a long-term peak. Thus, the maximal flow will soon be exceeded if the increasing trend continues. In contrast, fisheries are currently highly regulated in order to recover exploited fish stocks and are thus far below historical yields. Since the maximal flow value for fishing yield is based on historical values, the difference between maximal flow and the actual flow in the CSS is much higher in comparison to hunting yields. Furthermore, the maximal flow value was based on fishing yields from Denmark. Hence, one has to keep in mind that the maximal flow values used in this study should not only be representative for the three case studies, but for the Cfb-climate zone in general.

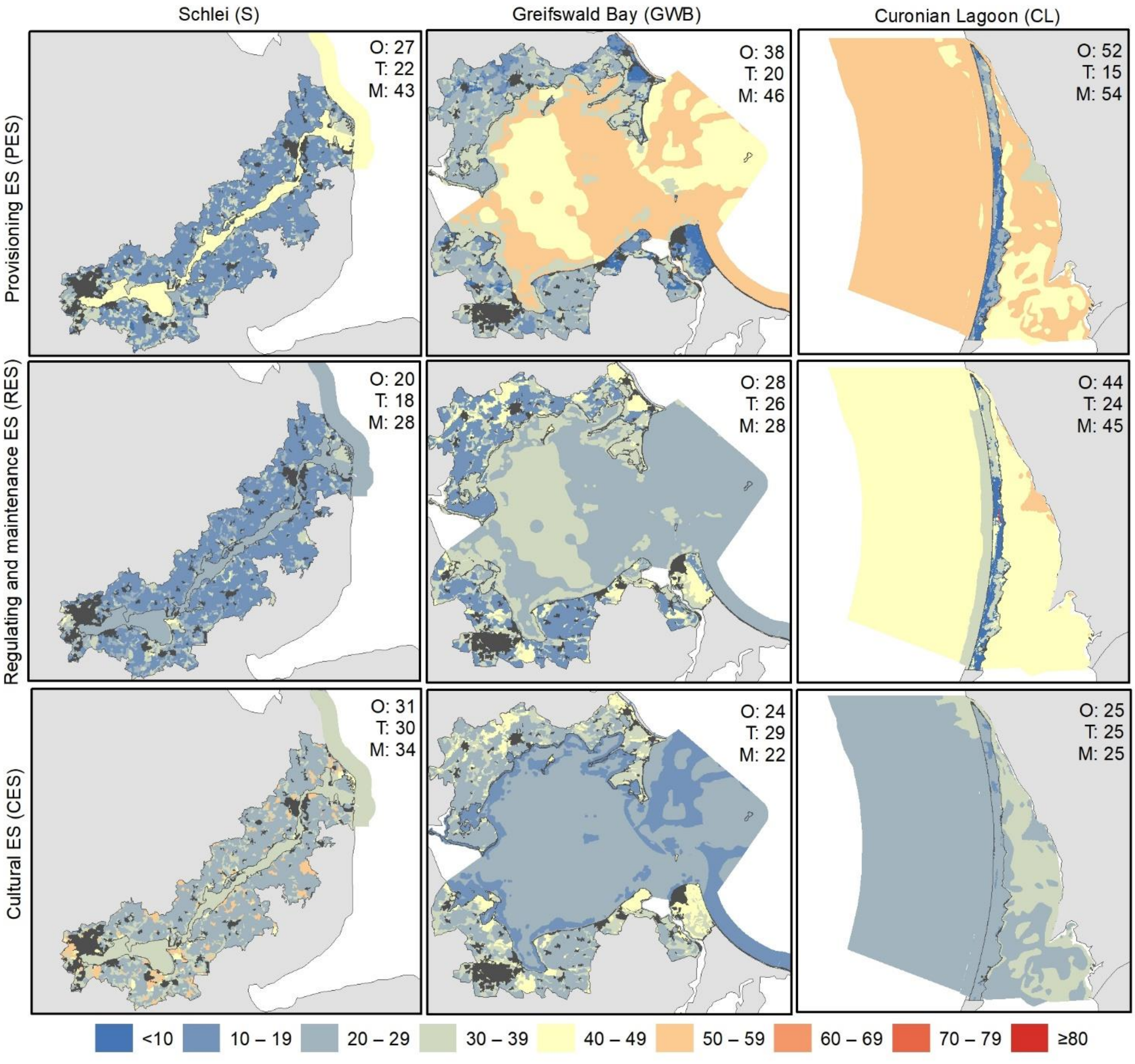


**Figure 5.** Differences between ecosystem service (ES) potential and flow shown on an aggregated level for provisioning, regulating and maintenance, and cultural ES. Low differences (shown in blue) indicate that the ES potential has largely used, and high differences (shown in red) indicate that there is still potential to increase the use of the ES (development capacity). Habitat-weighted use potentials are indicated for each site for the overall areas (O), and for terrestrial (T) and marine (M) areas separately.

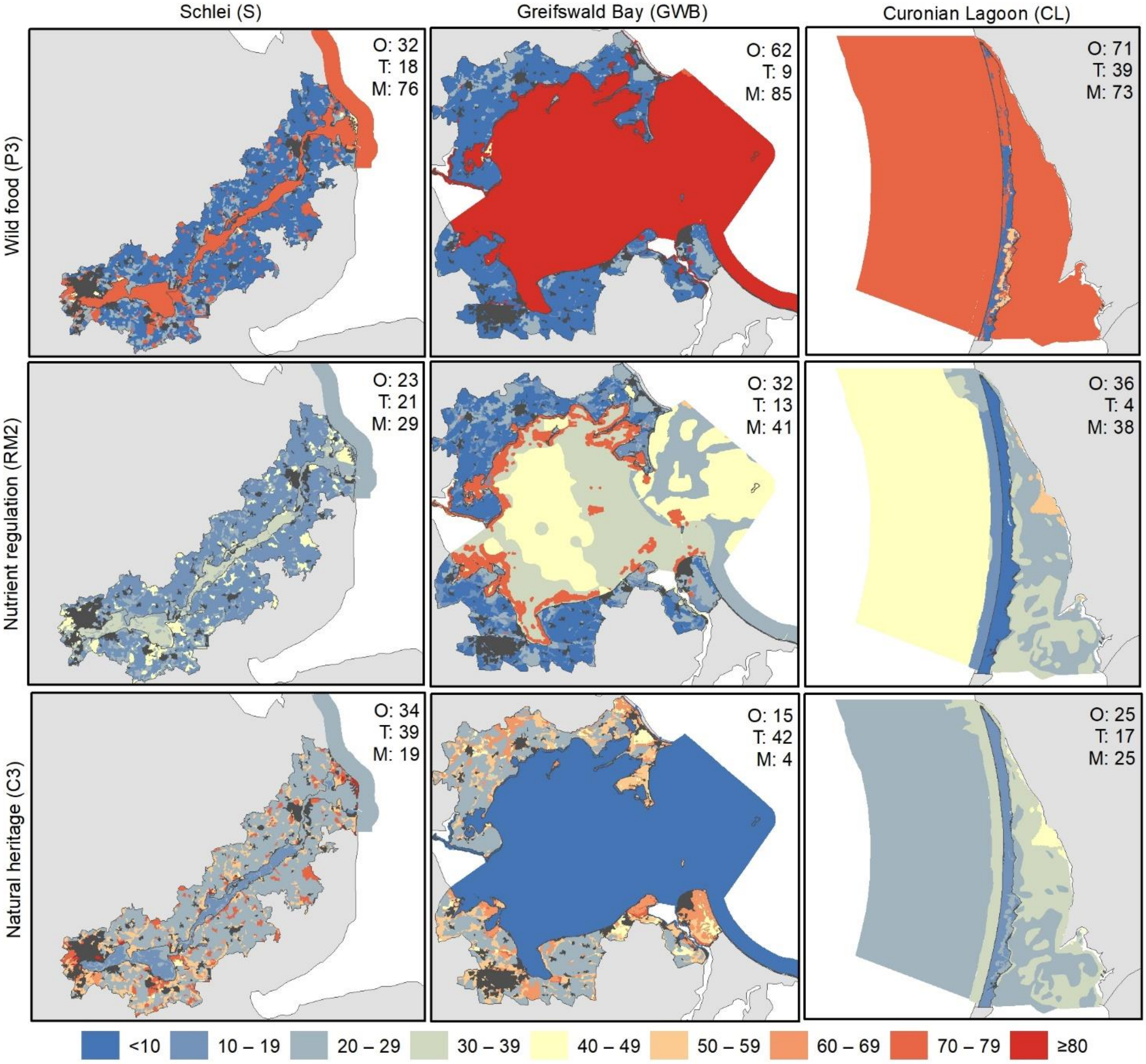


**Figure 6.** Differences between ecosystem service (ES) potential and flow shown for selected. Low differences (shown in blue) indicate that the ES potential has largely used and high differences (shown in red) indicate that there is still potential to increase the use of the ES (development capacity). Habitat-weighted development capacities are indicated for each site for the overall areas (O), and for terrestrial (T) and marine (M) areas separately.

'Nutrient regulation' (RM2) was assessed based on nitrogen cleaning. The spatial distribution of development capacities shows similar patterns at land and sea for the three CSS. Lower development capacities are shown at land, especially for the CSS Curonian Lagoon (RM2-CL T:4). Since the area is not agriculturally used, the Nitrogen surplus is low (15 kg N $ha^{-1}$ $yr^{-1}$), resulting in a high flow for nitrogen regulation. In contrast, higher development capacities are shown for RM2 for marine areas, especially for the CCS Greifswald Bay (RM2-GWB M:41) and CCS Curonian Lagoon (RM2-CL M:38), with highest development capacities for vegetated areas of the inner coastal waters.

'Natural heritage' (C3) was assessed based on the extend of protected (Natura 2000) areas. Land and sea were assessed separately, but the same maximal flow value (i.e., 100% protected area) was used for land and sea. The CSS Greifswald Bay has the largest flow for marine areas (95%). This is well reflected in the development capacity map (Figure 6.

C3-GWB). In contrast, only 14% of the CSS's terrestrial area is protected, which is reflected in a habitat-weighted development capacity of 45 for the terrestrial area. However, areas with very high development capacities (around 60 to 80) are shown for areas covered by forest ecosystem types and salt and inland marshes and peat bogs, which are also included in the list of habitats of special importance (Annex I of the HD). Thus, they are included in the CSS's Natura 2000 sites, and are already fully protected. Thus, when considering habitats separately, their development capacity for the specific habitat should be 0, as the maximal flow for the specific habitat has been reached. We used a simplified approach to derive CSS-specific flow matrices and we multiplied the relative flow values of the CSS (0.14 for GWB) with the values of the Baltic ESP Matrix. This has the effect that habitats with high potentials are more impacted by relative flow values compared to habitats with low potentials. This illustrates the need for separate flow values for different habitats.

## 4. Discussion

### *4.1. Practical Relevence for Supporting Policy Implementation*

The recently published EU report on mapping and assessment of ES stresses the existing knowledge gap between terrestrial and marine ecosystem service assessments [34]. Despite a continuously growing number of studies on coastal and marine ES research, there is still a clear research gap and integrated studies that map multiple coastal and marine ES are still rare [54]. This has also been demonstrated by the national ES mappings that result from the demand of the Biodiversity Strategy 2020, which required all EU member states to map and assess ES in their national territories. Despite the immense importance of coastal and marine ES, resulting maps of coastal member states like Germany [20] are exclusively focused on terrestrial territories. However, ES assessment across the land–sea interface is needed to support spatial planning, to enable the ES applications for supporting the HD in general, and the deployment of blue–green infrastructure in particular [8]. Only few examples exist in which multiple ES have been spatially assessed across the land–sea interface (e.g., [55,56]). However, these integrated studies were solely based on CLC types, which include merely three marine habitats (i.e., estuaries, lagoons, and sea and ocean). Our spatial habitat typology balances terrestrial, coastal and marine habitats more evenly and allows for better comparability of terrestrial and marine systems. To support spatial planning across the land sea interface, it could for instance be applied to assess implications of regional development plans on the provision of ES. For this, an assessment of the impact of various human uses on the ES potential or flow could be assessed.

Furthermore, the integrated ES assessments were limited to the assessment of ES potentials. Our approach allowed a (simplified) comparison of ES potential and flow. This is considered beneficial for supporting planning and decision making through the identification of unsustainably used areas [26]. Results of our case study applications show that development capacities exist especially for provisioning ES in the marine areas of the balanced and sea-dominated system. The identification of development capacities could serve as basis for promoting a sustainable blue economy. For this, our indicator-based flow assessment provides a promising approach. Previous matrix-based comparisons of ES potentials and flows (or ES supply and demand) were focused on expert-based assessments [24], which enable a relatively fast and easy assessment. However, due to the high level of subjectivity, results are affected by expert-bias. This reduces comparability among CSS results when different expert groups conducted the assessments. In contrast, the indicator-based approach provides quantifiable results and allows direct comparisons among different CSS and across land and sea, as it has been exemplarily shown for the ES "wild food", "nutrient regulation", and "natural heritage" for which directly comparable indicators for land and sea were applied. While a comparison of ES flow and potential helps to identify unused potentials (i.e., development capacities), it bears the risk of overexploitation. For instance, the flow of the ES 'wild food' could be raised through increased fishing yields, as a result of higher catch quotas. However, a maximal ES flow does not correspond to the most sustainable outcome, and one has to keep in mind the anthropocentric focus of the ES concept, which is particularly pronounced for provisioning and cultural ES. Comparison between ES flows and sustainable reference values could be a more suitable approach for supporting planning and decision-making. As one of our indicator selection criteria was policy relevance, sustainable reference values could be based on target and thresholds values as defined in EU policies, as they provide politically and socially acceptance standards. The need for thresholds for ecosystem service use is in line with Drakou et al. [54], who additionally pointed out the need for a novel integrated indicator set that combined ecological and social aspects. Broszeit et al. [57] assessed the applicability of biodiversity-related MSFD indicators in supporting ES assessment. The study could be used as background for an extension of our exemplary flow assessment, especially when ecological attributes are included, which are covered by our Baltic ESP Matrix, but were not further considered in this study.

### 4.2. Transferability of the Approach

The spatial habitat typology presented in this study was tested in three Southern Baltic CSS. Our approach to build the habitat typology upon existing spatial definitions of the WFD and HD was beneficial. Geospatial data was easily accessible from public geoportals or could be acquired from public authorities responsible for policy implementation. Since all EU member states are required to regularly provide geospatial data on the distribution of WFD water bodies and HD habitats, the approach can be generally transferred to other EU member states. This was successfully shown through the application to the Lithuanian CSS.

However, one has to keep in mind that our definition of marine habitats is based on the water body classification of the German Baltic Sea, which is characterized by brackish waters and mostly low hydrodynamic properties. Thus, for an application within the North Sea/Atlantic Ecoregion, which is characterized by higher salinities and hydrodynamic properties, additional marine habitats need to be defined for the spatial typology. Likewise, additional CLC types and coastal habitats (based on the HD habitat types) might be needed when transferring the approach to other areas. Consequently, we presume that a direct application of the spatial habitat typology is only possible within the Southern Baltic Sea Region. Nevertheless, the general approach of defining coastal and marine habitats based on WFD water bodies, HD habitats, and seabed sediments is transferable to other EU countries.

Spatial habitat maps are further needed for the inclusion of ES assessments in the MSFD or MSP Directive. A more detailed assessment of ES in the Baltic Sea is also foreseen for the next Holistic Assessment of the Baltic Sea (HELCOM HOLAS III) report, which supports the implementation of the MSFD in the Baltic Sea. However, studies by Kuhn et al. [58] and Inácio et al. [59] show that marine ES assessments are lacking for most parts of the Baltic Sea. In its current version, our spatial habitat typology is limited to the 12 nautical mile zone and thus only covers territorial waters. Thus, a spatial extension would be needed to allow for applications within the scope of the MSFD or MSP Directive.

In line with the WFD classification, we separate coastal and marine surface waters by the 15 m isobaths, and classified all marine waters (up to 12 nm) as 'Open coastal waters: seasonally stratified'. The implications of this approach are visible in the spatial maps of the Lithuanian CSS, which includes a large share of marine waters that are mostly covered by a single, homogenous habitat type. For the purpose of assessing differences across land and sea, the spatial definition was found to be sufficient. However, a better differentiation of marine waters is needed for national or Baltic Sea wide ES assessment. This should be based on the HELCOM sub-basins and further differentiation using the aphotic benthic habitats of the HELCOM HUB classification, which provide the necessary information of seabed sediments and habitats. Since the geospatial data required for the extension is publicly available in in the HELCOM Map and Data Service [51], it could be easily implemented. The HELCOM HUB classification is also used as background for other ES assessments in the Baltic Sea. For instance, Armoskaite et al. [60] developed an

ES assessment tool which assesses the contribution of HELCOM habitats to ecosystem functions and services.

Being based on the initial "ES potential matrix for terrestrial, coastal and marine ecosystem types of Northern Germany" by Müller et al. [18], we assumed that our Baltic ESP Matrix is generally applicable for all CSS. This is certainly a simplification, especially with regard to an application in Lithuania. Campagne et al. [16] recommend that existing ES matrices cannot be directly applied in different contexts or regions without being re-evaluated. However, the Baltic ESP Matrix includes only values for the ES potential which refers to the capacity of an ecosystem to provide an ES [26]. Thus, in contrast to ES flow or demand, ES potentials do not depend on societal factors, but solely on ES providing ecosystem. Thus, we assumed a general transferability within the Cfb climate zone. A brief comparison of the Baltic ESP Matrix, with an ES potential matrix developed for the same study area [56], showed similarities, but also major differences between the matrices. Because of its focus on terrestrial systems, different ES definitions, and evaluation scale (0–5 vs. 0–100) used, we did not quantify the variations but only compared results for single ES. This showed that the variation between both matrices was in the same range, as the general variation of scores shown among the large group of participating experts in the study by Müller et al. [18]. Thus, while acknowledging the high level of uncertainties inherent in expert-based assessments, we conclude that a general applicability of the Baltic ESP matrix within the Southern Baltic Sea Region can be assumed, and certainly provides better comparability among different case studies. An extension to other areas within the Cfb climate zone would be possible. However, as mentioned above, an extension of the marine habitats to the North or Atlantic Sea and subsequent addition of potential values would be required.

For the indicator-based flow assessment, we tried to define the maximal flow value according to the maximal value found for each indicator within the Cfb climate zone. This has the advantage, that our approach can be directly applied to CSS over a wider geographical region and that result would be comparable. In our CSS applications it had the effect that differences among CSS were less pronounced. Thus, differences among the land-dominated system Schlei, the balanced system Greifswald Bay, and the sea-dominated Curonian Lagoon became less pronounced. Consequently, if our approach is specifically used for a regional assessment, for eyample, an ES assessment for the Baltic Sea Region, maximal flow values could be based on the maximal flows found in the particular region. However, the focus on the Cfb climate zone would further allow comparison across regions, and thus enable a national assessment across the land–sea interface for Germany or a comparative ES assessment of the North and Baltic Sea Region.

### *4.3. Methodological Limitations and Perspective for Future Research*

To our best knowledge, this is the first integrated study that jointly assesses ES potentials and flows of a large variety of terrestrial, coastal, and marine habitats. Our application results provided a holistic overview of ES potentials, flows and development capacities in three Baltic CSS. However, our results are affected by some methodological limitations that need to be highlighted and shall be addressed in future studies:

First, a lack of geospatial data partly affected the application of the spatial habitat typology in the CSS. To obtain spatial maps on sediments and submerged vegetation was most difficult. The lack of geospatial data on seabed sediments is likely a particularity of inner coastal waters, where areal mappings with traditional methods, like sediment echo sounders or side view sonars, are restricted to shallow water levels [50]. Furthermore, information of the distribution of submerged vegetation was largely lacking for all CSS. Thus, the best available data was used, which varied strongly among CSS. This affected the spatial mapping of submerged vegetation in particular. An application of satellite, aerial, and underwater drone imagery could be beneficial to support habitat mapping of coastal habitats and shallow water areas.

Second, the definition of maximal flow values and assessment of CSS-specific flow values was based on literature and public databases, geoportals, and statistics. Due to language barriers the approach to define a maximal flow was partly adjusted and only based on data for Germany, which was available on a smaller spatial scale. In addition, some of the CSS flow values are highly affected by the available literature and data used. For instance, literature-based values were used to define flow values for the indicator 'nitrogen cleaning'. Due to the different scope of analyzed studies, indicated values are not reliable. Particularly for regulating ES, the potential use of modelling results should be further explored, to ensure better comparability.

Third, for the purpose of this study, we multiplied the relative flow values with the ES potential values included in the Baltic ESP Matrix, to generate CSS-specific flow matrices. This is certainly a huge simplification. While it serves as a fast solution and provided comparable results for the purpose of this study, it has major weakness and should not be used for practical applications to support decision-making. In future studies, habitat-specific flow values need to be defined, for the maximal flow (or alternatively sustainable reference) and the flow values of the CSS.

## 5. Conclusions

We have presented a novel approach for spatial ES assessments across the land–sea interface. Our underlying spatial habitat typology builds upon CLC types and major elements of EU environmental policies. The CSS applications showed that needed geospatial data is readily available and that the typology is easily applicable within the Southern Baltic Sea Region. In general, the approach can be expanded beyond territorial waters and transferred to other areas within the EU. However, additional marine habitats have to be added to be applicable in systems with higher salinities and hydrodynamics, such as the North Sea, and better differentiation of marine waters is suggested. The approach could then be used to support ES assessments within the scope of the EU MSFD or MSP Directive.

The expert-based Baltic ESP matrix allows for a holistic assessment of ES. Despite the inherent uncertainties of expert-based approaches, it was found to be suitable for comparing ES potentials among different Baltic case studies and can serve as a basis for subsequent comparisons of ES potentials and ES flows.

Our indicator-based approach to assess ES flows enables a quantification and ensures comparability among different CSS. Being based on maximal flow values within the Cfb climate zone, it potentially allows an application across a large geographical area. In addition, the choice of policy relevant indicators ensures practical relevance and enables user to use data, which is required for EU policy reporting and should thus be publicly accessible. Instead of comparing ES potentials and flows, a comparison of ES flows with sustainable reference values, based on policy relevant thresholds and targets, is suggested. To overcome current limitations, habitat specific flow and sustainable reference values need to be further explored.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/app112411799/s1, Table S1: Baltic ESP Matrix, File S2: Description of flow indicators.

**Author Contributions:** Conceptualization, J.S. and G.S.; methodology, J.S., S.L., F.M. and G.S.; software, J.S. and S.L.; writing—original draft preparation, J.S.; writing—review and editing, J.S., S.L., F.M. and S.L.; visualization, J.S.; supervision, G.S. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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