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Gap identification in coastal eutrophication research – Scoping review for the Baltic system case

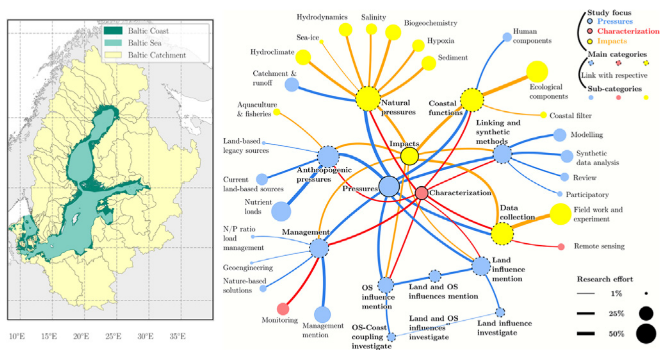
Guillaume Vigouroux *, Georgia Destouni

Department of Physical Geography, Stockholm University, 106 91 Stockholm, Sweden

HIGHLIGHTS

- Scoping review of research effort with classification of land-coast-sea interactions
- Ecosystem feedbacks in coastal eutrophication found to be understudied.
- Human and filtering aspects of coastal functions found to be understudied.
- The sources, including legacies, of nutrient load pressures found to be understudied.
- More studies needed on cross-scale, multi-solution management and incentives.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal eutrophication is a major issue worldwide, also affecting the Baltic Sea and its coastal waters. Effective management responses to coastal eutrophication require good understanding of the interacting coastal pressures from land, the open sea, and the atmosphere, and associated coastal ecosystem impacts. In this study, we investigate how research on Baltic coastal eutrophication has handled these interactions so far and what key research gaps still remain. We do this through a scoping review, identifying 832 scientific papers with a focus on Baltic coastal eutrophication. These are categorized in terms of study focus, methods, and consideration of coastal system components and land-coast-sea interactions. The coastal component categories include coastal functions (including also socio-economic driver aspects), pressures that are natural (or mediated by a natural process or system) or directly anthropogenic, and management responses.

The classification results show that considerably more studies focus on coastal eutrophication pressures (52%) or impacts (39%) than on characterizing the coastal eutrophication itself (20%). Moreover, few studies investigate pressures and impacts together, indicating that feedbacks are understudied. Regarding methods, more studies focus on data collection (62%) than on linking and synthetic methods (44%; e.g., modelling), and very few studies use remote sensing (6%) or participatory (3%) methods. Coastal links with land and open sea are mentioned but much less investigated. Among the coastal functions, studies considering ecological aspects are dominant, but much fewer studies investigate human aspects and the coastal filter function. Among the coastal pressures, studies considering nutrient loads are dominant, but much fewer studies investigate the sources of these loads, especially long-lived legacy sources and possible solutions for their mitigation. Overall, few studies investigate synergies, trade-offs and incentives for various solutions to address cross-scale multi-solution management.

* Corresponding author.
E-mail addresses: guillaume.vigouroux@natgeo.su.se (G. Vigouroux), georgia.destouni@natgeo.su.se (G. Destouni).

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1. Introduction

Coastal zones are home to a large share of the human population (Neumann et al., 2015) and play an important socio-economic role by providing a variety of provisional and recreational ecosystem services (Nicholls et al., 2007; Barbier et al., 2011). Due to their location at the land-sea interface, coastal areas are strongly affected by both land-based and sea-based processes and human pressures, as well as by atmospheric conditions and changes interacting with these (Malone and Newton, 2020). This makes the coastal areas a melting pot of various pressures (Vigouroux et al., 2021), influencing the coastal environment (including and additional to its own internal dynamics and processes). These include both direct anthropogenic (e.g., nutrient loads) and natural(-mediated) (e.g., hydroclimatic, biogeochemical changes) pressures (Elliott et al., 2017), with many of the latter also to some degree created by human drivers, such as economic growth and industrial agriculture. For example, human needs and activities have increased nutrient loads to the coast, which are causing coastal eutrophication (Nixon, 1995) and can further act in synergy with hydroclimatic changes (Glibert et al., 2014) to complicate eutrophication mitigation (Vigouroux et al., 2020). In turn, eutrophication impacts the functioning of the coastal zone, modifying its ecosystem services and creating hypoxic dead zones all over the world (Diaz and Rosenberg, 2008; Altieri and Diaz, 2019). Management responses targetting both eutrophication drivers (e.g., through policy) and pressures (e.g, through policy and direct management solutions) have been put in place, but have not yet led to desired recovery (only 70 out of 700 hypoxic coastal areas in recovery; Diaz et al., 2019).

Eutrophication is a recognized major issue also in the Baltic Sea (Voss et al., 2011). During the twentieth century, nutrient loads to the sea have more than doubled, due to increased anthropogenic activities and over 85 million inhabitants living in the Baltic catchment, of which more than 20% reside close to the coast (Savchuk et al., 2008; Hannerz and Destouni, 2006). This has led to eutrophication of both the coastal and the open sea waters, which is also accentuated by the semi-enclosed nature of the Baltic Sea (Gustafsson et al., 2012). While nutrient loads have to some degree decreased over the last three decades (Reusch et al., 2018), coastal eutrophication is a major issue, still remaining and worsened by the open sea eutrophication in addition to ongoing hydroclimatic and ecosystem changes (Saraiva et al., 2019; Eriksson et al., 2009). In particular, responses to coastal eutrophication in terms of management and mitigation solutions require a better understanding of the complex coastal system interactions. This system is characterized by multiple pressures from the hydrosphere, biospere, atmosphere and anthroposphere, which interact with each other and with the internal coastal processes and associated coastal ecosystem impacts and feedbacks (Vigouroux et al., 2021). Key questions for coastal eutrophication research are then how it has addressed so far this coastal complexity and whether it has left important gaps that need to be bridged in order to achieve the required improved understanding and scientific underpinning to efficiently respond to and manage coastal eutrophication.

In this paper, we aim to answer these questions by investigating the topics addressed by coastal eutrophication research reported in the scientific literature. We consider a general definition of the eutrophication process, referring to ecological and biogeochemical changes in coastal waters as a direct and indirect result of increased nutrient loading from anthropogenic activities (Cloern, 2001). The study concentrates on the Baltic Sea coast, as a known case of major and still unresolved coastal eutrophication issues, and follows the coastal-offshore division from the Helsinki Commission (HELCOM; see Section 6.2). This implies management by overlapping frameworks (including the European Water Framework Directive and Marine Strategy Framework Directive) with possible mismatching goals (Borja et al., 2010; Friedland et al., 2019).

Our study focuses on uncovering important but relatively uninvestigated system linkages among the coastal eutrophication drivers, pressures, processes, impacts, feedbacks, and their possible management. This is done through a scoping literature review, as basis for quantifying research effort and answering the following main research question: What important gaps and inconsistencies exist and need to be bridged in research on the Baltic coastal system and its eutrophication? To answer this question and identify and highlight gaps and inconsistencies, we based our analysis on the scoping review quantification of research effort and the developed novel classification of land-coast-sea system component and interaction categories that link the hydrosphere, biospere, atmosphere and anthroposphere. The gaps and inconsistencies are determined from what the quantification reveals about how the research so far has covered and linked the complex coastal system, and what this implies for future research needs for scientific underpinning of coastal eutrophication management and solutions.

2. Methods

2.1. Scoping review

The main research question of this study is tackled by a scoping literature review aimed at quantifying and mapping the research carried out so far on Baltic coastal eutrophication, and identifying important research gaps that need to be bridged. The scoping review methodology is described in detail 6. In summary, the literature search, performed on the Web of Science (WoS) search engine, has yielded 1854 publication results. Each published study has been assessed against three criteria of having a focus on the Baltic Sea and eutrophication, and considering the coast, resulting in the inclusion of 832 scientific publications for data extraction.

The data extraction has been carried out by manually categorizing each publication into different topic categories, regarding main issues, questions, processes and/or subsystems that the paper mentions or considers in relation to coastal eutrophication. The categorization has mainly been based on the title, abstract and keywords of each paper, thereby mostly focusing on its main messages, as selected by its authors, but the full text has also been considered when further clarification has been necessary. In combination, the manual categorization focuses on a concept (represented by a keyword, Table C.1) rather than just its associated keyword and clarifies whether a concept is actually investigated or just mentioned (which may not be evident from solely a keyword search), while the focus on title, abstract and keywords captures the key points of each study (as put forward in these highlight items by the authors).

The structure of the considered topic categories is illustrated schematically in Fig. 1 and fully outlined in Table C.1. In summary, each eutrophication study is structured based on its main focus on one (or more) of the following three super-categories of topics: “Pressures on eutrophication”, representing studies that investigate unmanaged exogenic (natural), endogenic (directly anthropogenic) and internal stressors in the coastal eutrophication process chain; “Ecosystem impacts of eutrophication”, representing studies that investigate impacts of eutrophication (which is in itself one of the seven pressures on the Baltic Sea environment identified by HELCOM, 2021) on coastal ecosystems and societies; and “Characterization of eutrophication status”, representing studies that investigate the coastal eutrophication status and conditions themselves (including through methodological development). Further structuring under these super-categories is done in three overarching category sets, considering: (i) Methods of coastal system study; (ii) Coastal system links to other water systems (on land and the open sea); and (iii) Coastal system components. Each of these overarching sets includes main categories and associated sub-categories and sub-sub-categories, as illustrated in Fig. 1 and outlined and explained in more detail in Table C.1.

To arrive at this structure of super-categories and overarching sets with main, sub-, and sub-sub-categories below these, an initial topic structure was first defined prior to performing the data extraction. This was further modified by adding categories in order to account for topics missing in the initial categorization, and logically distinguishing the different category levels and sets during the data extraction process. The super, main, sub and sub-sub categories represent different levels of classification detail represented by the category. The super-categories represent main objective

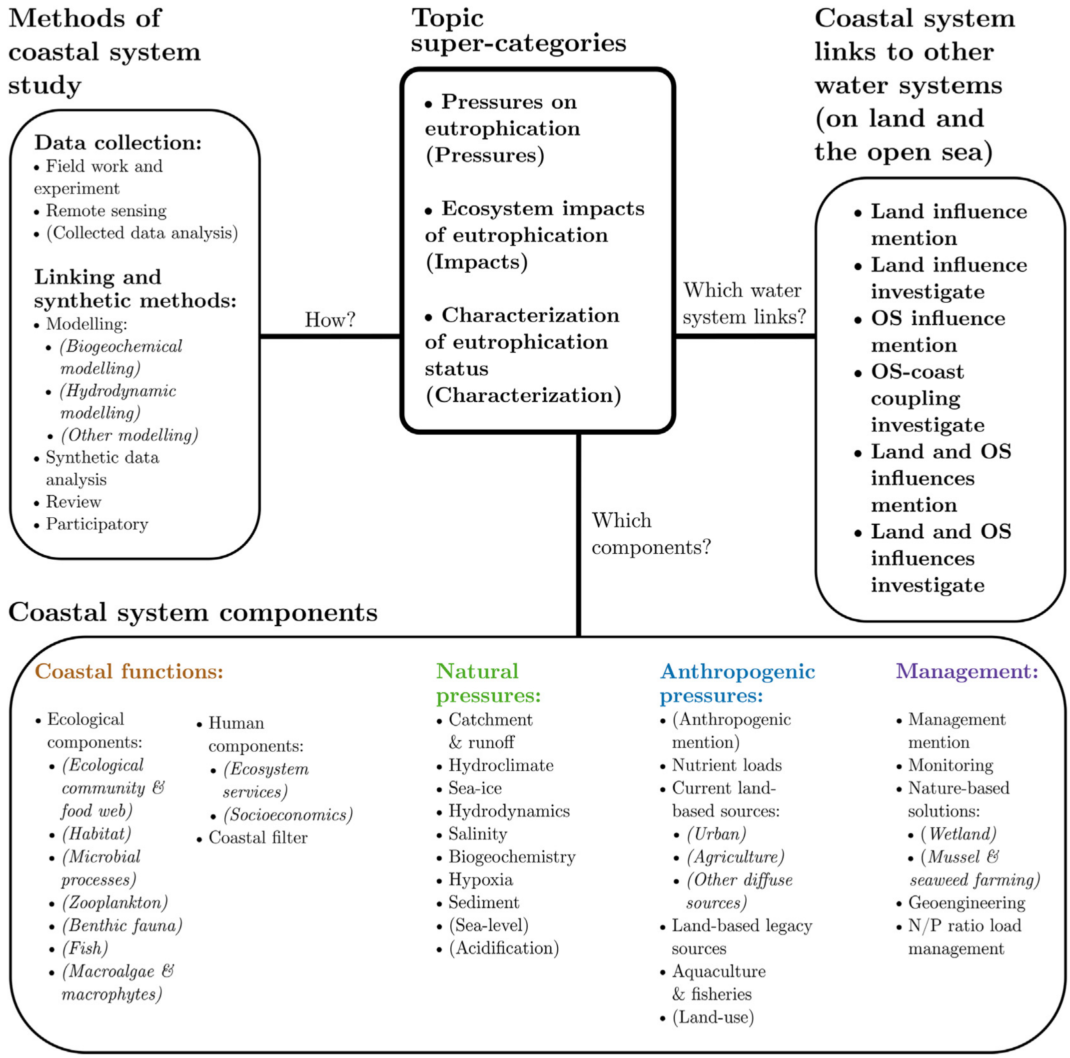

Fig. 1. Schematic representation of the topic categories, structured into super-categories, overarching category sets below these, and main categories (in bold inside the boxes), sub-categories and sub-sub-categories (in italic), under each overarching category set. For each main category, the total number of publications associated with at least one of its sub-category is calculated. Parentheses indicate categories not shown in the paper for conciseness but still considered through their respective higher category levels (the full results including these categories are shown in Fig. D.1).

(s) of each study. The main-categories represent general concepts and the sub-categories and sub-sub-categories go further into more conceptual detail.

For the final categorization structure (Fig. 1), the percentage of publications per category has been calculated for all publications, as well as for publications under each of the super-categories “Pressures on eutrophication”, “Ecosystem impacts of coastal eutrophication”, and “Characterization of eutrophication status”. Additionally, the percentage of scientific publications per category has been refined to also consider only the first decile of the most cited scientific works, and the first decile of the most cited scientific works per year, as presented in Fig. D.1.

2.2. Calculations and graphics of system interaction consideration in research

To illustrate the weight (frequency) of research in each topic category, as well as the research on system component interactions between any pair of categories, two different types of undirected network diagrams have been created (Fig. 2). In the network diagram (Fig. 2A), the nodes represent the different topic categories with a weighting equal to the percentage of scientific publications in each category (illustrated by circle diameter in Fig. 2A), and the edges represent the category links with weighting equal to the percentage of scientific publications in both categories. The network diagram is a simplification of the full network graph that displays only research relationships between categories separated by one level (super and main, and main and their sub-categories), as showing all 1953 connections would not be informative. In additional chord diagram illustration of results (Fig. 2B), the perimeter length of a node represents the relative degree of the node in the local interaction network represented by the chord diagram, proportional to the ratio of the number of researched connections between any given category node and other category nodes to the total number of researched category connections in the chord diagram.

The graph calculations have been implemented in the open source graph database Neo4j (Cattuto et al., 2013). Figures that illustrate the connections between researched categories are displayed using chord diagrams from the HoloViews Python library. The Louvain algorithm, a community detection algorithm based on optimizing the modularity (measure of edge density in communities relative to edge density outside) of network graphs (Blondel et al., 2008), has also been implemented for comparison of resulting researched topic communities with the manual classification into the three super-categories of researched topics. The network visualization (Fig. 2A) in this paper is inspired from the Neovis library.

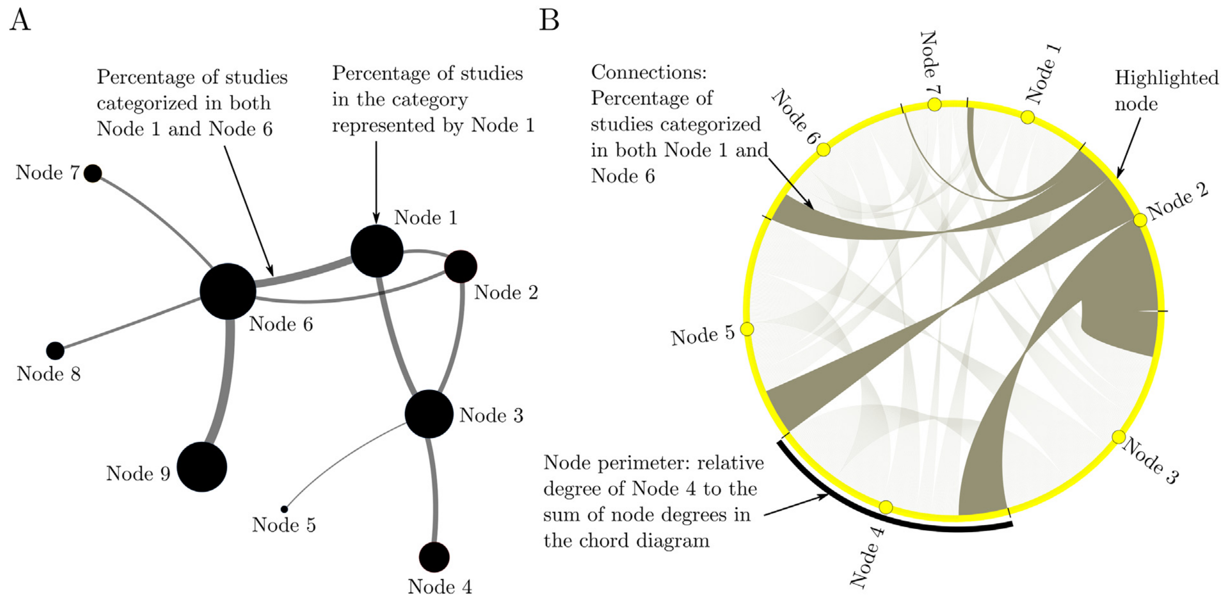

Fig. 2. Type of network diagrams used to illustrate the structure of the research topics and research links between categories. Panel A: Simplified network diagram representing the network structure. Panel B: Chord diagram representing connections between considered categories (nodes).

Fig. 3. Percentage of publications considering or focusing on the categories used for the literature classification (Fig. 1). The bar colours correspond to the Louvain community classification of each category (Blue: pressures, yellow: impacts, red: characterization; Fig. 4).

3. Results and discussion

3.1. Research effort and connections across super-, main and sub-categories

Fig. 3 shows the percentage of studies in each super-category ("Pressures on eutrophication" - in short, pressures; "Ecosystem impacts of eutrophication" - in short, impacts; "Characterization of eutrophication status" - in short, characterization), and the main categories and sub-categories under the three overarching category sets ("Methods of coastal system studies" - in short, coastal methods; "Coastal system links to other water systems" - in short, coastal links; "Coastal system components" - in short, coastal system). All main and sub-categories under each overarching category set have also been classified into one of the three super-categories (pressures, impacts, characterization), by use of the Louvain algorithm. This classification is shown in the network graph in Fig. 4 for the connections between the super-categories and the main and sub-categories of the three overarching category sets.

Figs. 3A and 4 show that considerably fewer studies focus on characterization (20%) than on pressures and impacts (52% and 39%, respectively), and few studies investigate both pressures and impacts (6.5% of total publications), but those studies tend to be relatively well cited (Fig. D.1). Figs. 3A and 4 also show that the main method used in 62% of all studies is data collection (dominated by field work and experiment at 58% of all studies) rather than linking and synthetic methods (44%, dominated by modelling at 21% and synthetic data analysis at 19% of all papers). The more used data collection methods are under-represented in the most cited studies (Fig. D.1), even though data collection is a necessary basis for understanding the system and setting up models. The less used linking and synthetic methods, which are over-represented in the most cited studies, tend to be more associated with pressure studies (54% of pressure publications; Fig. 3B) than with characterization and impact studies (42% and 38%, respectively; Fig. 3C and D), and make up 70% of well-cited publications for both pressure and impact studies (Fig. D.1B and C). This shows an interest (relative over-representation in highly cited studies) for studies that link different areas, parts, and spheres of influences and impacts on the coastal system, beyond what is directly measured.

Moreover, distinguishing between pressures on and impacts of eutrophication is not straightforward, due to feedbacks between ecological communities and eutrophication dynamics and conditions. For example, decline in predatory fish populations provides a top-down control that promotes phytoplankton over macroalgae by altering the food web and decreasing phytoplankton grazing (Eriksson et al., 2009). Therefore, studies also need to link and investigate eutrophication pressures and impacts together. Modelling facilitates investigation of feedbacks between ecology and eutrophication, but is mainly used for pressure studies (30%; Fig. 3B) and much less to address impacts (only in 10% of the impact-focused studies; Fig. 3C). This result supports a recently stated need for model development and use in research on ecosystem-based management and species distribution (Skov et al., 2020).

Remote sensing is used much less (5.7% of all studies) than other data collection methods (field work and experiment, 58% of all studies), but is over-represented in the most cited characterization papers per year (23% of characterization publications and 44% of most cited per year, Fig. D.1D). Remote sensing is also mostly used in characterization research

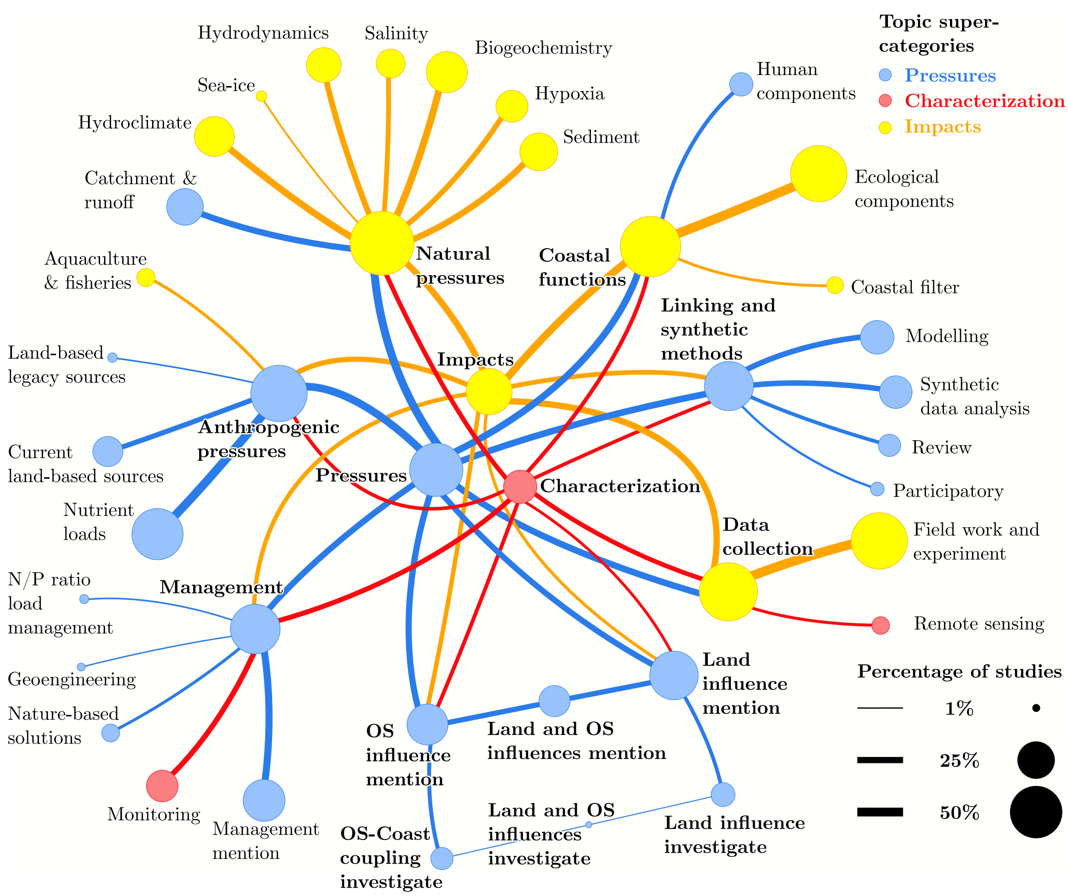

Fig. 4. Research relationships between the super-categories of Pressures (blue), Impacts (yellow), and Characterization (red) and the main categories of the three overarching category sets (Methods of coastal system study; Coastal system links to other water systems; Coastal system components; see category outline in Fig. 1), and between the main categories and their respective sub-categories. The size of each link is proportional to the square root of the percentage of publications classified in both categories. The size of each node circle is proportional to the square root of the percentage of publications classified in that category, while the node colour represents the most strongly associated super-category for that node based on the Louvain community classification (Blue: pressures, yellow: impacts, red: characterization).

(red super-category in Figs. 3 and 4) rather than in impact research (yellow super-category), into which the Louvain algorithm has classified the main "Data collection" category. While remote sensing methods thus are used, including in combination with models, for characterizing eutrophication conditions and status (e.g., Kratzer et al., 2019; Kratzer and Tett, 2009), they are seldom used in pressure and impact studies (Fig. 3B and C). This gap may be due to technical difficulties in combining remote sensing with other data (e.g., novel steps required for combination and validation with in-situ data; Kratzer et al., 2019), issues with some remote sensing products for discerning chlorophyll a, especially in the coastal zone (e.g., MERIS; Beltrán-Abaunza et al., 2014), and relatively short time series lengths.

Finally, with regard to methods, only 3.5% of all publications include stakeholder and public involvement in participatory studies (Fig. 3A). This is an important gap considering that stakeholder involvement can improve collaboration for water management (Franzén et al., 2011), and public preferences are important for understanding costs and benefits of changes in the coastal environment (Bertram et al., 2020) and thus for decisions on associated environmental policies (Ahtiainen et al., 2014).

The links of the coastal waters with water conditions on land and in the open sea (OS) are mentioned in 31% and 43% of all studies regarding the land and the OS influence, respectively (Fig. 3A). However, only 18% of all studies mention both links, and even fewer studies explicitly investigate the links they mention (around 10% of all publications for either the land or the OS influence on the coast), and less than 1% investigate both links. This is a major research gap for coastal environments, where both links indeed affect both their conditions (Vigouroux et al., 2021; Walve et al., 2021) and their restoration opportunities (Vigouroux et al., 2020), and points at a need to further investigate both the land and the open sea influences on coastal eutrophication together.

The link studies further focus relatively little on pressures (around 15% for either the land or the OS influence; Fig. 3B) and even less on impacts (less than 5%; Fig. 3C). These are also important research gaps, since both OS (Bryhn et al., 2017; Raateoja and Kauppila, 2019) and land-based (Andersson et al., 2013; Wagner and Zalewski, 2016) biogeochemical and ecological processes determine nutrient loads that impact the coastal ecosystem. These interactions also imply an important scale coupling of pressures and impacts from both the local land-catchment and the large-scale open sea and its total land-catchment on the coastal waters (Vigouroux et al., 2021) and community assemblages (Pollumaee et al., 2009). These results indicate that most coastal eutrophication studies focus on just the coastal subsystem itself, without explicitly investigating its pressure-impact and scale coupling with land and OS processes, which is indeed necessary to understand their relative influence and importance, e.g., for mitigation of coastal eutrophication.

With regard to the overarching category set of coastal system components, and its main management category, Fig. 4 shows that characterization research (red super-category) focuses on monitoring, while pressure research (blue super-category) mentions management but does not focus much on actually investigating various management options (relatively few papers investigate possible nature-based solutions, such as wetlands, and even fewer investigate options of N/P ratio management and geoengineering). Pressure research tends to consider anthropogenic pressures somewhat more than natural pressures, but 60% of pressure studies mention both types together. Impact research (yellow super-category) considers mostly natural pressures and coastal functions, but most studies on both pressures and impacts consider also coastal functions (58% and 93%, respectively; Fig. 3B and C). Coastal functions and natural pressures tend to be investigated together, as do also management and anthropogenic pressures (Fig. 4). However, only 12% of all publications mention all the main coastal system components together and 8% do that also using linking and synthetic methods. Overall, the links among super-, main, and sub-categories quantified and illustrated in Figs. 3 and 4 show that coastal eutrophication is a complex process involving interactions between components and processes related to the hydrosphere, atmosphere, biosphere, and anthroposphere. They also show that Baltic coastal research reported in the literature spans over this complexity, with some important research gaps still emerging, as noted above. The following section investigates and quantifies further the interlinkages of all category levels with focus on the overarching category set of coastal system components (see outline in Fig. 1).

3.2. Research effort and connections across coastal system components

Fig. 5 focuses on the research links under the main coastal functions category, among its sub-categories of human components (including the sub-sub-categories of ecosystem services and socioeconomics; Panel A), ecological components (including several sub-sub-categories of various coastal ecological communities and their interactions; Panel B), and coastal filter (representing natural eutrophication mitigation in the coastal system; Panel C), and between these and the super-categories and other main categories. The results highlighted in Fig. 5 show that the human components (10% of all publications) and the coastal filter function (5%) are strongly under-investigated compared to the ecological system components (58%; Fig. 3A). Human components are mostly considered in pressure-focused studies and seldom in impact and characterization studies (Fig. 5A). Human components are also more investigated in relation to anthropogenic pressures and management, than to natural pressures and other coastal functions. As such, the human component category is mainly associated with the super-category of pressure research (Louvain classification, blue in Fig. 4), and thus not classified homogeneously with the other coastal function sub-categories under the super-category of impact research (yellow in Fig. 4). Indeed, papers on human components tend to consider, e.g., management cost and acceptance aspects (e.g., Ahtiainen et al., 2014; Elofsson, 2012) without accounting for potentially important influences from ecological and natural processes (e.g., hydroclimate; Boesch, 2019).

In contrast, ecological components (Fig. 5B) are strongly linked to impact studies and considered in 89% of them, while also being considered in around 50% of both the pressure and the characterization studies (Fig. 3B and D). Ecological components are then mostly considered together with natural pressures (40% of all publications), and to lesser degree with anthropogenic pressures and management (29% and 20%, respectively).

Furthermore, the coastal filter category is almost exclusively considered in pressure studies, in relation to both anthropogenic and natural pressures, but seldom in relation to research on management or on other coastal functions. However, the coastal filter function does not only depend on natural physical pressures, like hydrodynamics and temperature (Nilsson and Jansson, 2002; Carstensen et al., 2020), but also on ecological components of coastal functions, such as microbial and other ecological communities and processes that affect burial and remineralization rates of nutrients in the sediments (Carstensen et al., 2020; Thoms et al., 2018). Moreover, the coastal filter function is highly relevant to consider in choosing additional local and regional measures for coastal eutrophication mitigation, as it influences nutrient interactions with other coastal waters and the open sea (Almroth-Rosell et al., 2016; Gren, 2013).

Overall, the results highlighted in Fig. 5 show that research on the human components, the ecological components, and the natural filter function of the coastal system is disconnected. In particular, Baltic coastal eutrophication research tends to decouple the relatively well-investigated coastal ecology from its roles in essential biogeochemical processes, including the coastal filter function, and from the generally under-investigated human components of coastal eutrophication and its mitigation and management responses.

Natural pressures are relatively well investigated, with most of the sub-categories considered in 15–31% of all publications (Fig. 3A). Sea-ice, however, is understudied in relation to coastal eutrophication, even though it can influence the formation of freshwater plumes (Granskog et al., 2005) and affect phytoplankton communities (Haecky et al., 1998). Salinity is more considered in impact and characterization studies than in pressure studies, as it influences species distribution (Bertos-Fortis et al., 2016; Schumann et al., 2006) and is influenced by the mixing between land-

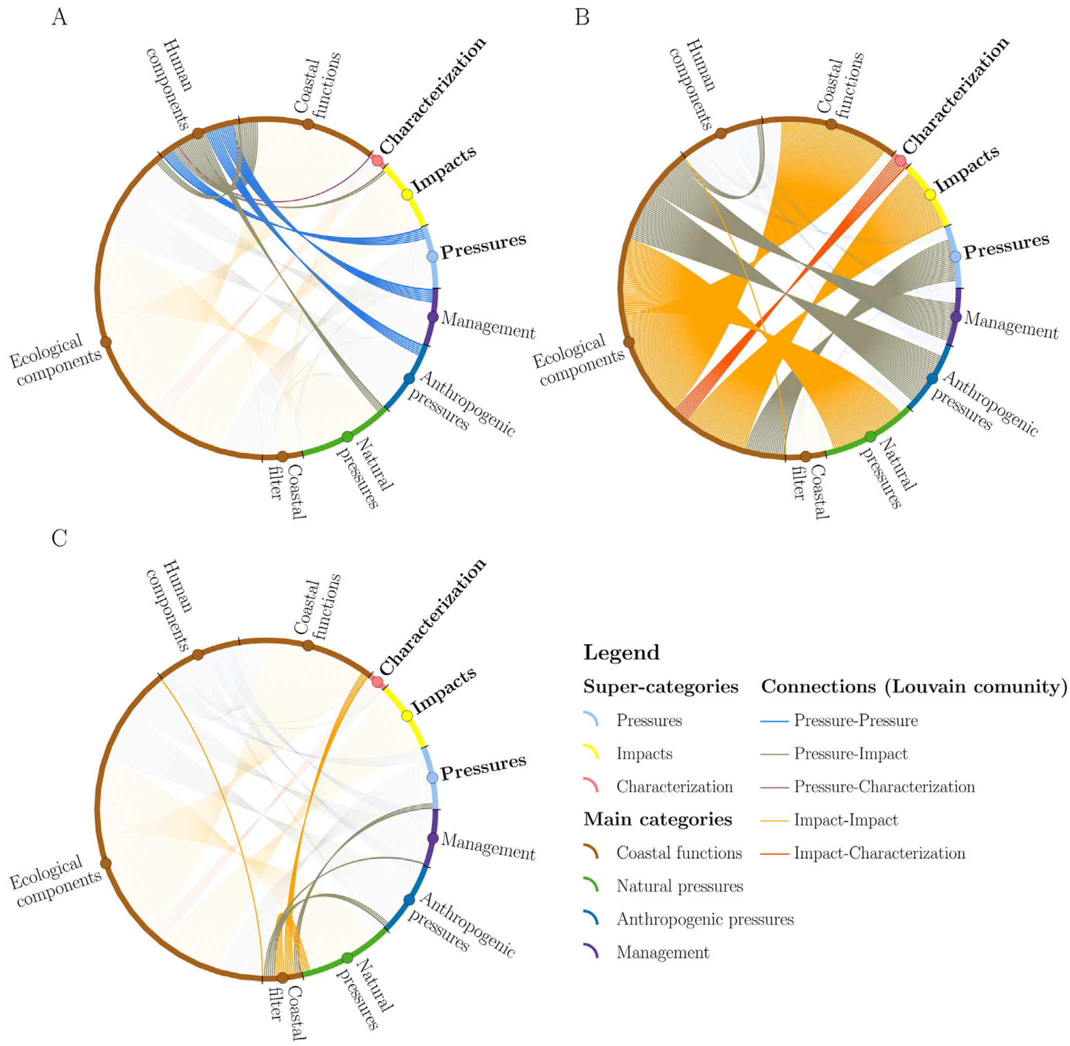

Fig. 5. Research links under the main coastal functions category, among its sub-categories of human components (Panel A), ecological components (Panel B), and coastal filter (Panel C), and between these and the super-categories (Pressures, Impacts, Characterization) and other main categories (coastal functions, natural pressures, anthropogenic pressures, management). The circle colour show the topic super-categories (light blue: pressures, yellow: impacts, red: characterization) and main categories (brown: coastal functions (brown), green: natural pressures, blue: anthropogenic pressures, and purple: management). Relations between categories (number of links proportional to percentage of publication classified in both categories), where the colour represents the associated topic super-category (Louvain classification; Fig. 4). Connections accounting for less than 1% of publications are not shown.

based runoff and open sea waters (Reissmann et al., 2009). It is much less investigated as a pressure on eutrophication, likely because its role is commonly accounted for as part of the hydrodynamic processes. Pressure studies consider the sub-category of catchment & runoff much more than impact studies (35% and 9%, respectively; Fig. 3B and C). This explains why its super-category classification (pressure, blue) differs from that of other natural pressures (impacts, yellow), even though the chemical composition of freshwater runoff may have essential local ecological impacts (e.g., in terms of humic substances; Andersson et al., 2013). The pressure super-category classification of catchment & runoff is also consistent with few impact studies mentioning and investigating the land influences on coastal waters impacts. Biogeochemistry is also more considered in pressure than in impact studies (44% and 17%, respectively; Fig. 3B and C). These results, together with those showing that few studies investigate together both the pressures on and the impacts of coastal eutrophication, show that impact research tends to consider the ecological eutrophication conditions in isolation from their pressures, including the internal physical coastal dynamics. This is an important research gap, because ecology and eutrophication processes are linked and need to also be researched as such, in order to accurately represent the complex coastal feedbacks, e.g., in model development needed to support ecosystem-based management (Skov et al., 2020).

The research on anthropogenic pressures is dominated by nutrient loads, with few studies considering the main sources and further processes on land that lead to these loads from land to sea. This is also the case for pressure studies that consider currently active urban, agricultural and other diffuse sources on land (27% of the pressure studies, Fig. 3B), while the nutrient loads to the sea that result from these are mentioned by many more studies (68%, Fig. 3B). Pressure research seldom considers legacy sources (mentioned in only 3% of pressure studies; Fig. 3B), even though such sources are shown to still remain in soil, slow-flowing groundwater, and sediments on land, and continuously release and greatly contribute to the total nutrient loads to the sea from previous (cumulative past-to-present) active source inputs on land (Le Moal et al., 2019; Chen et al., 2021). As such, this is an important research gap, considering also that nutrient loads from legacy and other diffuse sources may be large and are particularly challenging to quantify in unmonitored coastal catchment areas (Hannerz and Destouni, 2006; Destouni et al., 2008). From these areas, the nutrient loads may also to large degree be carried to the coastal waters by the hidden, diffuse, and also difficult to quantify submarine groundwater discharge in the Baltic region (Szymczycha et al., 2012) and globally (Santos et al., 2021).

Characterization studies are decoupled from any specific anthropogenic pressure other than mentioning nutrient loads (Fig. 3D). In impact studies, aquaculture & fisheries directly in the coastal environment are the main specific anthropogenic pressures considered (11%; Fig. 3C). These are less considered in pressure studies, even though they act in synergy with other pressures on eutrophication (Malone and Newton, 2020), modifying fish communities and the coastal food web to accentuate coastal eutrophication (Eriksson et al., 2009; Bergström et al., 2019), in addition to the direct nutrient emissions.

As also noted in the previous section, while 33% of all studies mention management and policy responses, few actually investigate concrete management solutions. The measures investigated include mostly nature-based solutions (6% regarding wetlands and mussel & seaweed farming; Kotta et al., 2020), or potential geoengineering (1% Fig. 3A; Rydin et al., 2017). The measures are also principally investigated in pressure research, while impact research rarely investigates their potential ecosystem impacts (Fig. 3B and C); an exception is, e.g., the study by Schernewski et al. (2019) that assessed ecological and socio-economic impacts of zebra mussel farming. This is another research gap, indicating needs for additional research on coastal management solutions, to quantify their effects on nutrient load mitigation and on coastal ecological communities, such as benthic fauna and fish.

As one example of solution complexity that requires further research, nature-based solutions may be effective against legacy and other diffuse sources (Kotta et al., 2020; Berthold et al., 2018), while also producing valuable goods, such as feed for fish or chicken (e.g., for mussel farming; Kotta et al., 2020), but quantification of their nutrient load removal capacity and cost-effectiveness is uncertain (e.g., for wetlands; Arheimer et al., 2004; Jansson et al., 1998). Moreover, coastal wetlands may promote recruitment of predatory fish (Nilsson et al., 2014), but sedimentation of organic materials from mussel farms can also increase risk of hypoxia (Stadmark and Conley, 2011; Schernewski et al., 2019). Furthermore, geoengineering methods, generally focused on reducing benthic nutrient release, may locally decrease phytoplankton production and increase macroalgae and predatory fish populations (Rydin et al., 2017), but also stimulate denitrification (De Brabandere et al., 2015) and reduce hydrogen sulfide and methane production by changing microbial communities (Broman et al., 2017). However, most coastal waters are also strongly influenced by open sea conditions (Bryhn et al., 2017), limiting the applicability of geoengineering methods as they would then need to be used on the open sea scale, with significant associated risk and cost (Conley et al., 2009). Only few studies mention the importance of solutions to also control the N/P nutrient loading ratio (2%; Fig. 3A), since changes in the nitrogen to phosphorus ratio in coastal waters can lead to negative shifts in phytoplankton species composition and for example promote rather than mitigate cyanobacteria blooms (Elmgren and Larsson, 2001). Monitoring is finally mainly considered in characterization research (Fig. 3D, mentioned in 67% of those studies), but is also an essential component of any management solution, for tracking actual effects and ecosystem changes (Carvalho et al., 2019), even though this seldom mentioned in pressure studies.

3.3. Implications for management

Societal responses for management of coastal eutrophication in the Baltic Sea and throughout the world have historically focused on reducing nutrient loads at the source (Le Moal et al., 2019). For the Baltic system, management has been particularly successful at reducing point source pollution from cities and industries mainly through improved waste water treatment (Boesch, 2019). However, further nutrient reductions are required to meet the still far from reached Baltic Sea Action Plan goals (HELCOM, 2007), which have therefore now been updated with compliance requirements for them also further delayed (HELCOM, 2021), and necessitate targeting diffuse agricultural (Boesch, 2019) and additional diffuse legacy sources (Destouni and Jarsjö, 2018; Chen et al., 2021). Long residence times of both nitrogen (Juston et al., 2016) and phosphorus (McCrackin et al., 2018) in the Baltic Sea catchment make such reductions even more challenging as mitigation effects propagate slowly through the system. This needs to be more acknowledged and accounted for in research (only mentioned in 2% of studies; Fig. 3A) and management frameworks (Carvalho et al., 2019).

Land-based nutrient reductions at the source are necessary to tackle coastal eutrophication in the long-term, and are also relevant for circular economy and food security (Nedelciu et al., 2020). However, these reductions are not sufficient for a sufficiently fast recovery of Baltic coastal eutrophication. Indeed, the residence time of phosphorus has been estimated to 30 years on average over the whole Baltic catchment (McCrackin et al., 2018), which indicates an important delay between land-based measures and decrease in coastal loads. Moreover, most open Baltic Sea areas suffer from eutrophication (Fleming-Lehtinen et al., 2015), and the residence time of phosphorus in the Baltic Sea is also around 30 years (28 to 46 years; Eilola et al., 2011), which also indicates considerable delays between decrease in loads from land and decrease in marine nutrient concentrations. The eutrophied open sea conditions exacerbate coastal eutrophication along with the coastal sediments that have also accumulated nutrients from previous loads (Walve et al., 2021), and thus also represent diffuse legacy sources.

Coastal eutrophication management needs recognition and account for the paradigm shift implied by the nutrient source and load distributions now being dominated by legacy and other diffuse sources (Destouni and Jarsjö, 2018; Chen et al., 2021). That is, solutions need to be selected and implemented that can particularly target such sources, while our results show that such solutions are strongly under-investigated. More research is therefore needed on such solutions and their potential trade-offs and synergies; trade-offs may, e.g., consider negative impacts of mussel farming on benthic fauna (Stadmark and Conley, 2011), while synergies may, e.g., consider restoration of critical habitat, such as coastal wetlands that can both enhance the coastal filter function and support recruitment of predatory fishes (Malone and Newton, 2020; Nilsson et al., 2014). Moreover, policy incentives such as compensation for nutrient removal, are not yet implemented in current policies, which can be a bottleneck for such solution methods (Kotta et al., 2020; Schernewski et al., 2019).

Our results also show that the mix of anthropogenic and natural pressures and influences acting on different scales (e.g., land-based nutrient loads along with large-scale open-sea and climate influences) are well-mentioned in coastal eutrophication research, as are also the ecosystem impacts of eutrophication. However, some pressures are still much under-investigated (e.g., legacy sources, sea-ice) and the scale interactions are seldom quantified. Similarly, impacts of ecological changes on eutrophication are also under-investigated, with few pressure studies addressing specific ecological components (Fig. D.1B). Selection and implementation of relevant management responses and solutions, however, requires better understanding of these links, for example through development of finer-scale ecological models (Skov et al., 2020), and integration of rapidly increasing remote sensing data in pressure and impact studies. This is also needed for development of decision support tools that can synthesize and quantify the cumulative drivers, pressures and impacts of and on the socio-ecological system (Schumacher et al., 2020). Such tools can, e.g., support effective ecosystem-based management (Andersen et al., 2015), and also consider social dimensions, such as in the Baltic Health Index (Blenckner et al., 2021).

4. Conclusions

This study has analysed coastal eutrophication research considering the Baltic Sea by classifying and quantifying the research efforts in such a way as to identify key research gaps from how the coastal system complexity has been handled in published research so far. The classification is in terms of study focus on pressures on, and impacts and/or characterization of coastal eutrophication, of study methods and consideration of coastal interaction links with land and the open sea, and of different components of the coastal system itself (coastal functions, natural(−mediated) pressures, direct anthropogenic pressures, management). The classification can be applied to other coastal systems and for general understanding and further study of coastal system complexity. Specific recommendations summarizing the results and discussion are given in Appendix A. The main research gaps and inconsistencies identified through this research classification and quantification are summarized as follows:

- Considerably more studies focus on eutrophication pressures (52%) and ecosystem impacts (39%) than on characterization of the coastal eutrophication itself (20%). Few studies investigate both pressures and impacts together. Thereby, complex ecosystem feedbacks, such as effects of ecological community changes on eutrophication, are relatively uninvestigated, even though such combined studies have higher scientific impact.
- More studies use direct data collection methods (62%, field studies and experiments) than linking and synthetic methods (44%, e.g., modelling, review). The latter are overrepresented in well-cited studies, indicating interest for more studies to link various coastal system components beyond what is directly measured in individual studies.
- Links in the land-coast-sea water continuum are mentioned in the literature, but much fewer studies actually investigate and quantify these links.
- The main coastal system components are generally well-mentioned and investigated in the research, separately or considering some component connections. However, specific coastal functions (in particular the coastal filter function), pressures (long-lived legacy sources, sea-ice), and concrete management solutions are understudied. More research is needed to quantify the influences and impacts of these understudied pressures and to identify trade-offs and synergies of concrete management solutions that account for the coastal filtering function and can specifically target legacy and other diffuse sources and their impacts.
- Research on the human and the ecological components of the coastal system and its functions is disconnected. This implies a need for coastal eutrophication research to couple the relatively well-investigated coastal ecology with its role in essential biogeochemical processes, including the coastal filter function, and with the generally under-investigated human components of coastal eutrophication and its mitigation and management responses.

The shift from nutrient loads previously being dominated by point sources, to now being dominated by long-lived legacy and other diffuse sources, on land and from the atmosphere, and the open sea, and ecosystem-wide changes, calls for a corresponding paradigm shift in management responses to coastal eutrophication. More research is needed on cross-scale and multi-solution coastal eutrophication management, considering the local land-catchment and the large-scale open sea and its total catchment, as well as legacy sources that are diffuse over both time and space across both scales, and climatic changes and their manifestations on these different scales. In addition to nutrient source mitigation, research is also needed on management solutions that mitigate loads and impacts directly at and in the coastal ecosystem, e.g., by maintaining and promoting predatory fishes, macroalgae, and nature-based solutions, such as coastal wetlands and mussel farming, which can aid in reducing coastal nutrient loads regardless of their sources. Research is also needed on policy for incentivising such management solutions, applied locally but along entire coastlines so that they can also have large-scale mitigation effects, while being in line with European blue growth initiatives.

CRediT authorship contribution statement

Guillaume Vigouroux: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Georgia Destouni:** Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Specific recommendations

Specific recommendations for coastal eutrophication research from the Results and Discussion Section 3 are summarized as follows, for:

- **Study goals:** Investigate both pressures and impacts of coastal eutrophication together to reveal complex ecosystem feedbacks.
- **Study methods:**
  - Use and further develop linking and synthetic methods (modelling, meta-analysis of synthesized data of different types) to decipher complex ecosystem feedbacks.
  - Develop decision support tools capable of synthesizing and quantifying cumulative drivers, pressures and impacts for the coupled socio-ecological system (Schumacher et al., 2020) in support of ecosystem-based management (Andersen et al., 2015; Skov et al., 2020) that also considers social dimensions (e.g., Baltic Health Index; Blenckner et al., 2021).
  - Make greater use of remote sensing to study pressures and impacts, and develop methods to facilitate this use for complex feedback resolution.
  - Increase public and stakeholder participation and involvement in the research process.
- **Links to other water systems:** Investigate both land and open sea influences on coastal eutrophication together.
- **Anthropogenic pressures:** Acknowledge the existence and investigate and quantify the roles of legacy sources (and other diffuse sources, including submarine groundwater discharge) for coastal eutrophication.
- **Natural pressures:**
  - Consider and account also for natural pressures (including coastal internal physical dynamics) in research on coastal eutrophication impacts, to better resolve and represent complex feedbacks in ecosystem modelling.
  - Investigate the role of sea-ice for coastal eutrophication.

- **Coastal functions:**
  - Consider and account for the human-related (e.g., ecosystem services, socioeconomics) along with the ecological and other natural coastal system components and aspects in research on coastal eutrophication impacts.
  - Study the role of the coastal filter in relation to coastal eutrophication management, as well as ecological and other natural processes.
- **Management:**
  - Study coastal management solutions (e.g., wetlands, mussel & seaweed farming, local geoengineering) to quantify their effects on coastal eutrophication and ecological communities, such as benthic fauna and fish.
  - Investigate spatially differentiated and specific management solutions in relation to different types of sources of coastal nutrient loads (e.g., agriculture, fish farms, wastewater treatment plants, as well as active or legacy, diffuse or localized).
  - Investigate trade-offs and synergies among different management solutions and between these and other prevailing biogeochemical, ecological, and socioeconomic conditions and processes, including policy incentives.

Appendix B. Scoping review methodology

B.1. Search and selection criteria

A comprehensive scoping review is a suitable tool for this open and broad study aim rather than, for example, a systematic review looking for evidence in support of a particular answer to some specific management question (Munn et al., 2018). For rapid scoping reviews, some components of systematic reviews can be simplified (Khangura et al., 2012). In this case, the scoping review has been performed by one reviewer and focused on the study abstracts to identify the main points of each study as selected by its authors.

The Web of Science™ (WoS) search engine has been used to perform the literature search, across all available databases, including the WoS core database, MEDLINE and the Russian Science Citation Index. A topic search, encompassing title, abstract, and paper and WoS generated keywords has been performed with the following search key on January 4th 2021:

$$\left(\left(\left({}^{\rceil}Baltic\,Sea^{\rceil}\right)AND\right.\right.\tag{B.1}$$

$$(coast^{*}\ OR\ estuar^{*})\ AND\tag{B.2}$$

$$\begin{pmatrix} eutrophic^{*}\ OR\ (nutrient^{*}\ NEAR/2\ concentration^{*})\ OR \\ (alg^{*}\ NEAR/2\ bloom^{*})\ OR\ (hypox^{*})\ OR\ (water\ NEAR/3\ quality)\ OR \\ ((ecosystem\ OR\ environment^{*})\ NEAR/3\ status) \end{pmatrix}\tag{B.3}$$

The search key is composed of three parts. The first part aims to select Baltic Sea related literature, the second targets studies investigating the coastal zone, and the third targets studies investigating eutrophication. The search terms have been defined to also include synonyms and internal eutrophication processes, such as nutrient concentrations and ecosystem status. The asterisk (*) is a wildcard representing any group of characters (including no character) that complete the word, and NEAR/x allows the joined search terms to be within x words of each other. Results have been refined to only include scientific publications written in English.

The WoS literature search has yielded 1854 results (of which 1849 from the WoS core database). Title, abstract, keywords, authors, publisher, publication data and number of citations are the search results that have been exported for the further literature screening.

B.2. Literature screening

Each study has been evaluated against the three criteria: a focus on the Baltic Sea and eutrophication, and considering the coast. The Baltic Sea criterion selects studies that focus solely on the Baltic Sea, or consider the Baltic Sea together with other marine areas, such as reviews and comparative analyses. The eutrophication criterion selects studies that focus solely on eutrophication and its biogeochemical processes relating to seawater nutrient concentrations and algae blooms, or consider eutrophication in relation to other issues and processes. Studies focusing on water quality and ecosystem status where eutrophication is relevant are also selected. The coast criterion ensures that study results consider the coastal environment, either generally, or some specific Baltic coastal area(s). For example, studies using large scale models (e.g., BALTSEM) that aim to describe basin-wide conditions and are not representative of coastal conditions are not included in the review, and studies using gridded whole-sea models are included only if results substantially describe and focus on specific coastal areas or the coastal zone in general. Defining the coastal zone in terms of processes is not straightforward (e.g., Kratzer and Tett, 2009). Thereby, the coastal-offshore division of the HELCOM (Helsinki Commission) marine monitoring and assessment strategy (http://www.helcom.fi/action-areas/monitoring-and-assessment/), which is internationally consistent and agreed upon, and relevant for coastal management, has been used in this study. Fig. B.1 shows the flow chart of the review process.

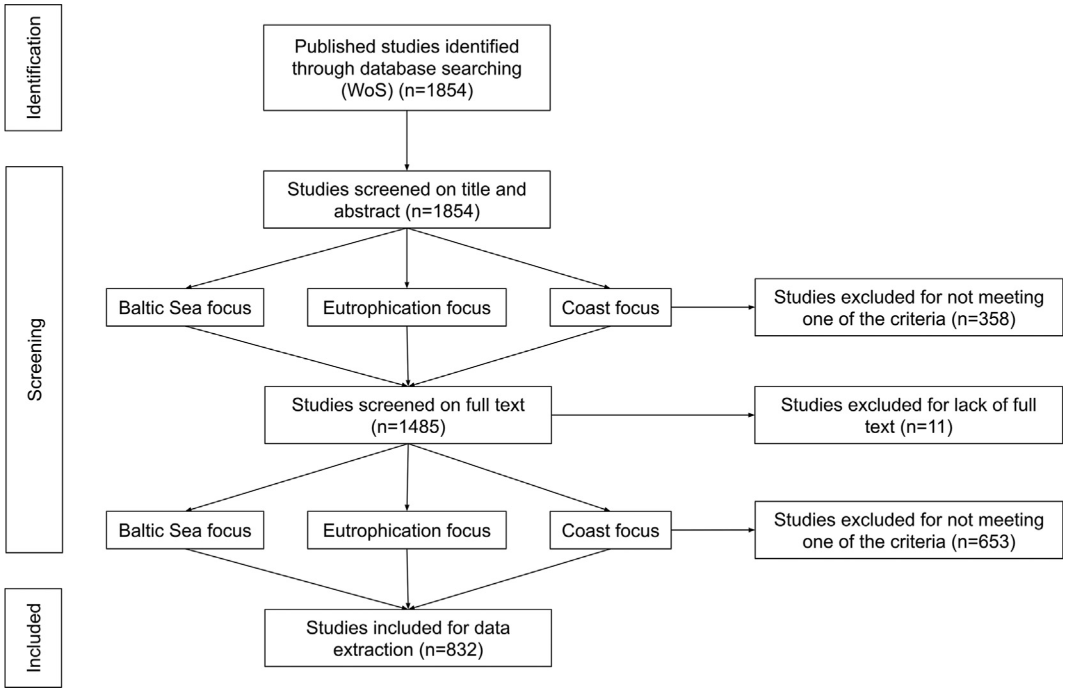

Fig. B.1. Literature review flow chart.

The first rapid screening based on title and abstract has been carried out using the CADIMA tool for literature review (Kohl et al., 2018), in order to exclude publications clearly not meeting one of the criteria. The second screening has been carried out based on the abstract and keywords, and the full text when necessary. In total, 832 scientific publications have been included for further data extraction. The included scientific publications have not been critically appraised or quality checked since this is a study of the topics addressed by coastal eutrophication research for the Baltic, and does not aim to find evidence for correctness of methods or findings in this research.

Appendix C. Definition of the studied categories and validation of the manual classification

The literature search, screening and classification results are available in the Supplementary Materials. The manual classification is susceptible to miscategorization and omission errors, but is also necessary because automatic search can lead to even greater errors or be infeasible, for example in categorizing between the super-categories "Pressures on eutrophication", "Ecosystem impacts of coastal eutrophication", and "Characterization of eutrophication conditions", and differentiating between mention and explicit consideration of open sea-coast coupling, as these categorizations require a deeper understanding of each study. The problem of miscategorization has been tackled by clearly defining the categories (Table C.1) and going through a second categorization round for papers subject to doubts. As a test, we also carried out refined automatic searches for topics that are relatively simple to categorize, automatically and manually, on the unscreened search results (obtained May 8th 2021). We found these automatic searches to be in good agreement with the manual classification results, for example for papers considering wetlands (50 of 1963 papers, or 2.5%, in the refined search and 2.3% in the manual classification), and studies using methods of remote sensing (5.4% and 5.7) and modelling (27% and 21%).

Table C.1
Structure of studied categories for extraction and analysis of literature data on coastal eutrophication in the Baltic Sea.

Category set	Main category	Sub-category	*Sub-sub-category*	Description (Studies mentioning/considering)
Super-category	Pressures on eutrophication	–	–	Investigation of internal and external pressures on the eutrophication process
	Ecosystem impacts of eutrophication	–	–	Investigation of ecosystem impacts of eutrophication
	Characterization of eutrophication status	–	–	Characterization of and methodological developments for characterization of eutrophication status and conditions
Methods of coastal system study	Data collection	Field work and experiment	–	Studies collecting field and/or experimental data
		Remote sensing	–	Studies collecting remote sensing data/developing remote sensing analysis methods
		Collected data analysis	–	Studies analysing collected data (calculated as intersection between studies analysing observational data, and studies within field work and experiment or remote sensing categories)
	Linking and synthetic methods	Modelling	*Biogeochemical modelling*	Studies using/developing biogeochemical models
			Hydrodynamic	Studies using/developing hydrodynamic models

(continued on next page)

Table C.1 (*continued*)

Category set	Main category	Sub-category	*Sub-sub-category*	Description (Studies mentioning/considering)
			modelling	
			Other modelling	Studies using/developing other numerical and/or statistical models than biogeochemical and hydrodynamic models for simulations/projections (does not include statistical models used solely for data analysis)
		Synthetic data analysis	–	Studies synthesizing and generalizing from observational data (calculated as the difference between studies analysing observational data and the collected data analysis category; while the calculation does not perfectly distinguish between collected and synthesizing data analysis, the over-representation of this category in most cited studies increases our confidence in the calculation)
		Review	–	Studies at least partly based on literature review (includes discussion and comment publications)
		Participatory	–	Studies involving stakeholder/public participation
Coastal system links to other water systems (on land and the open sea)	Land influence mention	–	–	Mention influence of land-based processes and conditions
	Land influence investigate	–	–	Explicit investigation of influence of land-based processes and conditions
	Open sea (OS) influence mention	–	–	Mention influence of OS processes and conditions
	OS-coast coupling investigate	–	–	Explicit investigation of influence of OS processes and conditions
	Land and Open sea influences mention	–	–	Mention influences of both land-based and OS processes and conditions
	Land and OS coast coupling investigate	–	–	Explicit investigation of influences of both land-based and OS processes and conditions
Coastal system components	Coastal functions	Ecological components	*Ecological community & food web*	Relations between eutrophication and species populations and distributions, and/or the food web
			Habitat	Relations between eutrophication and ecological habitats
			Microbial processes	Relations between eutrophication and coastal bacterial and microbial processes
			Zooplankton	Relations between eutrophication and zooplankton dynamics, populations and processes
			Benthic fauna	Relations between eutrophication and benthic fauna dynamics, populations and processes
			Fish	Relations between eutrophication and fish populations and dynamics
			Macroalgae & macrophytes	Relations between eutrophication and macroalgae and macrophyte (e.g. extent, species distribution, depth distribution) habitats
		Human aspects	*Ecosystem services*	Relations between coastal eutrophication and ecosystem services (mentioning ecosystem/cultural services)
			Socioeconomics	Socio-economic drivers and impacts of coastal eutrophication
		Coastal filter	–	Nutrient retention and losses through the coastal zone
Coastal system components	Natural pressures	Catchment & runoff	–	Influences of catchment processes and/or runoff/river discharge
		Hydroclimate	–	Influences of weather and hydroclimatic conditions (including sea surface temperature)
		Sea-ice	–	Influences of sea-ice
		Hydrodynamics	–	Influences of hydrodynamic (water exchange, flow and stratification) conditions
		Salinity	–	Influences of seawater salinity conditions
		Biogeochemistry	–	Influences of biogeochemical processes and conditions
		Hypoxia	–	Relations between eutrophication and hypoxia
		Sediment	–	Relations between eutrophication and sediment properties and processes (e.g. nutrient fluxes), and use of sediments for eutrophication characterization
		Sea-level	–	Influence of sea-level (rise)
		Acidification	–	Influences of seawater acidification
	Anthropogenic pressures	Anthropogenic mention	–	Mention anthropogenic influences
		Nutrient loads	–	Influence of nutrient loads in the land-coast-sea continuum, including also atmospheric deposition and nitrogen fixation
		Current land-based sources	*Urban*	Influence of urban/industrial nutrient sources
			Agriculture	Influence of agricultural nutrient sources/practices
			Other diffuse sources	Influence of land-based spatially diffuse nutrient sources (other than agriculture or undefined)
		Land-based legacy sources	–	Influences of land-based legacy sources (temporally diffuse sources)
		Aquaculture & fisheries	–	Influence of aquaculture and fisheries on eutrophication (through nutrient loads/ecosystem impacts)
		Land-use	–	Influence of land-use
	Management	Management mention	–	Mention eutrophication management and/or associated policies
		Monitoring	–	Monitoring of eutrophication conditions
		Nature-based solutions	*Wetland*	Role of wetlands (inland or coastal) for eutrophication remediation
			Mussel & seaweed farming	Farming of mussel/seaweed for eutrophication remediation
		Geoengineering	–	Geoengineering methods for eutrophication remediation
		N/P ratio load management	–	Management of nutrient load stoichiometry for eutrophication remediation

Appendix D. Literature distribution per category, eutrophication focus and citation

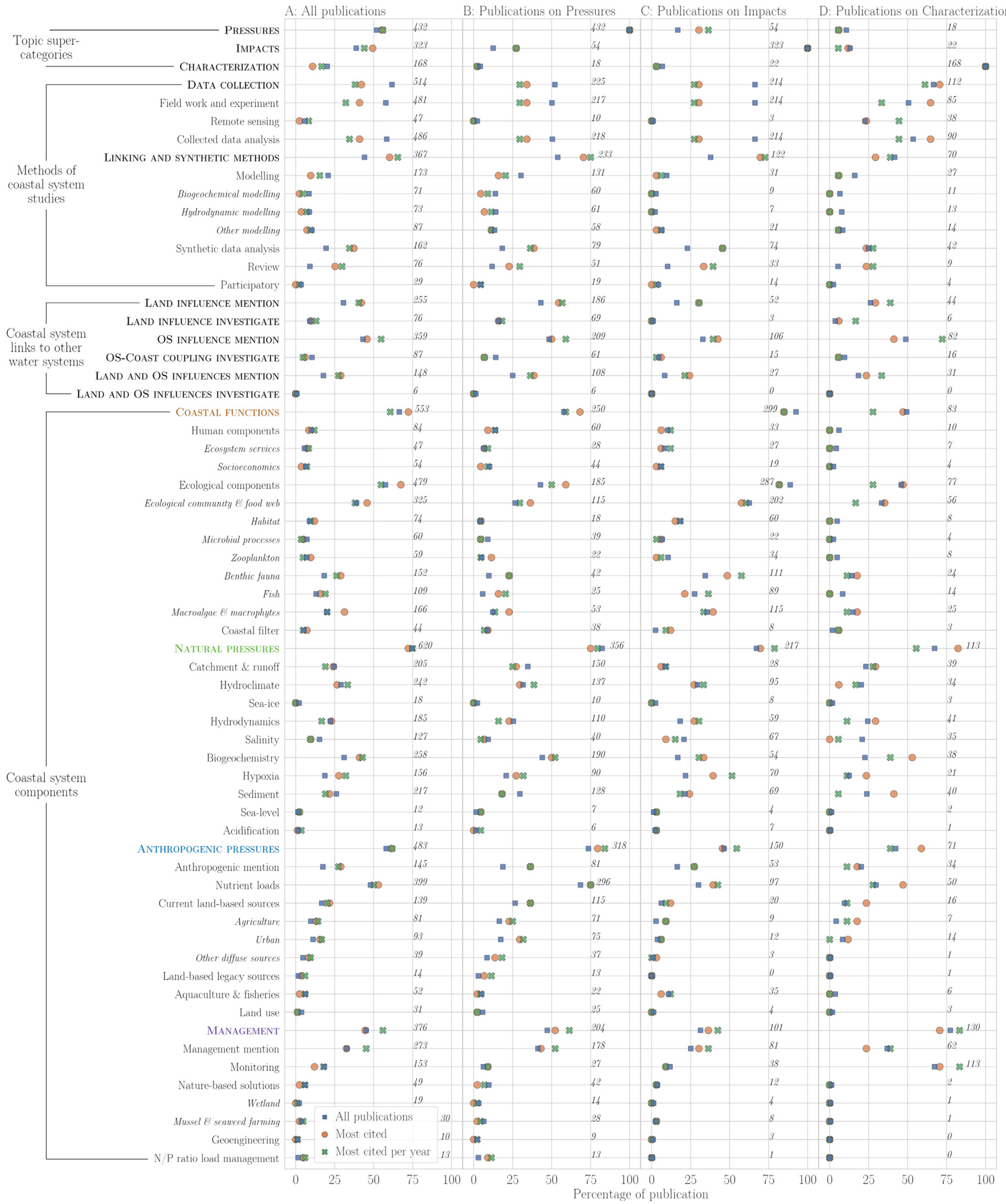

Fig. D.1. Percentage of publication considering or focusing on the categories used for the literature classification, divided between all publications (blue square), most cited (first decile, orange circle) and most cited per year (first decile, green cross). The numbers to the right of each panel indicate the total number of publications that consider or focus on this category by eutrophication topics (all publications, and publications focusing on pressures, impacts and characterization).

Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156240.

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