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Ecosystem Accounting Table

Marine ecosystem extent and condition pilot accounts for Finland

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Abstract

Ecosystem accounting provides a standardised framework for evaluating the economic value of ecosystems to society. Following the international accounting standard, System of Environmental Economic Accounting – Ecosystem Accounting (SEEA EA), we present first marine ecosystem extent pilot accounts for Finland, based on three habitat classification systems: the Marine Strategy Framework Directive (MSFD), the EU Habitats Directive (HD) and the IUCN Red List of Ecosystems (RLE). We assess their condition using indicators from the Water Framework Directive, which measure ecosystem quality through biological, ecological and physico-chemical parameters.

We found that MSFD habitats have the largest extent, exceeding the areas covered by HD and RLE habitats. A large portion of the assessed habitats, particularly in the inner archipelago and shallow areas close to shore, were in poor condition, reflecting the eutrophication status of coastal waters. We identify considerable challenges in reporting marine ecosystem extent and condition accounts, which most likely recur across (European) countries. For instance, MSFD habitats are rather coarse for accurately reporting ecosystem extents, potentially overlooking declines in ecosystem condition, while HD habitats cover only a subset of habitats. RLE habitats provide more ecological detail, although they may be less compatible with classifications used in other countries.

Our research provides a baseline for future ecosystem accounts and emphasises the need for improved data and methods to enhance the accuracy and comparability of marine ecosystem assessments. Additionally, we discuss the compatibility of SEEA EA with EU policy reporting requirements, the spatial scale of reporting ecosystem extents and condition and highlight the limitations of current habitat classifications in representing the full diversity of marine ecosystems. The findings underscore the importance of integrating multiple habitat classification systems, development of crosswalks between habitat classifications and monitoring frameworks to ensure comprehensive and accurate ecosystem accounts.

Keywords

Baltic Sea, ecosystem accounting, ecosystem extent, marine habitats

Introduction

The importance of ecosystems and their services to human well-being and the economy is widely recognised (Burkhard et al. 2010, Haines-Young and Potschin 2010) and various international commitments, including the Kunming-Montreal Global Biodiversity Framework (CBD 2022) , advocate for a system capable of monitoring and quantifying ecosystem changes across spatial and temporal scales. The System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA EA) is an integrated statistical framework for organising biophysical data, measuring ecosystem services, tracking changes in ecosystem extent and condition and linking this information to economic and other human activities (UN 2021).

According to SEEA EA, ecosystem assets are contiguous, mappable areas of a specific ecosystem type, defined by unique biotic and abiotic components and their interactions. An ecosystem accounting area (EAA) is the geographical region where an ecosystem account is compiled, determining which assets are included (UN 2021). Ecosystem assets should be geographically and conceptually exhaustive and exclusive; for example, within a marine EAA, each horizontal depth layer or area of the seafloor should be occupied by only one ecosystem asset, though multiple assets of the same type may exist. Together, extent and condition define the ecosystem´s capacity to provide ecosystem services (UN 2021). The asset´s value is the discounted future exchange of services between the ecosystem and society, linked to ecosystem capacity, which depends on its condition. In the SEEA EA framework, degradation occurs when there is a loss in the asset´s value due to changes in extent or condition. Well-defined extent and condition accounts are essential for accurately determining ecosystem service flows and their value, as they provide a solid basis for assessing the integrity and capacity of ecosystems, which is critical for effective ecosystem management and decision-making.

Studies on ecosystem extent and condition have slowly evolved with the aim to increase the transparency regarding the value ecosystems hold for people and, so far, 35 countries have produced SEEA EA accounts (UN 2023). For instance, Gomez Cardona et al. (2023) developed ecosystem accounts for a wetland ecosystem in Colombia, Gacutan et al. (2022) for a lake ecosystem in Australia, Bruzón et al. (2022) for Spanish terrestrial ecosystems and Alarcon Blazquez et al. (2023) for the North-East Atlantic regional sea. Compared to terrestrial environments where a wealth of data is easily available from Earth Observation and usable for assessing land use and cover, data for marine systems are more difficult to acquire. Concerns have also been raised about the quality of data used in ecosystem accounting (Navarro et al. 2024) and how the uncertainty inherent in marine data, resulting from the dynamic and highly variable nature of marine ecosystems, can undermine the reported accounts and the credibility of resulting management decisions. Accounts should always be based on best available knowledge, which most often is national data of high taxonomic and spatial accuracy, though not necessarily comparable with data from other countries. For instance, in Europe, various habitat classification systems have been developed for reporting requirements of various marine management and conservation policies. Thus, a considerable research gap exists on how ecosystem accounts differ depending on the ecosystem data used and how the reporting requirements of other policies can support or complement ecosystem accounting, including condition indicators.

Amendments to EU Regulation 691/2011 on environmental-economic accounts currently lack mandates for marine ecosystem service reporting, risking their exclusion from key policy and resource allocation decisions. To prevent marine ecosystems from being overlooked as critical societal assets, it is essential to advance accounting methods tailored for marine ecosystems and ecosystem services. This need is further underscored by, for example, the EU Nature Restoration Law, Marine Strategy Framework Directive (MSFD), Habitats Directive (HD), maritime spatial planning initiatives and the Kunming-Montreal Global Biodiversity Framework, all of which could benefit from and have synergies with accurate and comprehensive marine ecosystem accounts.

Here, we report the first pilot accounts of marine ecosystem extent and condition for Finland. Lai et al. (2018) previously linked some ecosystem service indicators to the Finnish ecosystem accounting framework, while Jernberg et al. (2024) compiled comprehensive information on ecosystem services provided by marine habitats in the northern Baltic Sea. Detailed marine habitat maps in Finland are available through comprehensive biological surveys (Forsblom et al. 2024), which are essential for assessing ecosystem services, such as blue carbon that involve complex processes operating at fine spatial scales (Asplund et al. 2021). The SEEA EA provides a useful framework that can support Finland´s national commitments to EU policies and also provide valuable input for national conservation status assessments and for evaluating environmental impacts of development. Similarly, existing EU and national policies can complement and support SEEA EA reporting, reducing the bureaucratic burden. We aim to provide a baseline on ecosystem extents for future studies and show how existing EU policies can support the implementation of the SEEA EA. We base our ecosystem extent evaluation on three ecosystem classifications, usually broadly available across the European Union that support various policy requirements: *i*) broad habitat types of the

MSFD, *ii*) habitat types of the HD and *iii*) threatened habitat types of the IUCN Red List of Ecosystems (RLE). We discuss the compatibility of SEEA EA with EU policy reporting requirements, the spatial scale of reporting ecosystem extents, data requirements and challenges, as well as the suitability of indicators.

Data and methods

An account table for SEEA EA compiles spatially referenced data on the assets into a tabulated form and presents aggregated information by ecosystem type. This process necessarily leads to the loss of information on the details and distribution of the spatial dimensions and condition of the assets. However, aggregation is necessary to provide data consistent with the structure and measures used in the system of national accounts. The extent of marine ecosystems can be defined in several ways, depending on the taxonomic unit, spatial scale and ecosystem classification system in use.

Habitat data

We report ecosystem extents, based on three existing habitat classification systems used in Finland to facilitate future ecosystem accounting and support the integration with EU reporting standards:

1. benthic broad habitat types of the Marine Strategy Framework Directive (MSFD) (2008/56/EC),
2. marine habitat types of the EU Habitats Directive Annex I (92/43/EEC) (HD) and
3. marine habitat types described in national threatened status assessment, based on IUCN Red List of Ecosystems criteria (RLE).

Habitat types within these classification systems vary in spatial scale, abiotic characteristics and ecological properties.

Marine Strategy Framework Directive benthic broad habitat types

MSFD benthic broad habitats are defined by biological zone, seabed substrates, riverine input, habitat descriptors, energy class, as well as oxygen and salinity regimes. In this study, we consider 15 benthic broad habitat types, based on information from the EMODnet Seabed Habitats (Vasquez et al. 2021), with local modifications for shallow areas for the latest MSFD reporting (Syke 2024). These habitats are categorised by depth into three zones: deep circalittoral, shallow circalittoral and infralittoral, with five substrate classes, including hard, coarse, sandy, muddy and mixed substrates.

Habitats Directive Annex I habitat types

The Habitats Directive (92/43/EEC) habitat types are primarily defined by morphological or geological parameters. Of the 69 habitats found in Finland, six are marine (Annex I habitat type code): Boreal Baltic narrow inlets (1650), coastal lagoons (1150), estuaries

(1130), large shallow inlets and bays (1160), sandbanks (1110) and reefs (1170). The data used to calculate the extent of these were based on the most recent Habitats Directive reporting from 2019 (Kaskela and Rinne 2018, EIONET 2019).

Habitat types of the IUCN Red List of Ecosystems

The assessment methodology of IUCN Red List of Ecosystems (RLE) is a global standard for assessing the extinction risk of ecosystems and monitoring their status (Keith et al. 2015). Threatened status of both habitat types and species in Finland were assessed in 2018 and 2019, respectively, using the IUCN RLE criteria (Kontula and Raunio 2018, Hyvärinen et al. 2019 In the assessment, habitats are defined, based on dominant biota, such as habitat forming algae, seagrasses or invertebrates. As such, the RLE habitat types are more detailed than those of the MSFD or HD and include benthic habitat types from the littoral and deeper zones, as well as pelagic (open water) (Fig. 2). Data for these were available from species distribution models (Virtanen et al. 2018), based on comprehensive biological surveys (Forsblom et al. 2024). We include 19 habitats in the present assessment (see Suppl. material 1). By evaluating the extent and condition of habitats based on three classification systems presently in use, this allows a foundation for future ecosystem accounting at appropriate levels. Input data sources for calculating ecosystem extents and their spatial and temporal resolution are shown in Fig. 1.

Ecosystem extents

Both the MSFD benthic broad habitats and the HD habitats were available in polygon format. We calculated the extent of the habitats (in hectares) using the R package sf and exactextractr (Pebesma 2018, Pebesma and Bivand 2023, Baston 2023). For the 19 RLE habitat types, we used predicted occurrence probabilities, based on a previously published species distribution modelling approach (Virtanen et al. 2018). To calculate their extent, we transformed each habitat model into binary output, using a threshold value that maximises sensitivity (true positives) and specificity (true negatives) (Liu et al. 2015), generating 19 gridded habitat maps. The resolution of the prediction for each individual habitat was 20 m x 20 m (400 m^2), while the (biological) field observations used for modelling typically cover 1–4 m^2 (Forsblom et al. 2024).

The fragmented nature of Finnish marine habitats means that more than one RLE habitat is often predicted to occur within the same 400 m^2 grid, given the high spatial variability of habitats that usually exist within an area on small spatial scale. Therefore, it is unrealistic to assume that a full grid of 400 m^2 size would be occupied by a single habitat type. Due to the uncertainty in estimating the exact cover within each grid, we report the extent of RLE habitats as the number of “extent units”, which correspond to the number of 20 m x 20 m grid cells in which each habitat is predicted to occur. SEEA EA´s term Basic Spatial Units (BSUs) are typically designed to be non-overlapping and cover the entire ecosystem accounting area (EAA), aligning with the principles of national and ecosystem accounts. This setup allows BSUs to fully represent spatial units in a systematic, standardised way. In contrast, the "extent units" used in this context are potentially overlapping and do not fully cover the EAA, meaning they are not exhaustive or mutually exclusive, which may limit their ability to create a comprehensive ecosystem account. However, this approach ensures future reporting at more detailed levels as higher-resolution data become available, since the relative occurrence of RLE habitats within the extent units remains stable. A detailed description of the modelling approach for the RLE habitats is provided in Suppl. material 1.

	Spatial resolution	Temporal resolution	Source
Marine Strategy Framework Directive habitats			
Coarse - deep circalittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Coarse - infralittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Coarse - shallow circalittoral	20 x 20 m	2004-2020	Syke data, Velmu project, Vasquez et al. 2021
Hard - deep circalittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Hard - infralittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Hard - shallow circalittoral	20 x 20 m	2004-2020	Syke data, Velmu project, Vasquez et al. 2021
Mix - deep circalittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Mix - infralittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Mix - shallow circalittoral	20 x 20 m	2004-2020	Syke data, Velmu project, Vasquez et al. 2021
Mud - deep circalittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Mud - infralittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Mud - shallow circalittoral	20 x 20 m	2004-2020	Syke data, Velmu project, Vasquez et al. 2021
Sand - deep circalittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Sand - infralittoral	Varying resolution	2019-2021	Vasquez et al. 2021
Sand - shallow circalittoral	20 x 20 m	2004-2020	Syke data, Velmu project, Vasquez et al. 2021
Habitats Directive Annex I habitats			
Boreal Baltic narrow inlets (1650)	Expert delineation	2013	EIONET 2019
Coastal lagoons (1150)	Expert delineation	2013-2019	EIONET 2019
Estuaries (1130)	Expert delineation	2016-2018	EIONET 2019
Large shallow inlets and bays (1160)	Expert delineation	2013	EIONET 2019
Reefs (1170)	Varying resolution, 1:20 000, 1:250 000, 1:1 000 000	2018	Kaskela & Rinne 2018, EIONET 2019
Sand banks (1110)	Varying resolution, 1:20 000, 1:250 000, 1:1 000 000	2018	Kaskela & Rinne 2018, EIONET 2019
Habitat types of Red List of Ecosystems			
Aquatic moss habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Chorda filum and/or Halosiphon tomentosus habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Eleocharis habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Exposed Charales habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Filamentous annual algae habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Floatingleaved plants habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Fucus habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Hippuris habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Myriophyllum spicatum and/or M. sibiricum habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Najas marina habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Perennial filamentous algae habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Potamogeton and/or Stuckenia pectinata habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Ranunculus habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Red algae habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Sheltered Charales habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Unattached Ceratophyllum demersum habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Vaucheria habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Zannichellia and/or Ruppia habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018
Zostera marina habitats	20 x 20 m	2004-2020	This study, based on Virtanen et al. 2018

Figure 1.

Input data sources for calculating ecosystem extents and their spatial and temporal resolution.

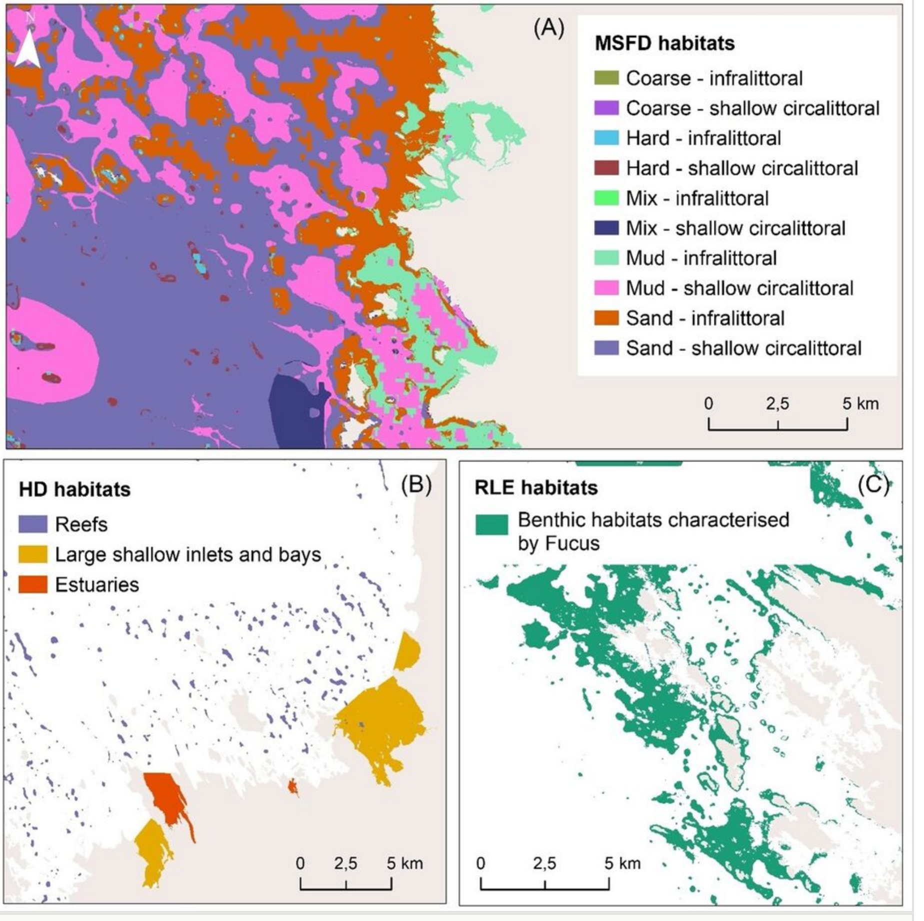

Figure 2.

Example maps of ecosystem classification used to report ecosystem extents: **(A)** Marine Strategy Framework Directive benthic broadscale habitats (MSFD habitats), **(B)** Habitats Directive habitats (HD habitats) and **(C)** habitat types used in national threatened status reporting, based on threatened status of Red List of Ecosystems (RLE habitats).

Ecosystem condition indicators

Ecosystem condition accounts provide a structured approach to recording and aggregating data on the condition of different ecosystem assets and types. In the SEEA EA framework, ecosystem condition refers to the quality of an ecosystem, assessed through its abiotic and biotic characteristics, defined using condition variables that indicate how far an ecosystem is from its desired state. Indicators are rescaled versions of the variables that allow comparison across areas and ecosystem types. The SEEA ecosystem condition typology offers a structured way of assessing the state of ecosystem, including physical, chemical, compositional and structural characteristics (Vallecillo Rodriguez et al. 2022).

The Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) require Member States to develop condition indicators that are comparable across sea basins and countries, to ensure the compatibility of ecosystem status assessments. Since SEEA EA aims to take advantage of existing monitoring frameworks, we define ecosystem condition based on the ecosystem status assessment of the 2021 WFD reporting period. WFD and MSFD both have rather similar goals regarding the status of marine waters and management measures within the WFD apply also to MSFD, delivering set environmental targets (Van Hoey et al. 2010, Puharinen 2023). In the EU ecosystem accounting framework, it is assumed that MSFD and WFD indicators are directly applicable as condition indicators (Vallecillo Rodriguez et al. 2022).

Finland´s sea area is divided into 276 WFD areas and their status is primarily assessed using biological indicators, supplemented by physio-chemical and hydrological-morphological indicators (e.g. Secchi depth, nutrients, oxygen, salinity (ELY centres 2022)). Good ecological status or the reference level is defined in national legislation and mainly relies on chlorophyll *a*, benthic fauna communities and the maximum occurrence depth of the brown alga, bladderwrack (*Fucus vesiculosus*). Thresholds for different water quality variables are specific to each WFD area and the ecological quality is assessed as high, good, moderate, poor or bad. The latest assessment from 2021 is based on monitoring data from 2012–2017, with some data from 2018. Ecological status, along with biological and physico-chemical quality, is reported for each of the 276 WFD area.

We defined the condition of ecosystems (MSFD benthic broad habitat types, HD habitats, RLE habitats) based on the WFD status assessment, by calculating the overlap of each habitat within the WFD area. However, we were unable to assess the condition for habitats that extend beyond territorial waters to exclusive economic zones, areas where the coastline did not completely align with WFD areas and for areas lacking biological or physico-chemical quality data. For these, only extent information is reported.

Accounting tables and results

The accounting tables in Suppl. materials 2, 3 provide data of the total ecosystem extent and condition of habitats, along with the proportion of the extent of habitats that could be assessed using the WFD indicators. To facilitate interpretation of results, we present aggregated versions of accounting tables in Tables 1, 2, 3 as well as in Figs 3, 4. SEEA EA offers two alternative presentation types for aggregated ecosystem condition indices and the tables presented here use the presentation method of the table as per paragraph 5.97 of the SEEA EA manual (UN 2021).

Shallow, circalittoral, mixed and muddy substrate habitats are the most common MSFD habitats in Finland, as their combined extent exceeds that of all other MSFD habitats. MSFD habitats also cover much larger areas compared to HD habitats, with extents approximately ten times greater (Fig. 3). The RLE habitats are not directly comparable with MSFD and HD habitats, as their extents are reported in extent units, i.e. the number of pixels where each RLE habitat type is predicted to occur. The RLE extent units can be used to calculate RLE extent accounts, but would require assumptions on how large area of the grid cells each habitat covers. The largest RLE habitat is the filamentous annual algae habitat, followed by the red algae habitat, which are predicted to occur in over 12 million and 9.5 million extent units, respectively (Fig. 3).

Table 1.

Extents of Marine Strategy Framework Directive benthic broad habitat types. The total extent (ha) represents the combined area of habitats across Finnish sea areas, while the percentage in brackets represents the share of habitats for which condition assessments were possible, based on the assessment area of the Water Framework Directive. ND (Not Defined) refers to WFD areas where status was not assessed. Values rounded to closest integer for values > 1.

	Coarse - deep circalittoral						**Coarse - infralittoral**					
Total extent (ha)	0.8 (100%)						15359 (100%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	0	0.8	0	0	0	0	366	14347	637	5	0
Biological Quality	0	0	0.8	0	0	0	0	381	14591	376	7	0.8
Physico-chemical Quality	0	0	0.8	0	0	0	25	1021	13501	797	0.8	11
	Coarse - shallow circalittoral						**Hard - deep circalittoral**					
Total extent (ha)	56284 (68%)						333 (80%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	5027	31444	1528	1	0	0	0	267	0	0	0
Biological Quality	0	5282	31983	734	1	0.9	0	0	267	0	0	0
Physico-chemical Quality	922	5095	30224	1757	0.2	1	0	0	267	0	0	0
	Hard - infralittoral						**Hard - shallow circalittoral**					
Total extent (ha)	318716 (98%)						350843 (80%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	59833	244344	7807	27	0	0	33645	225503	23104	6	0
Biological Quality	0	54949	250242	5821	346	655	0	29355	234805	17857	24	216

	Coarse - deep circalittoral						Coarse - infralittoral					
Physico-chemical Quality	6445	50716	246057	7729	65	1000	5650	38210	214616	23507	41	233
	Mix - deep circalittoral						**Mix - shallow circalittoral**					
Total extent (ha)	71872 (3%)						3605907 (26%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	0	2489	0	0	0	0	149334	757439	18494	3	0
Biological Quality	0	0	2489	0	0	0	0	145250	764520	15335	16	147
Physico-chemical Quality	0	0	2489	0	0	0	25697	108158	751871	39337	44	162
	Mix - infralittoral						**Mud - deep circalittoral**					
Total extent (ha)	120889 (100%)						239208 (0.3%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	0	672	0	0	0	0	0	672	0	0	0
Biological Quality	0	0	672	0	0	0	0	0	672	0	0	0
Physico-chemical Quality	0	0	672	0	0	0	0	0	672	0	0	0
	Mud - infralittoral						**Mud - shallow circalittoral**					
Total extent (ha)	414947 (100%)						2249789 (32%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	18516	295474	98847	2095	0	0	31220	593201	87537	1109	0
Biological Quality	0	40450	276280	81669	3661	12873	0	42890	595521	69038	1322	4298
Physico-chemical Quality	2918	30667	254914	94089	18619	13725	1409	73206	537111	94541	2980	3822
	Sand - deep circalittoral						**Sand - infralittoral**					
Total extent (ha)	8 (100%)						179646 (95%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	0	8	0	0	0	0	21815	142940	6418	60	0

	Coarse - deep circalittoral						**Coarse - infralittoral**					
Biological Quality	0	0	8	0	0	0	0	29443	125368	7809	894	7717
Physico-chemical Quality	0	0	8	0	0	0	3702	62442	89186	14796	63	1041
	Sand - shallow circalittoral											
Total extent (ha)	518256 (45%)											
	Condition:											
Condition variable	High	Good	Moderate	Poor	Bad	ND						
Ecological status	0	53918	175170	5438	12	0						
Biological Quality	0	57062	171489	5333	143	511						
Physico-chemical Quality	3382	132368	64601	34001	12	174						

Table 2.

Extents of Habitat Directive Annex I habitats. The total extent (ha) represents the combined area of habitats across Finnish sea areas, while the percentage in brackets represents the share of habitats for which condition assessments were possible, based on the assessment area of the Water Framework Directive. ND (Not Defined) refers to WFD areas where status was not assessed. Values rounded to closest integer for values > 1.

	Boreal Baltic narrow inlets (1650)						**Coastal lagoons (1150)**					
Total extent (ha)	36947 (100%)						69831 (88%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	0	11276	24273	1353	0	0	2071	36074	23060	581	0
Biological Quality	0	0	11819	22855	1353	876	0	4111	36288	18641	810	1936
Physico-chemical Quality	0	0	12563	21937	1527	876	509	3081	30087	19394	6550	2167
	Estuaries (1130)						**Large shallow inlets and bays (1160)**					
Total extent (ha)	76674 (98%)						49760 (100%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND

	Boreal Baltic narrow inlets (1650)						**Coastal lagoons (1150)**					
Ecological status	0	17	34318	39424	1353	0	0	5582	27412	15550	1027	0
Biological Quality	0	1101	34479	35001	2690	1842	0	9325	22798	13870	1418	2161
Physico-chemical Quality	0	5669	16512	36599	12212	4120	4900	2076	19624	14956	3905	4110
	Reefs (1170)						**Sand banks (1110)**					
Total extent (ha)	245086 (70%)						54577 (70%)					
	Condition:						**Condition**:					
Condition variable	High	Good	Moderate	Poor	Bad	ND	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	35527	128811	7557	11	0	0	2362	34255	1658	0	0
Biological Quality	0	34856	130605	6275	22	148	0	2382	33790	2095	0	8
Physico-chemical Quality	8011	25100	129633	8969	49	143	23	11873	22910	3458	0	10

Table 3.

Ecosystem extent units (number of 20 m x 20 m grid cells where the habitat occurs) of Red List of Ecosystems habitat types. The number of extent units represents the number grid cells where habitat occurs across Finnish sea areas, while the percentage in brackets represents the share of extent units for which condition assessments were possible, based on the assessment area of the Water Framework Directive. ND (Not Defined) refers to WFD areas where status was not assessed. Values rounded to closest integer for values > 1.

	Aquatic moss habitats					
Number of extent units	409871 (94%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	704	177365	202538	5949	0
Biological Quality	0	3450	220184	152273	6206	4444
Physico-chemical Quality	48	54319	115961	175788	38147	2294
	***Chorda filum* and/or *Halosiphon tomentosus* habitats**					
Number of extent units	3083732 (97%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	233	2924404	81554	1	0
Biological Quality	0	233	2922111	76223	1	7625

	Aquatic moss habitats					
Physico-chemical Quality	1	3931	2916270	77349	1016	7625
	***Eleocharis* habitats**					
Number of extent units	562703 (93%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	5711	434936	79506	668	0
Biological Quality	0	65368	315617	70227	705	68903
Physico-chemical Quality	34	63666	196391	182547	49824	28357
	Filamentous annual algae habitats					
Number of extent units	12211926 (96%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	2531666	8735793	403160	1996	0
Biological Quality	0	2411262	8830046	329269	54986	47052
Physico-chemical Quality	342547	3151859	7598724	471811	9773	97900
	Floating-leaved plant habitats					
Number of extent units	722631 (93%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	5293	253071	404583	9085	0
Biological Quality	0	30229	264840	340257	17753	18954
Physico-chemical Quality	2791	23728	181067	289822	152430	22194
	***Fucus* habitats**					
Number of extent units	4367312 (97%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	370299	3492795	352433	1145	0
Biological Quality	0	377911	3518524	282287	4754	33196
Physico-chemical Quality	95426	519211	3294257	264978	3466	39334
	***Hippuris* habitats**					
Number of extent units	36540 (90%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	114	11705	21003	195	0
Biological Quality	0	565	13496	17640	230	1086
Physico-chemical Quality	21	840	9311	14759	7213	873

	Aquatic moss habitats					
	Myriophyllum spicatum **and/or** ***M. sibiricum*** **habitats**					
Number of extent units	5816560 (95%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	452944	3495617	1535477	42551	0
Biological Quality	0	684028	3349285	1207449	88295	197533
Physico-chemical Quality	123002	436302	3168273	1296941	257979	244093
	Najas marina **habitats**					
Number of extent units	1257450 (96%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	31922	701731	449117	18541	0
Biological Quality	0	53324	702558	368788	28261	48379
Physico-chemical Quality	8771	49806	647880	373531	66231	55092
	Perennial filamentous algae habitats					
Number of extent units	2050272 (86%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	290382	1202882	262240	9348	0
Biological Quality	0	373463	1164890	176368	13917	36215
Physico-chemical Quality	45826	409301	1014092	255953	19237	20442
	Potamogeton **and/or** ***Stuckenia pectinata*** **habitats**					
Number of extent units	7017454 (98%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	569188	5047911	1208085	24862	0
Biological Quality	0	824714	4765099	962193	75693	222346
Physico-chemical Quality	183044	491012	4524755	1162372	205609	283253
	Ranunculus **habitats**					
Number of extent units	5699 (86%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	130	2724	2034	7	0
Biological Quality	0	411	2620	1687	16	161
Physico-chemical Quality	10	312	2797	933	676	167
	Red algae habitats					

	Aquatic moss habitats					
Number of extent units	9578675 (93%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	729401	8003982	201932	97	0
Biological Quality	0	732293	8050381	144624	4801	3313
Physico-chemical Quality	86685	1658507	6986338	194947	416	8520
	Unattached *Ceratophyllum demersum* habitats					
Number of extent units	1244628 (98%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	18334	820568	364090	12775	0
Biological Quality	0	20695	846096	304748	13155	31074
Physico-chemical Quality	2293	16963	851731	293010	19841	31930
	***Vaucheria* habitats**					
Number of extent units	2254469 (99%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	219529	1338296	658147	18100	0
Biological Quality	0	392729	1247496	503777	39731	50338
Physico-chemical Quality	16135	328562	1019376	668964	100531	100502
	***Zannichellia* and/or *Ruppia* habitats**					
Number of extent units	4890818 (96%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	364425	3786597	556800	6677	0
Biological Quality	0	473887	3642938	444945	45771	106957
Physico-chemical Quality	111530	337138	3547193	498010	62273	158355
	***Zostera marina* habitats**					
Number of extent units	536517 (99%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	1904	521558	8532	0	0
Biological Quality	0	1910	523749	6285	0	49
Physico-chemical Quality	254	4970	499071	26407	11	1280
	Exposed Charales habitats					
Number of extent units	4233244 (97%)					

	Aquatic moss habitats					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	527338	2942303	650874	3007	0
Biological Quality	0	850049	2373421	521073	55110	323869
Physico-chemical Quality	115944	803985	1992704	754084	219144	237662
	Sheltered Charales habitats					
Number of extent units	4014706 (98%)					
	Condition:					
Condition variable	High	Good	Moderate	Poor	Bad	ND
Ecological status	0	504235	2793455	632716	9485	0
Biological Quality	0	834584	2271659	488539	46490	298619
Physico-chemical Quality	97174	788915	1976394	682009	199010	196390

A large portion of the assessed habitats were in poor condition, regardless of the habitat classification used (Fig. 4). Habitats that occur in the inner archipelago (e.g. estuaries), or closer to the shore in shallow areas (e.g. lagoons or benthic habitats characterised by *Hippuris*), were found to be in poor condition. In contrast, habitats occurring deeper and in more exposed areas, such as reefs or benthic habitats characterised by red algae, were in better condition. Overall, MSFD habitats were generally in moderate condition, apart from shallow and circalittoral muddy areas.

Discussion

In this study, we present ecosystem extents for Finland, based on three common classification systems typically available across EU Member States: MSFD benthic habitat types, HD habitats and RLE habitat types. As condition indicators, we used variables reported under the Water Framework Directive, which describe ecosystem condition through ecological status to which biological, ecological and physico-chemical quality assessments contribute.

We found that the majority of habitats in the inner archipelago and shallow nearshore areas were in poor condition, which reflects the eutrophication status of our coastal waters (Syke 2024). Agriculture is the primary source of nutrient load in Finland, except in the Bothnian Bay, where natural runoff and forestry dominate. Despite extensive water protection efforts, achieving good water quality within the next 30 years remains unlikely, partly also due to climate change, which is expected to increase nutrient runoff (Fleming et al. 2023). Across the Baltic Sea countries, eutrophication is the primary pressure affecting marine ecosystems (Gustafsson et al. 2012, Andersen et al. 2015, Meier et al. 2018). Therefore, indicators that monitor eutrophication status (e.g. those under the WFD), are crucial for meeting EU policy requirements, including SEEA EA. WFD indicators are also suggested to be used by the SEEA EA (UN 2021) and they are part of the indicator variables of the Habitats Directive reporting (structure and function parameters) used in Finland. Thus, WFD indicators are useful measures for describing ecosystem condition for SEEA EA. However, as WFD concentrates on coastal areas, the status of offshore areas is not assessed. Many marine habitats extend beyond Finnish territorial waters and require use of additional indicators. A similar situation most likely applies also to other countries. An alternative option could be to use MSFD indicators (i.e. descriptors), but a potential challenge is the extensive geographical scope of the MSFD reporting areas. Finland´s marine areas are divided into six MSFD reporting areas, in contrast to 276 WFD areas, which provide more detailed information on ecosystem condition. A critical aspect of assessing ecosystem condition with WFD indicators is the length of the WFD reporting period. Given the rapid warming of surface waters, which may amplify impacts of eutrophication (Safonova et al. 2024), the condition of marine ecosystems could change significantly over the six-year reporting cycle. Some WFD water quality variables are already monitored with methods that allow annual assessments of ecosystem condition, such as Earth Observation used for measuring chlorophyll *a* (Attila et al. 2018). These advancements could technically support more frequent reporting of ecosystem condition, even on an annual basis. Additionally, habitat extents may also improve in precision, not necessarily due to habitat degradation, but as new, higher resolution data become available (Misiuk and Brown 2023).

Our results also show that habitat extent can be defined in several ways, depending on habitat classification in use and data availability. This also means that ecosystem accounting results vary, depending on the chosen classification and its spatial scale (e.g. Rahayu et al. (2024)). As the scale of assessed habitats differs, so does the condition assessment; then the question is: what condition indicator should be used? If the definition of ecosystem extents is based on the coarsest taxonomic and spatial scale (in our example, MSFD habitats), then condition indicators will have much lower impact on defining the actual change in habitats. The SEEA EA endorses the IUCN Global Ecosystem Typology (GET) for reporting ecosystem extents in an internationally standardised manner (UN 2021, Keith et al. 2022). The GET comprises six hierarchical levels (Keith et al. 2022), consisting of core realms (e.g. marine), which divide into biomes (e.g. marine shelf biome) and functional groups (e.g. subtidal rocky reefs). While the typology is useful for ensuring comparability between countries, it is rather coarse in terms of taxonomic representation and not fully aligned with national and local reporting requirements, as set out, for instance, by various EU policies and directives. Additionally, it adds to habitat classifications already in use, which are not necessarily in alignment with the reporting standards of ecosystem accounts. Only a small part of marine habitats in Finland are compatible with GET (e.g. seagrass meadows and rocky reefs), missing the diversity of marine habitats. This highlights the need for complementary approaches for defining ecosystem extents and development of crosswalks between the GET and habitat classifications currently in use in various countries.

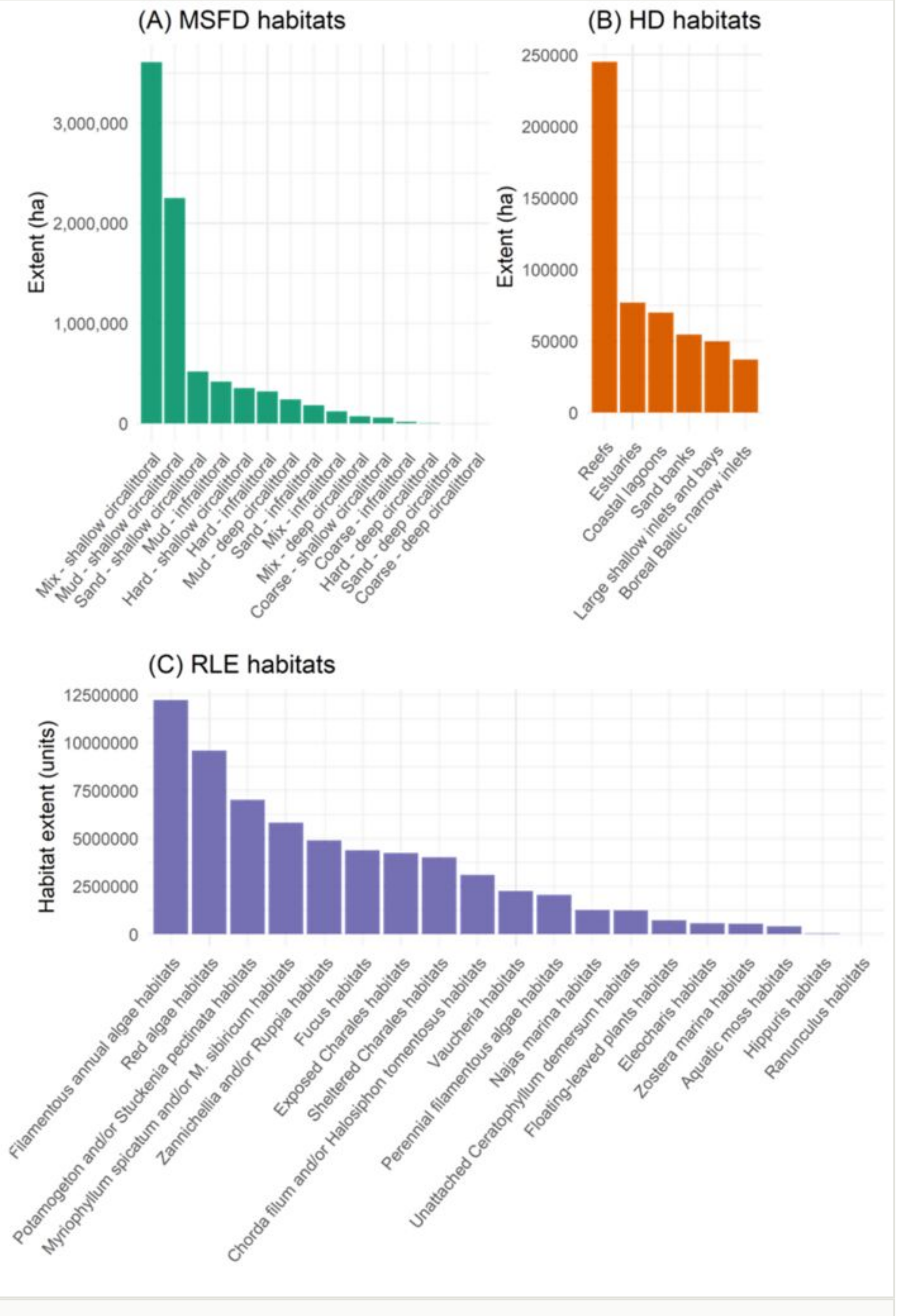

Figure 3.

Extent of **(A)** MSFD habitats, **(B)** HD habitats and **(C)** number of extent units for RLE habitats within Finnish marine areas. Each RLE extent unit has a maximum size of 400 m^2, determined by the used model´s resolution; it is unlikely that the habitat occupies the entire unit.

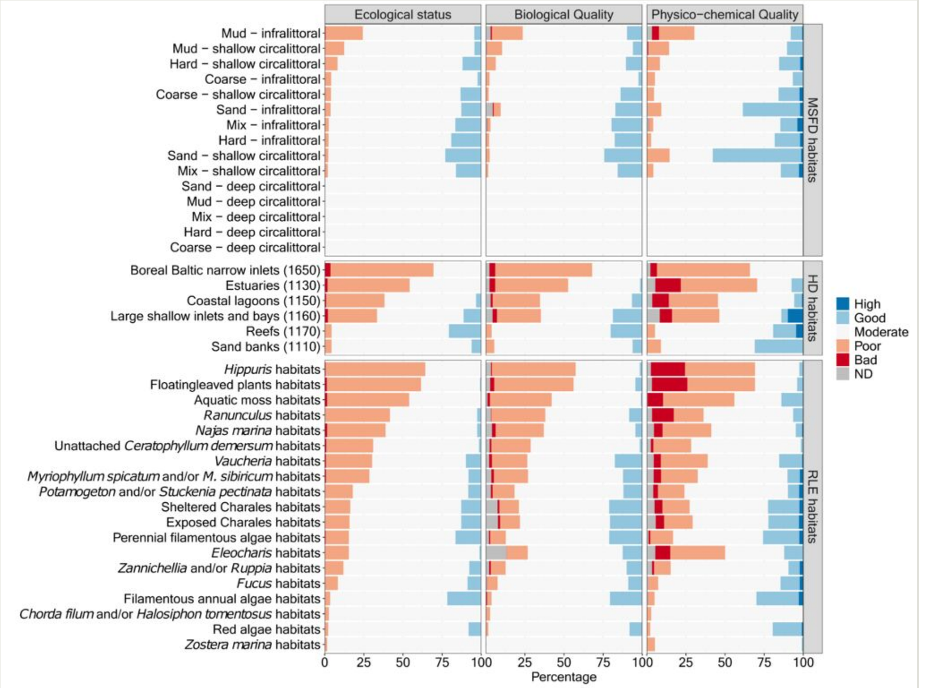

Figure 4.

Ecosystem condition expressed as the percentage of the total extent of ecosystem types including Marine Strategy Framework Directive broad-scale habitat types (MSFD habitats), Habitats Directive Annex I habitats (HD habitats) and Red List of Ecosystems habitat types (RLE habitats), based on the latest reporting period of Water Framework Directive. ND (Not Defined) refers to WFD areas where status was not assessed.

The SEEA EA framework emphasises both exclusivity and exhaustiveness, meaning each spatial unit should uniquely represent a habitat and collectively cover the entire area. Achieving this in marine environments is challenging, where data precision is limited and habitats often form patchy, overlapping distributions. This limitation complicates the creation of exhaustive ecosystem accounts, especially since only a subset of marine ecosystems may be fully represented, potentially leading to gaps in comprehensive regional or national ecosystem assessments. Given that the majority of habitat information of marine ecosystems relies on some type of modelling as mapping the seabed is expensive, the exclusivity requirement may be a severe hindrance to the development and implementation of SEEA EA in the marine context. This also applies to all habitats that are naturally patchy and biologically diverse, irrespective of the realm in question. In the Finnish context, many RLE habitats form belts at different depth zones, with much finer resolution than what current models can produce (Eriksson and Bergström 2005, Lappalainen et al. 2019). For example, filamentous algae, brown algae and red algae may co-exist within the same 400 m² area, making it difficult to justify selecting one over the other. Despite the limitations of the "extent units," which are overlapping and non-exhaustive, they can better capture the complex and irregular boundaries of marine ecosystems. This flexibility allows for finer spatial detail, especially in probabilistic models where multiple habitat types may co-occupy an area. In cases of limited data or resources, this approach offers a practical means of describing marine ecosystems and supporting specific management needs.

The requirement for exclusivity and exhaustiveness also strain the functionality of current habitat classification systems, emphasising the need to ensure that they adequately represent all habitats (Virtanen et al. 2018, Rinne et al. 2021). For instance, HD habitats cover only a fraction of marine ecosystems and, being primarily abiotic habitats, they are poor surrogates for marine biodiversity (Virtanen et al. 2018). MSFD and HD reporting rely on exclusive data (MSFD and HD habitats), though some overlap occurs due to Finland´s interpretation of HD habitat definitions. In the national threatened status assessment, spatial data on RLE habitats together with expert knowledge are used and each habitat type is assessed independently; therefore, non-exclusive data are not problematic. However, the non-exhaustive and non-exclusive nature of "extent units" can create challenges for marine governance and management. Overlapping units may lead to double-counting, inflating ecosystem service values, while unrepresented areas cause data gaps that may undervalue certain ecosystem services. Since ecosystem accounting aims to provide a comprehensive and standardised approach across ecosystems (terrestrial and aquatic), these units may hinder comparability with other standardised accounts and complicate national or regional ecosystem account compilation, reducing their effectiveness in supporting integrated environmental policy. Further, as SEEA EA focuses on separate ecosystem types, it does not fully capture the diversity between ecosystems and species. To address this limitation, thematic biodiversity accounts on species and diversity have been proposed to complement the SEEA EA framework (King et al. 2021, Luisetti and Schratzberger 2022). Although it could be possible to evaluate species-based extents (e.g. Virtanen et al. (2023)), reporting their condition would be problematic and comparability between countries impossible due to ecosystem differences.

Our study covered only 19 RLE habitats, missing particularly habitats defined by their fauna. Ecosystem extents of fauna are more challenging to compile and model, as the habitat definition relies on biomass (Kontula and Raunio 2018), for which data are limited. Additionally shoreline habitats, such as reed belts that are known to function as carbon sinks (Gu et al. 2020), were excluded from the present study, as they do not belong to any of the used habitat classifications or assessed as part of habitats on shore. The extent of reeds could be assessed using Earth Observation (e.g. Koponen et al. (2022)), since they have substantial above-water growth. It should also be stressed that RLE habitat types reflect the mean distribution of habitats over the past ~ 20 years. As the models predicting habitat extent already include explanatory variables related to eutrophication status (see Suppl. material 1), certain habitats may not be predicted to occur in WFD areas with poor condition. They can instead be viewed as a baseline to use for comparison in the SEEA EA framework.

Extent and condition accounts form the foundation for defining ecosystem service supply and use accounts, but they do not directly reflect the value ecosystems provide to society.

Clear, well-structured extent and condition accounts are essential for understanding the capacity of ecosystems to provide services. However, the supply and use of ecosystem services also depend on factors such as ownership and stewardship of ecosystem assets and the institutional context regulating and promoting the exchange of ecosystem services (Barton 2022). Without well-defined extent and condition accounts, it becomes challenging to accurately map how ecosystems contribute to human well-being. The global biodiversity loss (WWF 2024) and rapidly proceeding climate change (Ripple et al. 2024), threaten not only nature itself, but also world economies (World Economic Forum 2023). Demonstrating and quantifying the monetary value of ecosystem, habitat and population losses is crucial for enhancing acceptance of conservation and climate mitigation efforts between both decision-makers and the public. However, if the reliability of these assessments can be questioned, necessary actions may fall short of the urgency required. Therefore, clarifying the role of different habitat classification systems in evaluating extent and condition is essential for producing credible estimates of ecosystem value. The proposed amendments to the EU Regulation (EU) 691/2011 on environmental economic accounts do not include a mandatory requirement for reporting ecosystem service accounts for marine ecosystems. Consequently, marine ecosystems are overlooked in the methods and tools (European Commission 2023) designed to be used to allocate the supply and use of ecosystem services—such as global and local climate regulation and nature-based tourism—to different ecosystem types. The same also applies to studies on the Baltic Sea ecosystem services (Kuhn et al. 2021). Therefore, it is essential to improve methods related to marine accounting to ensure a sufficient data basis for including marine ecosystem services in mandatory ecosystem accounts in the future. Otherwise, marine ecosystems risk being neglected as critical sources of well-being for society (Storie et al. 2021).

Conclusions

Our work provides the first attempt for marine ecosystem accounting in Finland that is streamlined with other EU policies, thus simplifying and facilitating the reporting under the SEEA EA. The reported data on ecosystem extents are in line with other reporting requirements of the EU and with national policies, such as threatened status assessments. Building on our work, future steps could be to use complementary MSFD indicators on eutrophication for offshore areas. We concentrated only on eutrophication, while, in reality, also other human activities, such as coastal land use or offshore industrial activities, exert pressures on marine ecosystems, degrading their condition. Therefore, additional indicators that measure the integrity of seabed would be important to include for future studies. While SEEA EA aims to provide standardised methods for producing comparable accounts on ecosystems, the standard still offers a plethora of methods for compiling these accounts, which can result in ecosystem accounts that are difficult to compare. Although a large amount of observational data on the distribution of species and habitats exists in Finland, these may not be compatible with higher levels of ecosystem classification, because similar data and (or) methods for constructing extent units may not be available in the same breadth from other regions. The Finnish case serves as an example of relatively detailed level of classification that can be achieved if suitable data exist and it also demonstrates the importance of pursuing accuracy and realism in the accounting framework.

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Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: Description of Red List habitat distribution models doi

Authors: Louise Forsblom & Elina A. Virtanen
Data type: Description of habitat models.
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Suppl. material 2: Ecosystem accounting tables for MSFD and HD habitats doi

Authors: Elina A. Virtanen, Louise Forsblom, Liisa Saikkonen, Susanna Jernberg, Markku Viitasalo, Soile Kulmala
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Suppl. material 3: Ecosystem accounting table for RLE habitats doi

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