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Human impacts and their interactions in the Baltic Sea region

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Abstract. Coastal environments, in particular heavily populated semi-enclosed marginal seas and coasts like the Baltic Sea region, are strongly affected by human activities. A multitude of human impacts, including climate change, affect the different compartments of the environment, and these effects interact with each other. As part of the Baltic Earth Assessment Reports (BEAR), we present an inventory and discussion of different human-induced factors and processes affecting the environment of the Baltic Sea region, and their interrelations. Some are naturally occurring and modified by human activities (i.e. climate change, coastal processes, hypoxia, acidification, submarine groundwater discharges, marine ecosystems, non-indigenous species, land use and land cover), some are completely human-induced (i.e. agriculture, aquaculture, fisheries, river regulations, offshore wind farms, shipping, chemical contamination, dumped warfare agents, marine litter and microplastics, tourism, and coastal management), and they are all interrelated to different degrees. We present a general description and analysis of the state of knowledge on these interrelations. Our main insight is that climate change has an overarching, integrating impact on all of the other factors and can be interpreted as a background effect, which has different implications for the other factors. Impacts on the environment and the human sphere can be roughly allocated to anthropogenic drivers such as food production, energy production, transport, industry and economy. The findings from this inventory of available information and analysis of the different factors and their interactions in the Baltic Sea region can largely be transferred to other comparable marginal and coastal seas in the world.

1 Introduction

Anthropogenic climate change has been regarded as a major driver for environmental changes since the industrial revolution (IPCC, 2014). The IPCC has been the leading worldwide expert body to assess and document the currently available knowledge (Agrawala, 1998). Regional climate change assessment reports have taken the IPCC example to the regional scale, e.g. for the Baltic and North seas (BACC Author Team, 2008; BACC II Author Team, 2015; Quante and Coljn, 2016). However, a multitude of human-induced factors in addition to climate change affect the environments of coastal seas. For the Baltic Sea region, the following was concluded:

> When addressing climate impacts on, for example, forestry, agriculture, urban complexes, and the marine environment in the Baltic Sea basin, a broad perspective is needed which consider not only climate change but also other significant factors such as changes in emissions, demographic and economic changes, and change in land use (von Storch et al., 2015).

Furthermore, it was stated that climate change effects

> are not straightforward and are difficult to distinguish from other human factors such as atmospheric deposition, forest and wetland management, eutrophication and hydrological alterations (Humborg et al., 2015).

In this paper, we examine a number of different human factors (see definition of terms below) affecting the coastal environment of the Baltic Sea region. We assess what is currently known about the impact of climate change on these factors and how they influence each other.

Feedbacks within the complex regional Earth system (e.g. the atmosphere, land surfaces, water bodies, biosphere, biogeochemistry and geology) may be complicated and difficult to disentangle, more so when human impacts are involved (Gaillard, 2013; Gaillard et al., 2015). The different factors may affect each other, synchronously or cumulatively, creating negative or positive feedback effects. While a direct effect may be straightforward and easy to detect and explain, the indirect effects are mostly more difficult to uncover. Extreme precipitation events have meteorological causes, which may be connected to changing climate, but the impacts of such events on the human environment, like flooding, damage or drying crops, may be caused or exacerbated by human design (impervious surfaces or other land use changes such as mono-cultural agriculture).

In some cases, the local climate itself can be affected by human-induced changes in the environment (e.g. albedo changes due to afforestation, desertification, land use in general or constructions; Gaillard et al., 2015). Therefore, we face a complex and non-linear system of effects and feedbacks between climatic and non-climatic factors. Moreover, politically motivated management decisions, which have no or little natural scientific groundings may have more substantial impacts than natural ones and may be even more unpredictable than them. Some projects have attempted to include human behaviour in scenarios (e.g. BONUS BALTICAPP and others – Hasler et al., 2019; see also Arheimer et al., 2012; Zandersen et al., 2019; Bartosova et al., 2019; Pihlainen et al., 2020).

Complex analyses and modelling exercises have been performed to characterize the interactions between the different factors (e.g. Crain et al., 2008; Liess et al., 2016; Robinson et al., 2018; Stelzenmüller et al., 2018; Gissi et al., 2021). The present paper intends to make a novel and straightforward inventory of factors and connections, covering the above aspects as far as possible while information on individual factors must be limited and just of an overview character.

Since the early 1990s, the knowledge on the physical and biogeochemical environments of the Baltic Sea and their relationship has been systematically assessed, initially by BALTEX and since 2013 by its successor Baltic Earth. This study is one of the thematic Baltic Earth Assessment Reports (BEAR), which comprise a series of review papers that summarize and assess the available published scientific knowledge on climatic, environmental and human-induced changes in the Baltic Sea region (including its catchment). The BEAR reports in this special issue of *Earth System Dynamics* reflect the Baltic Earth Grand Challenges and scientific topics of Baltic Earth (Baltic Earth, 2017). While the other papers in this special issue deal with natural factors and their relation to climate change (salinity, biogeochemistry, natural hazards) and scenarios for future conditions in the Baltic Sea region, this paper addresses natural and anthropogenic factors in addition to climate change. We assess how they affect or are affected by climate change and how they interact. We believe that the findings elaborated in this assessment can largely be transferred to other marginal and coastal seas, which are also heavily used and affected by humans.

2 The region

The Baltic Sea region has been subject to dramatic environmental changes since the last glaciation (Borzenkova et al., 2015). Human activities have strongly affected the region since the withdrawal of the ice sheets. Fishers, gatherers and hunters inhabited the coasts of the early Baltic Sea already at 11 000 years BP, and Neolithic cultures practised crop cultivation and animal husbandry around 6000 years BP. Deforestation and changes in forest composition have been documented since around 4000 years BP (Gaillard et al., 2015). Over the centuries, the human impact on the environment extended to more detrimental effects such as pollution due to iron mining (Lavento, 2019). Currently, the Baltic Sea drainage basin covers about 20 % of the European continent, with roughly 85 million people living in the catchment (HELCOM, 2018a). It can be roughly subdivided into a sparsely populated, mostly pristine north with natural coastal (rocky) landscapes and a strongly transformed agricultural landscape in the highly populated south, with mostly low sedimentary coasts and graded shorelines (Fig. 1). Numerous rivers enter the Baltic Sea, some of them with catchments covering more than one country, draining nutrients, sediments and pollutants from the surrounding land areas into the Baltic Sea (HELCOM, 2018b).

The Baltic Sea features some special conditions, which make it vulnerable to specific pressures. It is almost enclosed from the open ocean, the exchange through the narrow Danish belts and sounds is very restricted, and the tidal range is very small (Feistel et al., 2008; Leppäranta and Myrberg, 2009). In addition to that, the Baltic Sea has a complex bottom topography, with deep basins separated by shallow sills, which hamper water exchanges. These factors together with the dense population and the prevalent agricultural lands in the southern catchment give rise to special biogeochemical conditions. Eutrophication has for many years been identified as a major threat to the Baltic Sea, which has resulted in the implementation of the HELCOM Baltic Sea Action Plan, “BSAP” (HELCOM, 2007). This strategic programme of measures and actions to achieve good environmental status of the Baltic Sea is being updated in 2021, with additional factors discussed, including climate change.

Various organizations are working on environmental issues of the Baltic Sea. HELCOM, the intergovernmental organization to protect the marine environment of the Baltic Sea, has for decades worked on describing the different drivers and stressors (e.g. HELCOM, 2018a) and has functioned as an interface between the science and political decision-making communities. HELCOM’s importance on the firm and largely successful management of various environmental issues in the Baltic Sea cannot be underestimated. In close collaboration with Baltic Earth, the HELCOM expert network on climate change EN Clime has produced a Climate Change Fact Sheet, including impacts on many environmental factors (HELCOM, 2021). BONUS (Kononen et al., 2014), the EU funding scheme for environmental Baltic Sea research, has funded many projects dealing with different anthropogenic factors and their interrelations (e.g. AMBER, BALTICAPP, BALTIC-C, ECOSUPPORT, INFLOW, INTEGRAL, MIRACLE, SHEBA and others; see BONUS (2021) and has also had a significant impact on management.

Natural variability in the region is very strong, and the anthropogenic climate signal attributable to greenhouse gases is just beginning to emerge from the background noise (Bhend, 2015; Barkhordarian et al., 2016). Parameters directly related to temperature, like ice extent or the seasonality of biota, show the most robust signals in climate-related changes (BACC Author Team, 2008; BACC II Author Team, 2015). For many other climatic parameters, including precipitation, wind, runoff and salinity, the signal is still small compared to the variability, precluding any conclusions about emerging trends (Christensen et al., 2021; Meier et al., 2021c).

Table 1. Matrix of different factors using the DPSIR analysis (drivers, pressures, states, impacts, responses). For a thorough description of the DPSIR concept, see Smeets and Weterings (1999) and Gari et al. (2015).

Factor	Driver	Pressure	State	Impact	Response
Climate change	Industrialization	GHG emissions	Current climate	Warming, modification of hydrological cycle, acidification, sea level rise	Climate change mitigation, reduction of GHG emissions, geoengineering
Coastal processes	Wind and waves, currents, human activities	Erosion, accretion, coastal infrastructure	Current coastal condition	Impacts on coastal ecosystems and human uses	Coastal management and infrastructure
Hypoxia	Food production	Nutrient releases	Current state of hypoxia	"Dead" zones, modification of redox state and biogeochemistry, impact on ecosystems	Reduction of nutrients, geoengineering
Acidification	Industrialization	GHG emissions, alkalinity	Current pH of sea water	Impacts on physiological functions of certain species, hampered calcification of shells	Reduction of GHG emissions, geoengineering
Subm. groundw. disch.	Hydrology, coastal aquifers	Modified concentrations of nutrients and chemical substances in coastal waters	Current groundwater release in some coastal areas	Impacts on nutrient and contaminant concentrations and related impacts on organisms and coastal ecosystems	Coastal management and infrastructure
Non-indigenous species	Globalization and transport, climate change	Ballast water/hull transport and other new pathways, e.g. through channels; new species invading indigenous ecosystems (migration northwards)	Current abundances of non-indigenous species in different regions	Modification of indigenous ecosystems, expulsion of indigenous species and ecosystem functions, species diversity potentially affected	Antifouling and ballast water regulations, climate change mitigation
Land cover and use	Food production, transport, industrialization	Monocultures, expulsion of indigenous ecosystems, modification of runoff substances, sealing of soils, fragmentation of ecosystems and landscapes	Current state of land use and cover	Eutrophication, inundations, adverse effects on species diversity	Land restorations
Agriculture/nutrient loads	Food production	Excess nutrients entering the ecosystems	Current state of agricultural release of nutrients to the sea	Eutrophication, hypoxia	Reduction of nutrient release
Aquaculture	Food production	Release of excess nutrients and chemicals/pharmaceuticals to coastal waters, indirect excess fisheries for fish meal in other parts of the world	Current state of aquaculture	Eutrophication, pollution	Land-based circulation systems, sustainable use of open systems

Table 1. Continued.

Factor	Driver	Pressure	State	Impact	Response
Fisheries	Food production	Removal of fish biomass and related ecosystem functions	Current state of fisheries and fish stocks	Decimation of commercial fish species, impacts on ecosystem functions and fisheries, cascading effects on other parts of the ecosystem	Fishery regulations
River regulations	Transport, energy and water management	Modification of river flows, construction of channels and dams	Current state of river regulation and restoration	Modification of flow rates and nutrients as well as nutrient ratios downstream, impacts on migrating fish and related fisheries	River restorations
Offshore wind farms	Energy production, climate change	Extensive wind farms in coastal and open waters	Current development of offshore wind farms	Impacts on local ecosystems, fish and marine mammals, bird migration routes, noise during construction phase	Regulation of offshore industry
Shipping	Transport, commercial shipping along international shipping routes, cruise and leisure shipping in coastal waters	Introduction of invasive species, antifouling, ballast water, black/grey and wastewater, scrubber water, underwater noise, various contaminants and nutrients; airborne exhaust and combustion products; GHG emissions	Current state of shipping, pollutant and GHG concentrations, underwater noise levels, current number of invasive species	Impacts on marine ecosystems through invasive species, underwater noise, acidification, various contaminants and nutrients, impacts on air quality, contribution to GHG emissions	IMO regulations
Chemical contaminants	Transport, industrialization, chemical production, food production, various economic activities	Diffuse release and point source emissions of organic contaminants and heavy metals to air, water and land, subsequent transport to the sea	Current concentrations of contaminants in waters, sediments and organisms	Impacts on physiological functions of various marine organisms, impacts on human health due to food chain bioaccumulation of some contaminants	Different regulations/technical guidance on chemical production, use and waste handling; global treaties
Dumped military material	World War II	Dumping of unexploded warfare agents in various locations	Current state of corrosion of dumped warfare agents	Potentially harmful impacts on marine ecosystems, potential danger of poisoning and accumulation up the food chain up to humans	Various national and international efforts to retrieve the dumped objects as far as possible
Marine litter	Industrialization, chemical production, various economic activities	Diffuse release via rivers and other pathways to the sea; concentrations on specific locations (eddies, coastal stretches, beaches)	Current concentrations and distribution patterns of marine litter and microplastics	Potentially harmful effects on the physiology of different organisms	Regulations in plastic production, distribution and use; efforts to retrieve larger fragments from sea water
Tourism	Human recreation	Coastal regions flooded with humans, cruise shipping, leisure shipping	Current state of tourism	Impacts on transport, waste management, coastal infrastructure in coastal regions, impacts on coastal ecosystems through fishing, angling, boating, bathing, etc.	Efforts to implement sustainable tourism

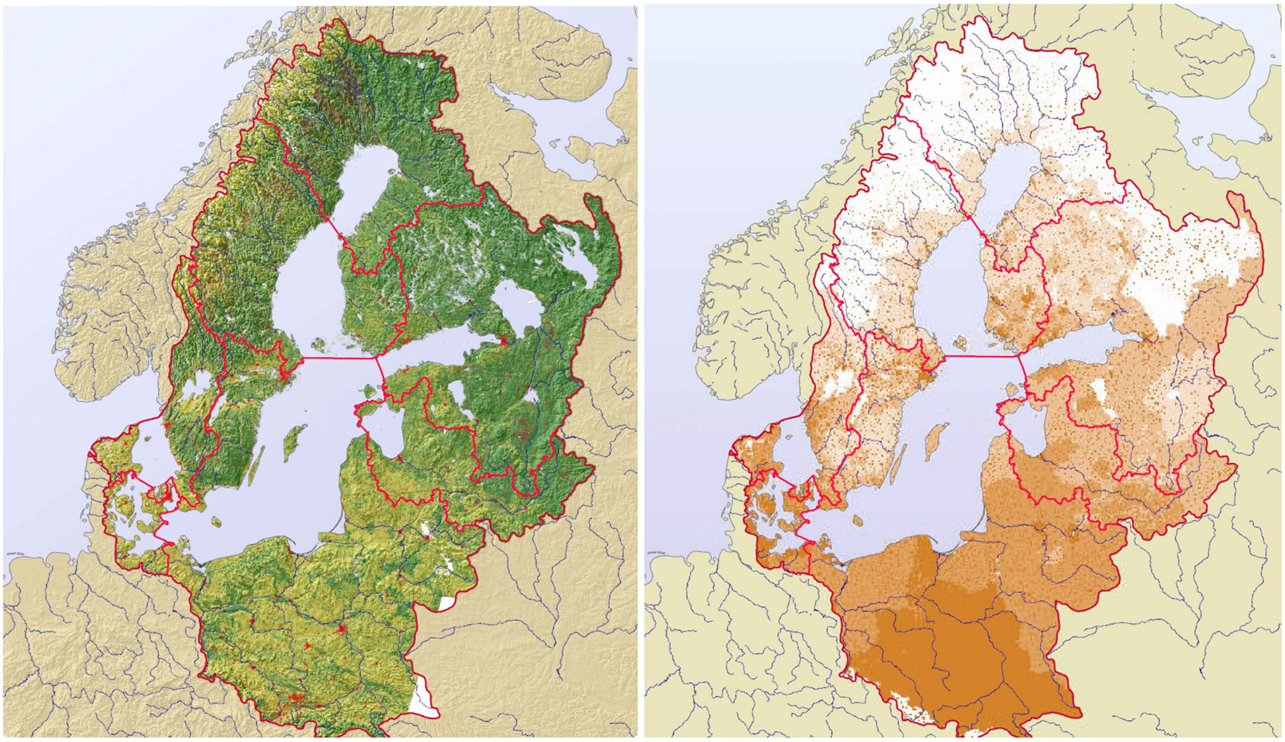


Figure 1. The Baltic Sea drainage basin with land cover (left) and population distribution (right). Dark green: forests; light green: open and agricultural spaces; different shades of orange: population density. Red lines designate drainage sub-basins. Figures are by Hugo Ahlenius, GRID-Arendal Baltic Environmental Atlas, http://www.grida.no (last access: 10 December 2021).

3 Terminology and the DPSIR description

The terms *drivers*, *pressures*, *stressors*, *impacts, cumulative impacts*, etc., are all commonly used in the literature, and they are generally not strictly defined. The term *cumulative* implies that effects add up to a final, stronger impact than each of the individual drivers, either immediately or (more frequently) over a longer time. This may not be the case for all combinations of drivers, as they may act additively, synergistically or antagonistically (Boldt et al., 2014). The terms drivers, pressures, states, impacts and responses are part of the DPSIR concept to assign a structure to the different factors and their links to environmental changes (Smeets and Weterings, 1999; Gari et al., 2015).

In Table 1, we use this concept to define the different factors we analyse in depth in Sect. 5. For each factor (except marine ecosystems and coastal management), we apply the DPSIR concept, which facilitates the understanding of the underlying driving forces, pressures and impacts. In the following analysis in Sect. 5 and thereafter, we focus on the impacts.

We classify our parameters into two groups, loosely following Boldt et al. (2014) (Table 4). Firstly, we consider natural environmental factors which would prevail on an Earth without humans, but which are strongly affected by human activities: climate, land cover, sea level, coastal processes, nutrient loads, hypoxia, acidification, submarine groundwater discharge and non-indigenous species. Then we consider the human factors offshore wind farms, shipping, fisheries, chemical contaminants, dumped ammunitions, marine litter and microplastics, agriculture, aquaculture, river regulations, tourism, and coastal management. A clear separation is sometimes difficult (e.g. for land cover and land use), but this is not relevant in this context.

We define the term *environment* here in an integrative manner as the non-living (abiotic) physical environment, like wind, temperature, precipitation, etc.; the living or directly affected environment, i.e. ecosystems and biogeochemical conditions; and the socio-economic environment, which is everything related to human activities including infrastructure at the coast or sea, or agriculture. Here, we define the term *climate change* to describe the human-induced changes to the climate. Indeed, the term *global change* (or *regional change*) describes the amalgam of current changes because climate change is but one human-induced factor, and it may not be the dominant one in many cases.

The human-induced changes and related environmental problems originate from human needs and the underlying values determining the levels of production and consumption. Human needs and aspirations are realized in consumption patterns, lifestyles and education. At an aggregate level, they can be described in terms of social cohesion, speed of urbanization and birth rate. These aspects of behaviour are driven by values, cultures, religion and habits. Socioeconomic impacts can be included in the climate models by prescribing specific emissions storylines based on socioeconomic developments and allowing studies of alternative future states. The large spread in the different scenarios reflects the uncertainties in future development (Hyytiänen et al., 2021).

4 Method of analysis and the impact matrix

To allow a comprehensive and straightforward approach to the problem, we introduce a matrix in which we show at a glance the impacts of the various factors on each other. This matrix is the core of our analysis (Table 2a and b). This analysis represents a critical review of the literature with the aim of identifying linkages between the different factors: is there evidence in the scientific literature for a connection or impact, or not? The text in Sect. 5 provides brief characterizations of the current knowledge of the factors, followed by bullet lists of potential interrelations for each factor according to the matrix (Table 2a and b) and describing the linkages in detail, as far as feasible in this context. References from the scientific literature are provided for the found linkages between factors (plus sign "+"). We also speculate on potential links (question marks, "?"), which have not (or sparsely) been confirmed in the scientific literature but which may be plausible, not to rule out a connection that has not yet been described. These items represent potential connections, which may be worth considering further. Connections with no apparent or plausible linkages are marked with a minus sign ("−") and not discussed further in the text. The bullet lists are followed by a brief consideration of knowledge gaps, based on this analysis and authors' expert assessment. This assessment is based on literature review, and expert judgement but does not claim to make judgements on the severity or urgency of the described connection or circumstance. This assessment is incomplete and largely subjective, despite all efforts to support any claims by references and reflects the large uncertainties and low evidence in many of the described relationships.

5 Factors of regional change

In this section, we provide short overviews of the current state of knowledge of some factors, which affect the regional Earth system of the Baltic Sea region, followed by a bullet list describing how it may have an impact on any other factor discussed here. For all described effects and interrelations, we refer to the regional scale of the Baltic Sea region.

Natural factors

The first part of this section addresses "natural" factors that would still be part of the environment even if no humans existed but which are also heavily affected by human activities today.

5.1 Climate change

In the context of this analysis, we very briefly describe here the immediate climate impacts on the environment: warming, precipitation and runoff changes, ice conditions, and sea level change. For a detailed analysis on climate change and modelling for the Baltic Sea region, see Christensen et al. (2021), Gröger et al. (2021) and Meier et al. (2021b, c).

Due to its proximity to the northern polar region, the Baltic Sea region is warming faster than the globe. Wintertime changes in *air temperature* are among the strongest climate change signals in Europe, and the land surface has been warming faster than the Baltic Sea. During the past century, an approximate increase of 1 °C was observed over the Baltic Sea region (BACC Author Team, 2008; BACC II Author Team, 2015; Rutgersson et al., 2014), and projected changes until 2100 range between 1.5–4.3 °C over land and 1.4–3.9 °C over sea, according to coupled atmosphere–ocean projections (Meier et al., 2021c), and depending on the emission scenario (RCP, Representative Concentration Pathway, IPCC, 2014), with stronger warming in the northern part of the basin, especially in winter (Gröger et al., 2021).

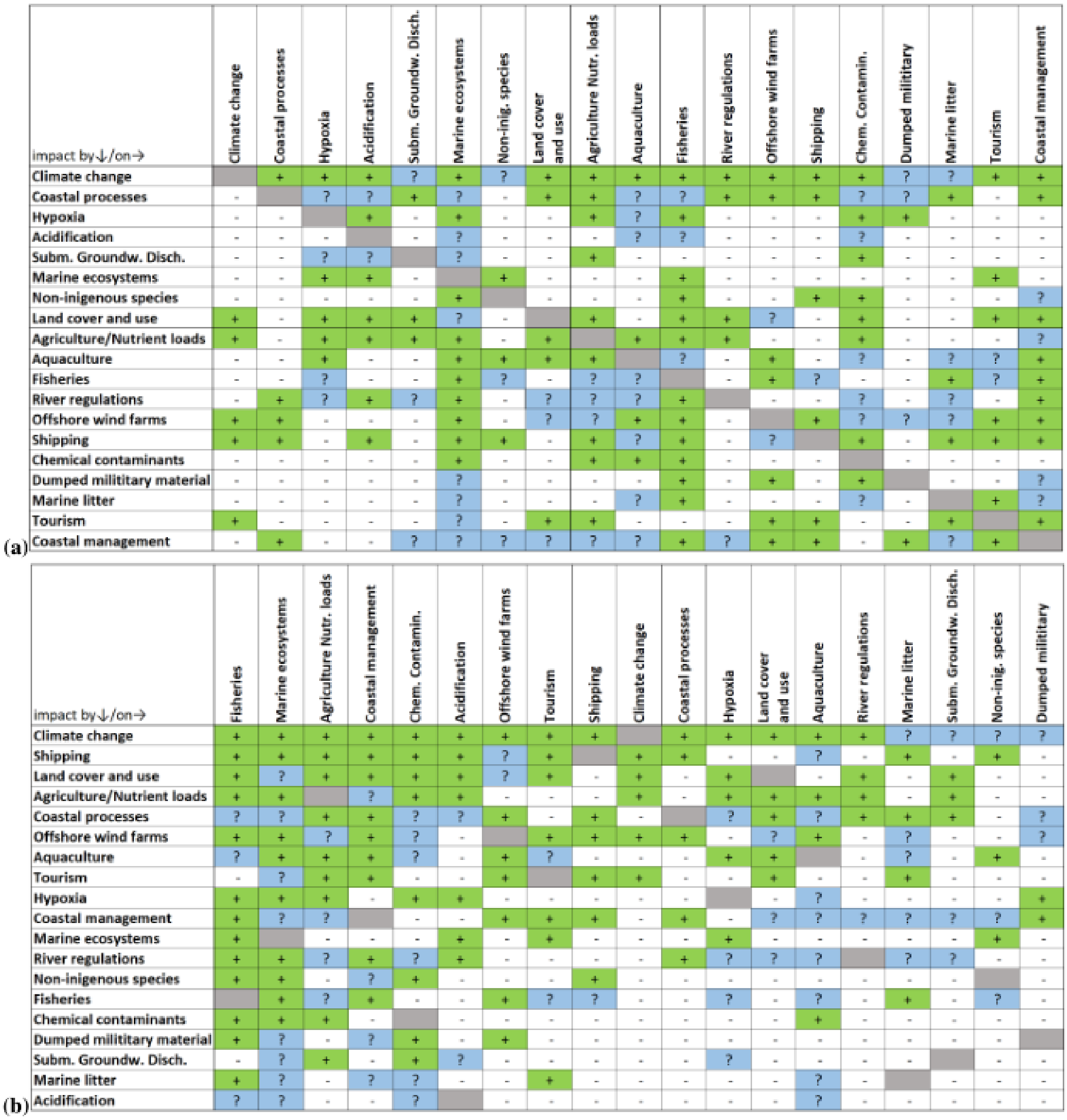
For *precipitation*, the uncertainties are larger. While there is a large variability between seasons and regions, there is a trend projected for the future for precipitation, with an increase for the entire region in winter, but only for the northern part in summer. For the southern part of the basin, the projections vary, and a clear trend cannot be given (Christensen and Kjellström, 2018). Also for *wind*, projections for the future vary considerably, so that no clear trend over the whole Baltic Sea region can be identified (Räisänen, 2017; Christensen and Kjellström, 2018; Christensen et al., 2021; Meier et al., 2021c).

Sea water temperatures have already begun to increase, both at the surface and in deep waters of the Baltic Sea (Mohrholz et al., 2006; Lehmann et al., 2011; Elken et al., 2015), and they are projected to increase further (on average 1.6–3.2° by the end of this century; Gröger et al., 2019; Meier and Saraiva, 2020; Meier et al., 2021c). The increase in sea surface temperature is projected to be the largest in the northern Baltic Sea during early summer, very likely due to the ice–albedo feedback causing earlier warming during the melting season.

All available scenario simulations for *sea ice* suggest a drastic decrease in sea ice cover in the future (Luomaranta et al., 2014; Meier, 2015). However, even the extreme scenarios do not suggest a complete disappearance of sea ice in the northernmost part of the Baltic Sea. The large interannual variability is expected to persist, with a decreasing probability of severe ice winters (Höglund et al., 2017).

Salinity in the Baltic Sea depends on freshwater inputs (river runoff, precipitation), evaporation and outflows

Table 2. **(a)** The matrix of factors. Natural (but affected by human activity) and entirely human factors are grouped together. Based on the current scientific literature, there is (+, green) evidence for a connection, (?, blue) no direct evidence for a connection but a connection is plausible (based on authors' judgement) and (−) no evidence for a connection (these combinations are not discussed in the text). The table is read (1) from left to right. For example, going to the right within the first line "Climate change" shows factors that climate change has an impact on (or not). (2) From top to bottom within a column, the table shows the factors that have an effect on, for example, climate change (using the first column). **(b)** As in **(a)** but sorted according to the number of positive connections (+).



(a)

impact by↓/on→	Climate change	Coastal processes	Hypoxia	Acidification	Subm. Groundw. Disch.	Marine ecosystems	Non-inig. species	Land cover and use	Agriculture Nutr. loads	Aquaculture	Fisheries	River regulations	Offshore wind farms	Shipping	Chem. Contamin.	Dumped milititary	Marine litter	Tourism	Coastal management
Climate change		+	+	+	?	+	?	+	+	+	+	+	+	+	+	?	?	+	+
Coastal processes	-		?	?	+	?	-	+	+	?	?	+	+	+	?	?	+	-	+
Hypoxia	-	-		+	-	+	-	-	+	?	+	-	-	-	+	+	-	-	-
Acidification	-	-	-		-	?	-	-	-	?	?	-	-	-	?	-	-	-	-
Subm. Groundw. Disch.	-	-	?	?		?	-	-	+	-	-	-	-	-	+	-	-	-	-
Marine ecosystems	-	-	+	+	-		+	-	-	-	+	-	-	-	-	-	-	+	-
Non-inigenous species	-	-	-	-	-	+		-	-	-	+	-	-	+	+	-	-	-	?
Land cover and use	+	-	+	+	+	?	-		+	-	+	+	?	-	+	-	-	+	+
Agriculture/Nutrient loads	+	-	+	+	+	+	-	+		+	+	+	-	-	+	-	-	-	?
Aquaculture	-	-	+	-	-	+	+	+	+		?	-	+	-	?	-	?	?	+
Fisheries	-	-	?	-	-	+	?	-	?	?		-	+	?	-	-	+	?	+
River regulations	-	+	?	+	?	+	-	?	?	?	+		-	-	?	-	?	-	+
Offshore wind farms	+	+	-	-	-	+	-	?	?	+	+	-		+	?	?	?	+	+
Shipping	+	+	-	+	-	+	+	-	+	?	+	-	?		+	-	+	+	+
Chemical contaminants	-	-	-	-	-	+	-	-	+	+	+	-	-	-		-	-	-	-
Dumped milititary material	-	-	-	-	-	?	-	-	-	-	+	-	+	-	+		-	-	?
Marine litter	-	-	-	-	-	?	-	-	-	?	+	-	-	-	?	-		+	?
Tourism	+	-	-	-	-	?	-	+	+	-	-	-	+	+	-	-	+		+
Coastal management	-	+	-	-	?	?	?	?	?	?	+	?	+	+	-	+	?	+	

(b)

impact by↓/on→	Fisheries	Marine ecosystems	Agriculture Nutr. loads	Coastal management	Chem. Contamin.	Acidification	Offshore wind farms	Tourism	Shipping	Climate change	Coastal processes	Hypoxia	Land cover and use	Aquaculture	River regulations	Marine litter	Subm. Groundw. Disch.	Non-inig. species	Dumped milititary
Climate change	+	+	+	+	+	+	+	+	+		+	+	+	+	+	?	?	?	?
Shipping	+	+	+	+	+	+	?	+		+	+	-	-	?	-	+	-	+	-
Land cover and use	+	?	+	+	+	+	?	+	-	+	-	+		-	+	-	+	-	-
Agriculture/Nutrient loads	+	+		?	+	+	-	-	-	+	-	+	+	+	+	-	+	-	-
Coastal processes	?	?	+	+	?	?	+	-	+	-		?	+	?	+	+	+	-	?
Offshore wind farms	+	+	?	+	?	-		+	+	+	+	-	?	+	-	?	-	-	?
Aquaculture	?	+	+	+	?	-	+	?	-	-	-	+	+		-	?	-	+	-
Tourism	-	?	+	+	-	-	+		+	+	-	-	+	-	-	+	-	-	-
Hypoxia	+	+	+	-	+	+	-	-	-	-	-		-	?	-	-	-	-	+
Coastal management	+	?	?		-	-	+	+	+	-	+	-	?	?	?	?	?	?	+
Marine ecosystems	+		-	-	-	+	-	+	-	-	-	+	-	-	-	-	-	+	-
River regulations	+	+	?	+	?	+	-	-	-	-	+	?	?	?		?	?	-	-
Non-inigenous species	+	+	-	?	+	-	-	-	+	-	-	-	-	-	-	-	-		-
Fisheries		+	?	+	-	-	+	?	?	-	-	?	-	?	-	+	-	?	-
Chemical contaminants	+	+	+	-		-	-	-	-	-	-	-	-	+	-	-	-	-	-
Dumped milititary material	+	?	-	?	+	-	+	-	-	-	-	-	-	-	-	-	-	-	
Subm. Groundw. Disch.	-	?	+	-	+	?	-	-	-	-	-	?	-	-	-	-		-	-
Marine litter	+	?	-	?	?	-	-	+	-	-	-	-	-	?	-		-	-	-
Acidification	?	?	-	-	?		-	-	-	-	-	-	-	?	-	-	-	-	-

through the Kattegat, as well as saltwater inflows. There have been large decadal variations in mean salinity in the past, but no long-term trend (Lehmann et al., 2021). Salinity projections for the future show large variations as the factors wind, runoff and sea level rise act antagonistically, and their effects are difficult to project (Meier et al., 2021a, c).

Sea level rise is treated here as a direct consequence of climate change. Its variations are caused by ice sheet melting, water thermal expansion and atmospheric circulation changes. Post-glacial land movement ranges from a sinking in the southwest ($-1\,\mathrm{mm\,yr^{-1}}$) to a rise of up to $9\,\mathrm{mm\,yr^{-1}}$ in the north (Harff et al., 2020). Water masses expand with warming, causing the sea level rise in the Baltic Sea. A second large factor is the melting of glaciers and of polar ice sheets. This elevates the globally averaged sea level, but its regional impact is more complicated. Due to gravitational effects, future trends in Baltic Sea sea levels will be mostly influenced by the melting of land ice in Antarctica and other remote regions, and much less by the melting of neighbouring land ice in Greenland (Mitrovica et al., 2001). The melting of Greenland ice will have a varying impact along Baltic Sea coasts (Hieronymus and Kalén, 2020). Changes in atmospheric circulation (Gräwe et al., 2019), sea ice and salinity (Ekman and Mäkinen, 1996) also affect Baltic Sea sea level. Global sea level rise is currently projected to range between 43 and 84 cm until 2100, depending on the scenario (Oppenheimer et al., 2019). In the Baltic Sea, sea level is estimated to rise (corrected for land uplift) between about 80 % (Grinsted et al., 2015; Hieronymus and Kalén, 2020) and 100 % of the global rise. For a full review on sea level change in the Baltic Sea, see Weisse et al. (2021).

5.1.1 Impacts of climate change on other factors

- There is good evidence that climate change has a strong impact on *coastal processes* (+), through sea level rise on coastal erosion (Defeo et al., 2009) and the translocation of sediments through erosion, currents and accretion (Slott et al., 2006; Fitzgerald et al., 2008). In general, coasts are expected to be subject to stronger changes not only by inundation of low-lying coastal regions but also through increased wave-driven sediment translocations (Deng et al., 2019). As Baltic Sea waves often approach sedimentary shores under relatively large angles (Soomere and Viška, 2014), alongshore sediment transport may be particularly intense with rising sea level in the Baltic Sea. A considerable reduction of sea ice increases erosion rates at soft shores (Orviku et al., 2003; Overeem et al., 2011; Farquharson et al., 2018). Due to the large variability in observations and projections, there is so far no clear indication for changes in storm frequencies, severity and tracks in the Baltic Sea region, so their impact on coastal processes remains speculative.

- There is good evidence that *hypoxia* (+) is strongly affected by climate change indirectly through temperature, salinity and stratification, possibly also by altered precipitation and runoff patterns in the southern Baltic Sea region (Zillén et al., 2008). It is unclear whether the frequency of Baltic inflow events which temporarily provide new oxygen-rich deep water for the deep basins of the central Baltic Sea will change. A higher sea level and associated larger cross section in the Danish straits may have an impact on the volumes of future Baltic inflows of high-salinity waters. This in turn may have an impact on hypoxia in the large basins through stronger saltwater inflows and associated stronger stratification in the deep basins (Meier et al., 2017). With more hypoxia, more phosphorus release from the deep anoxic basins may enhance cyanobacteria blooms and further deteriorate the oxygen situation in the deep basins. Still, the frequencies and consequences of possible stronger oxygen-rich saltwater inflows remain largely unknown and speculative.

- *Marine acidification* (+) is very much a product of anthropogenic CO_2 emissions, in the course of fossil fuel combustion and changes in land use (e.g. Doney et al., 2009). The increase in atmospheric CO_2 concentrations leads to enhanced dissolution of CO_2 in seawater. As CO_2 dissolved in seawater forms weak diprotic carbonic acid, its dissociation causes seawater pH to decrease (Kuliński et al., 2017). Acidification in the Baltic Sea is different from other ocean provinces and marginal seas as it is very much affected by alkalinity, in particular in the northern Baltic Sea (Müller et al., 2016). Another source of anthropogenic acidification is atmospheric deposition of sulfur and nitrogen oxides, also being combustion products. They cause the so-called acid rain, which is especially relevant for soils and inland waters (e.g. Tranvik, 2021). Shipping may also contribute to acidification through scrubber water.

- *Submarine groundwater discharge (?)* has been shown to affect coastal waters. There is no evidence that there is a direct impact of climate change on the quantity and quality of these submarine discharges, but looking at the driving forces of submarine groundwater discharges (SGDs), this is plausible. Driving forces of SGD involve topography-driven flow, wave set-up, precipitation, sea level rise and convection caused by salinity and temperature between the seawater and groundwater (Burnett et al., 2006; Taniguchi et al., 2019). Changing groundwater levels (lowering in dry seasons, or rising at times of strong precipitation) may be the effect of changing precipitation patterns and higher temperatures leading to stronger evaporation. The magnitude and relevance of these changes remain unclear; therefore impacts on SGD by sea level rise and changes in precipitation and/or evapotranspiration need to be evaluated (Taniguchi et al., 2019). There may be an effect of rising sea level (and geostatic land rise). Even though it is hard to project the direction and significance of the change due to missing data and investigations (Taniguchi et al., 2019; Kłostowska et al., 2020), modelling efforts signal that the total fluxes of submarine groundwater discharge may eventually decrease significantly with future sea level rise. This process is likely associated with a marked decline in the flux of nutrients and carbon to estuaries and the coastal ocean (Evans et al., 2020). Numerical studies imply that sea level changes may be responsible for an increase in recirculated SGD (RSGD), but this is not clear (Lee et al., 2013).

- *Marine ecosystems* (+) are affected strongly by climate change through warming and changing seasonality (Viitasalo and Bonsdorff, 2021; Viitasalo et al., 2015). For phyto- and zooplankton, longer and shifted growth periods have been shown, with selective impacts on specific species and functional groups (e.g. dinoflagellates, certain copepods) (Wasmund et al., 2019). Changes in benthic communities have been related to warming and eutrophication (Ehrnsten et al., 2020). A prominent potential victim of the anticipated reductions in sea ice in the northern Baltic Sea is the ringed seal which breeds on sea ice (Meier et al., 2004), while other marine mammals, e.g. harbour porpoises, may profit from warming (Dippner et al., 2008). Still, there are many complex interactions between species and functional groups within the ecosystem, and climate-change-related impacts on certain species or groups may have indirect propagations to other compartments of the system. These effects are mostly non-linear and may interact with one another, and they may be beneficial or detrimental for different ecosystem constituents or functions. A comprehensive description of climate change effects on the ecosystems of the Baltic Sea is provided by Viitasalo and Bonsdorff (2021) and references therein.

- Climate change has generally shifted the species boundaries northwards, so it is a plausible driver for the migration and occurrence of *non-indigenous species*, although there is no direct evidence (*?*). Shipping through ballast water, attachment to hulls or the disappearance of physical barriers (e.g. through the construction of canals between separated water bodies) have been identified as major vectors for the introduction of new marine species into the Baltic Sea ecosystem (Ojaveer et al., 2017). Therefore, the physical transfer is not climate change related, but a changing climate can provide favourable growth conditions in the target region, e.g. through changes in temperature and salinity or prey composition (Möllmann et al., 2005). Another way to introduce new species is the direct migration to regions where climate change has established favourable conditions. This is, however, negligible compared to marine traffic and represents a rather gradual introduction. Northward migration of land (Smith et al., 2008) and marine species (for which temperature is critical) has been observed and is expected for the future (McKenzie and Schiedek, 2007).

- Climate change affects air and water temperature as well as precipitation patterns, so there is a clear impact on *land use* and *land cover* (+). Sea level rise may also affect land cover and use by increased flooding or eroding coastal areas, which are thus lost to the sea or converted to wetlands (e.g. Gedan et al., 2020). Growth conditions on land and the vegetation zones are affected by changing temperatures and precipitation patterns (Smith et al., 2008), but also by political or management decisions, which in turn may or may not be influenced by climate change (Yli-Pelkonen, 2008). Higher temperatures and CO_2 concentrations in the atmosphere lead to thriving vegetation but declining water availability, presumably in the southern parts of the region, sets limits to this (Smith et al., 2008). The decisions on which part of land is dedicated to which use (e.g. agriculture) are very much management and political decisions, which in turn may be affected by climatic conditions.

- The most important type of land use, at least in the southern part of the Baltic Sea basin, is *agriculture* (+). Climate change has a strong impact on the different kinds of crops as different crops have different requirements concerning water availability and soil type. Any changes in temperature and precipitation may lead to the need for better adapted crops as a response (Fronzek and Carter, 2007). Socio-economic considerations may be still more important in defining the type of agricultural land cover than climatic ones (e.g. Rounsevell et al., 2005; Bartosova et al., 2019; Pihlainen et al., 2020). Climate change alters precipitation and runoff patterns from agricultural fields and thus largely determines the amounts of *nutrients* (+) entering the sea. Still, the effects of climate change on nutrient loads are rather uncertain. Climate projections indicate that the northern part of the Baltic Sea basin could be wetter, but for the south, changes are unknown (Christensen et al., 2021). That would imply that riverine and runoff fluxes of nutrients could decline as most nutrients enter the Baltic Sea in the southern part of the basin, but it is difficult to assess which sources dominate in different sea subbasins, and catchment-wide models of nutrient source apportionment are scarce (Bartosova et al., 2019, HELCOM, 2018b, c). Furthermore, it is not known how fertilization practices, crops grown and land use will change in response to climate change. Also unknown is the relative contribution of nitrogen from accumulated legacy sources to current riverine loads to the sea and how the accumulation and release of legacy nutrients will be impacted by climate change. Warmer winters without snow cover and non-freezing soil have resulted in proportionally more soil erosion, larger runoff and consequently more nutrients transported to the sea (Huttunen et al., 2015). Climate-related changes in the Baltic Sea like warmer temperatures, changed stratification patterns, altered ecosystems and biogeochemical pathways may change the fate of nutrients in the sea (Arheimer et al., 2012; Meier et al., 2012). Sea level rise may have an impact on the internal loading of phosphate, through potentially increased saltwater inflows in the future with rising sea levels, affecting ecosystems in micro-tidal lagoons (Huang et al., 2020) and increasing the hypoxic areas in the deep water and the associated phosphate release (Meier et al., 2017).

- *Aquaculture* (+) is directly affected by rising water temperatures. Surface water (0–10 m) temperatures often exceed the optimal range for rainbow trout, a major aquaculture fish in the Baltic Sea region (Kankainen et al., 2020). Farmers report longer periods of excessively warm waters, causing reduced physical fitness, impaired growth and even fish kills which may be related to warming and other associated impacts (Brander et al., 2017; Reid et al., 2019). Therefore, a trend towards more warm water species such as pikeperch, perch, etc., is possible. Salinity changes are unlikely to affect currently farmed fish species in the Baltic Sea. Warmer growth seasons might increase the risk of successful establishment of farmed rainbow trout in the wild, demanding the use of sterile fish as mitigation. Blue mussels and macroalgae aquaculture may be negatively affected by both warmer temperatures and, potentially, declining salinity. Any increase in waves and extreme events as well as predation by fish and birds would lead to higher mussel losses. All these climatic effects are to a large extent eliminated in enclosed, controlled, land-based farming facilities.

- *Fisheries* (+) are strongly affected by climate change impacts on the commercially interesting fish populations in the Baltic Sea, that is mostly cod, sprat and herring (Möllmann, 2019). Climate affects salinity and temperature, which in turn affect the reproduction and growth of several fish species (MacKenzie and Köster, 2004; MacKenzie and Schiedek, 2007; Köster et al., 2017), and thereby the availability of the resources that fisheries can exploit. Growth of planktivorous species or life stages is affected by climatic conditions that regulate zooplankton dynamics (Casini et al., 2011; Köster et al., 2017). Climate effects are also connected to oxygen conditions in the Baltic Sea, affecting the organisms and fish production in several ways, e.g. for cod (Köster et al., 2005). Climate impacts on one species can also propagate through the food web via food web interactions. For example, a high abundance of sprat due to favourable temperatures increases competition between sprat and herring and reduces their growth and condition (Casini et al., 2011). Changes in ice conditions in the future may affect the duration of fishing season in northern areas in the Baltic Sea, with potential consequences for some fish stocks (Bauer et al., 2019).

- Climate change can be expected to affect *river regulations* (+). Inland shipping and water management have resulted in river regulations for centuries, and the hydrology of many catchment basins, including the Baltic Sea, is heavily modified (e.g. Wanders and Wada, 2015). Increasing droughts with lower river water volume at certain times of the season may affect water management and shipping in the southern catchment basin. On the other hand, extreme rain events may lead to inundation, where the river was regulated and natural inundation areas have been separated from the river by levees and transformed to agricultural surfaces or housing areas (Kundzewicz et al., 2005). Arheimer et al. (2017) concluded that in snow-fed rivers globally the future climate change impact on flow regime is minor compared to the regulation downstream of large reservoirs.

- There is good evidence that *offshore wind farms* (+) and their energy production are impacted by climate change because, firstly, wind is a climate-related atmospheric feature and secondly because the wind farms are, at least partly, a political (management) response to mitigate climate change (Tobin et al., 2015, 2016). With increasing mitigation activities worldwide, we can expect a considerable increase in offshore wind energy production (ECDGE, 2019). Although it is not clear whether the harvested wind energy per unit will be higher in the future due to the uncertainty of wind projections (Rusu, 2020; Christensen et al., 2021), the number of wind farms will increase in the future due to a politically driven shift to renewable energies and the limited space and low acceptance for land-based wind energy devices. Offshore wind farms may in turn have a certain impact on the regional climate by absorbing atmospheric energy on the regional scale. There is, however, little information on the magnitude of this effect (e.g. Siedersleben et al., 2018; Lundquist et al., 2019). Rising sea levels may have an impact on offshore wind farms, but they are probably not affected severely as there is presumably a sufficient safety margin calculated for storm surges within the life span of a structure. The general perception is that interaction between the foundation and the surrounding soil is a significant source of uncertainty in estimating the safety margins of support structures (Smilden et al., 2020).

- There is strong evidence that *shipping* (+) is affected by climate change. Perils at sea for ships are all climate sensitive, ranging from storms to waves, currents, ice conditions, visibility and sea level affecting navigational fairways. Winter navigation is less impeded as a drastically decreasing winter sea ice cover is projected, but as winters with ice cover can also occur in the future (albeit less frequent), precautions for a safe winter shipping (e.g. the provision of ice-breaking vessels in the eastern and northern Baltic Sea) cannot be abandoned. Also, search-and-rescue missions in winter may increase because engine power may in the future be adapted to the lower expected ice cover and stringent energy efficiency requirements set by the International Maritime Organization (IMO). Inland and archipelago shipping is impacted by floods and depth changes of rivers or straits, which may prevent normal vessel operations during exceptional periods. Further aspects affecting shipping are a potential increase in leisure boating with increasingly warm and longer summers in the Baltic Sea and different noise propagation through warmer water. Regulations to reduce the SO_x concentrations in air emissions by large ships involve scrubbing, i.e. the stripping of the contaminated combustion air with seawater. The stripping efficiency depends on the alkalinity of the sea water, which eventually ends up contaminated in the Baltic Sea (Endres et al., 2018; Teuchies et al., 2020) and may increase acidification (Turner et al., 2018). Possible impacts by sea level change on shipping could be the modification of fairways/shipping routes. On the one hand, shallow passages may get deeper and wider in the future (Meyers and Luther, 2020), and passages may be safer through shallow and dangerous fairways like the Kadet channel. Increasing water depths at bottlenecks would allow deeper drafts or higher loadings of large vessels, but ship size is constantly increasing, which may offset this hypothetical effect (Lu and Yeh, 2019). On the other hand, harbours and docking terminals will need to be adapted to higher water levels and possible changes in the sediment transport patterns. The associated threats of direct wave attack and overtopping may require substantial modifications of the existing breakwaters (Contestabile et al., 2020), also resulting in an increase in operational shutdowns and subsequent economic losses (Izaguirre et al., 2021). There has already been major damage and disruption to ports across the world from climate-related hazards, and such impacts are projected to increase in the years and decades to come (Becker et al., 2018).

- Climate change impacts on the degradation and distribution of chemical *contaminants* (+) include an array of processes. Changing environmental temperatures affect diffusive partitioning between environmental phase pairs such as air–water, air–aerosols, air–soil and air–vegetation, leading to a different distribution between environmental compartments, like increased volatilization from seawater and soil to air (Macdonald et al., 2003; Noyes et al., 2009). Increasing temperatures can enhance photolysis, hydrolytic degradation and biodegradation of organic contaminants (Noyes et al., 2009). Atmospheric transport and air–water exchange can be influenced by changes in wind fields and, to a lesser extent, wind speeds (Lamon et al., 2009; Kong et al., 2014). Changing precipitation patterns influence chemical transport via atmospheric deposition (rain dissolution and scavenging of particles; Langner et al., 2005; Armitage et al., 2011) and runoff, transporting terrestrial organic carbon and contaminants associated with this carbon (Ripszam et al., 2015). As ice cover in lakes and the sea decreases, more organic contaminants may volatilize to the atmosphere (Macdonald et al., 2003; Undeman et al., 2015). Extended vegetation periods together with a reduced ice cover in the coastal zone allow both planktonic and benthic organisms to accumulate nutrients and toxic substances for a longer period. It has been estimated that, in an ice-free year, the average mercury concentration can be substantially higher in phytoplankton and macrophyto- and zoobenthos compared to ice winters (Bełdowska et al., 2016b; Bełdowska and Kobos, 2016). As a result, a greater load of mercury can be remobilized from sediment to benthic organisms (Bełdowska, 2015; Bełdowska et al., 2015). An increase in air temperature, especially in the late autumn–winter–early spring season, contributes to the reduction of coal combustion and consequently to a decrease in toxic metal emissions and other combustion products like dioxins and polyaromatic hydrocarbons (PAHs), compared to colder winters (Bełdowska et al., 2016b; Bełdowska, 2015). Still, reductions in emissions of contaminants have much stronger effects on concentrations of all contaminants than climate change (Simpson et al., 2015).

- *Dumped military material (?)* may be a great danger for the Baltic Sea in the future as poisonous material is expected to leak due to corrosion of hulls. This process may possibly be affected by climate change. Due to longer vegetation periods in a warmer climate, the extended transfer of carcinogenic degradation products of explosives may take place for a larger part of the year. Corrosion rates are temperature and oxygen dependent, so that good ventilation of dumping sites can be expected to enhance corrosion rates (Silva and Chock, 2016). Warming can significantly affect munitions in shallow waters, which were mostly used as dump sites for conventional warfare material. There, ammunition shells, as hard metal objects acting as substrates for colonization in soft sediment areas, can increase the local biodiversity of sessile species, but the chunks of organic compounds used as explosives can also attract primary and secondary producers as a source of nutrients, followed by various biofilm grazers. Longer vegetation seasons may contribute to oxygen deficiencies, which may reduce arsenic constituencies into more mobile and toxic arsenic species (Czub et al., 2021).

- There is no evident direct impact of climate change on *marine litter* or *microplastics (?)*. Still, there may be a connection via increased temperature- and photolysis-dependent physical degradation of microplastics and on the distribution due to changing currents. Furthermore, changes in precipitation and frequency of storm events may affect microplastic concentrations in the Baltic Sea due to changes in microplastic emissions, e.g. via storm water runoffs deposition and sediment resuspension.

- There is an impact of climate on coastal *tourism* (+) in general (Arabadzhyan et al., 2021), and also at the Baltic Sea coasts (Braun et al., 1999; Seetanah and Fauzel, 2019). A warmer climate with projected longer and warmer summers is clearly beneficial for most touristic activities in the Baltic Sea region (swimming, diving, sun bathing, surfing, boating, fishing), with its moderate to subarctic weather conditions (Nicholls and Amelung, 2015; Perch-Nielsen et al., 2010). Furthermore, the perception of climate change and changing social norms, preferences and ideals towards a carbon-neutral society and tourism may enhance the role of regional and local tourism in the Baltic Sea region (Kaján and Saarinen, 2013; Urry, 2015). On the other hand, ice-related activities in the northernmost parts in winter, like ice fishing and skating are expected to be less practicable in the future. There are negative implications of climate change which are relevant for tourism, e.g. potentially deteriorating water quality in coastal waters due to hypoxia and algal blooms (Nilsson and Gössling, 2013; Olofsson et al., 2020), novel toxic algae (Engstrom-Ost et al., 2015), and growth of infectious bacteria (e.g. *Vibrio*) (Baker-Austin et al., 2013). Beaches may suffer as well (Haller et al., 2011).

- *Coastal management* (+) as the process to mitigate problems in the face of multiple uses of coastal spaces and services is strongly challenged by climate change (Sánchez-Arcilla et al., 2016). There is strong evidence that climate change heavily affects coastal structures through sea level rise (Nicholls, 2011) and intensified coastal erosion (Toimil et al., 2017). Storm surges, which run up higher with rising sea level (Needham et al., 2015; Hague et al., 2020; Stephens et al., 2020) as well as changing current patterns (Nagy et al., 2019) and sediment relocations (Soomere and Viška, 2014), endanger levees, groynes and other coastal structures and call for coastal management decisions to cope with these changes (Le Cozannet et al., 2017). Harbours and cities are strongly affected, so that there is considerable economic (Di Segni et al., 2017) and ecological (Naylor et al., 2012) value at stake. Beaches as spaces for recreation with multi-billion value in the Baltic Sea (Czajkowski et al., 2015) and coastal biotopes are under pressure as well (Harff et al., 2017a; Vitousek et al., 2017; Vousdoukas et al., 2020). Sea level change in particular has a very strong impact on coastal management and the defence structures like levees and groynes, and generally on the management of low-lying coastal regions (Hoggart et al., 2014). Also, coastal cities (Balica et al., 2012) and harbours (Sierra, 2019) are highly vulnerable to sea level rise and require management actions. Different vulnerabilities and urgencies towards sea level rise require different management approaches in different countries and between the southern and the northern regions (e.g. Harff et al., 2017a, b; Støttrup et al., 2017): resilient high, rocky coasts with land uplift dominate in the north (Ristaniemi et al., 1997), while vulnerable low, sandy coasts; soft cliffs; and a slight land subsidence are strongly endangered in the southern regions (Zeidler, 1997).

5.1.2 Knowledge gaps

The large spread between different atmospheric simulations reflects the combined uncertainty between global climate sensitivity, regional response and natural variability. For assessing future climate change, modelling is the primary tool available, and fundamental research questions remain. These include a better representation of the large-scale thermohaline circulation influencing the North Atlantic, the large-scale atmospheric circulation including storm tracks influencing cyclone activity and high-pressure blocking situations, representation of microphysical processes involving clouds and aerosols, exchange processes at the surface including soil moisture and snow conditions, and a better representation of precipitation processes including convection-permitting modelling to better represent precipitation extremes.

Simulations with large ensembles of climate models where the only difference is the initial conditions show that such changes can be very large, and this is a considerable source of uncertainty in assessing changes in the regional climate. Climate models generally do not agree on the line dividing precipitation increases and decreases. Evaporation, on the other hand, will very certainly increase. As a consequence, there is an uncertainty to what extent conditions for drought will be more or less pronounced in the future. Furthermore, it is so far not clear whether salinity in the Baltic Sea will increase or decrease in the future, and thus how the modified salinities may affect sea level changes. There are major knowledge gaps concerning the effects of aerosols on the regional climate of the Baltic Sea region, and models are largely unable to simulate aerosol–climate interactions (Hansson and Bhend, 2015). Further questions involve the following.

- *Climate change and marine ecosystems.* There are large uncertainties related to the complex interactions in the pelagic and benthic ecosystems (from bacteria and fish) and how these respond to climate change.

- *Climate change and river regulations.* How is climate change affecting regulated river basins, e.g. through inundations, flooding or droughts? Current coupled climate models for the Baltic Sea region suffer from a poor representation of river regulations, floodplain storage and backwater effects (e.g. Hagemann et al., 2020).

- *Climate change and dumped military material.* What is the effect of warming temperatures on the corrosion rate and release of toxic substances from dumped materials?

5.2 Coastal processes

Coastal processes generally describe the impact of the sea on the direct coastline it is in contact with. This includes waves, currents, sediment translocations and coastal erosion, accretion, and silting processes. These processes differently affect different coastal types (sandy beaches and soft cliffs vs. rocky coasts).

About half of the shores of the Baltic Sea are sedimentary (Harff et al., 2017b) and thus susceptible with respect to different hydrometeorological loads. The submerged and soft coastal relief of the southern Baltic Sea area is under most threat (Labuz, 2015). The other half of shores are either extremely resistant bedrock (granite) or very slowly changing limestone shores. Most of the sedimentary shores suffer from erosion (Pranzini and Williams, 2013), and only relatively short sections (most notably Denmark) exhibit accretion (EMODnet Geology, 2021). Many shore segments exhibit rapid retreat rates (e.g. up to $2.5\,\mathrm{m\,yr^{-1}}$ in the Neva Bight; Ryabchuk et al., 2012) that may have large impacts on the coastal infrastructure and cause extensive land losses. For example, the projected shoreline retreat in some sections of the Pomeranian Bay may reach 100 m by the end of the 21st century (Deng et al., 2015) and 30–40 m on the northern shore of the Neva Bight (Leont'yev et al., 2015).

The major supplier of energy to the nearshore and the driver of sediment transport is surface waves, mostly during high storm surges when waves affect unprotected sediment (Soomere and Viška, 2014; Kovaleva et al., 2017; Björkqvist et al., 2018).

Such events are infrequent in the Baltic Sea, which hosts a highly intermittent wave climate. On the one hand, as little as 1 % of the total annual energy arrives on the shores of the eastern Baltic Sea within the calmest 170–200 d. On the other hand, 60 % of the annual energy arrives within 20 d with relatively high waves and as much as 30 % of the energy within the 3–4 stormiest days (Soomere and Eelsalu, 2014). Thus, the properties of single storms and the timing of storms in sequences may become decisive in the evolution of the coast (Coco et al., 2014; Dissanayake et al., 2015).

Hydrodynamic forces effectively reshape the shore, particularly when no ice is present and the sediment is mobile (Orviku et al., 2003; Ryabchuk et al., 2011; Nielsen et al., 2020). No ice means no protection against severe waves and high water levels (Barnhart et al., 2014). Storm surges are much higher during ice-free time than on the shore of even partially ice-covered water bodies (Orviku et al., 2003).

The potential additional sedimentation of fairways and river mouths and erosion of shores in the vicinity of built environments have direct economic consequences. The loss of stability of beaches (Haller et al., 2011) may severely damage communities that offer recreational services. Unexpected changes in the transport system may lead to, for example, intense cross-shore transport of very fine sediment to vulnerable areas such as spawning areas, with substantial consequences to fish stocks.

Many Baltic Sea shores suffer from a deficit of fine sediments (Pranzini and Williams, 2013), which makes them very vulnerable. However, a number of beaches of the Baltic Sea are stabilized (Soomere et al., 2017): as waves in the Baltic Sea are relatively short and thus their energy spectrum is relatively narrow, the surf zone is narrow and wave run-up phenomena are usually less powerful than on the open-ocean shores (Didenkulova et al., 2008). Postglacial rebound in some parts of the sea additionally stabilizes the affected beaches. Therefore, many Baltic Sea beaches with very small amounts of sand are in a fragile but almost equilibrium state. As sediment transport direction and its convergence (accumulation) and divergence (erosion) areas are highly sensitive with respect to the wave approach direction, even a minor climate-change-driven rotation of the predominant wind directions over the Baltic Sea may substantially alter the structural patterns and pathways of wave-driven transport and functioning of large sections of the coastline (Viška and Soomere, 2012).

Sediment extraction for the purposes of beach renourishment (Karaliūnas et al., 2020) or aggregate (Schwarzer, 2010) can negatively affect shorelines if the source zone is at depths less than the beach profile closure (López-Ruiz et al., 2020).

5.2.1 Impacts of coastal processes on other factors

- Coastal current systems and sediment relocations may possibly influence local *hypoxia (?)* in coastal embayments. Biogeochemical processes in the water column and sediments are the cause for hypoxia and anoxia, but coastal processes may be important for providing certain conditions (e.g. Conley et al., 2009; Kemp et al., 2009).

- Coastal processes, next to riverine inputs, may affect alkalinity and *acidification (?)* in some regions (Krumins et al., 2013; Gustafsson et al., 2014; Gustafsson and Gustafsson, 2020).

- Submarine groundwater discharge (+) can be defined as a coastal process. It is very much affected by other coastal processes like topography-driven flow, wave set-up, sea level rise and currents (Burnett et al., 2006; Kłostowska et al., 2020).

- Coastal processes may affect marine ecosystems (?), in particular coastal habitats. On the one hand, the loss or weakening of coastal barriers leads to saltwater intrusion into adjacent low-lying areas. Increased salinity levels moving inland have disrupted many wetland ecological functions (Davidson et al., 2018). On the other hand, improved water quality via coastal retreat may mitigate losses of seagrass from sea level rise (Luijendijk et al., 2018). Major changes in the sediment transport system may lead to increased (but not yet quantified) pressure to vulnerable areas, e.g. via transport of very fine sediment to spawning areas.

- Coastal erosion can affect land use (+) the coast, beaches and close to endangered cliffs where erosion often increases risk for landslides (Collins and Sitar, 2008). These aspects are well understood for the open-ocean shores (e.g. massive changes in the area of fish ponds owing to erosion and accretion; Kalther and Itaya, 2020) but have not been addressed in the Baltic Sea context. Accretion can generate new sand spits (Tõnisson et al., 2008; Ryabchuk et al., 2011) and associated coastal lagoons, marshes or polders and may lead to massive silting of harbours. On a long timescale the morphology and its associated land use are subject to change.

- Similarly, it can be significant for agricultural (+) fields and forests very close to the sea or a cliff endangered by coastal erosion. These processes are generally proportional to the shoreline retreat rate but may threaten important areas if, for example, a coastal barrier is lost. Coastal currents affect the distribution of landborne nutrients (e.g. near-shore currents in the Pomeranian and Gdansk bays, with little mixing with open waters; e.g. Pastuszak et al., 2003; Voss et al., 2005b).

- There is no direct evidence for an impact on aquaculture (?), but erosion and sediment translocations may affect open aquaculture cages in coastal locations.

- There may be an impact of coastal processes on coastal fish habitats and fishing (?) grounds. Intense cross-shore transport of very fine sediment to spawning areas may adversely affect fish stock, but this potential effect has not been quantified.

- Coastal processes can possibly affect the regulation of river (+) mouths and estuaries, and the associated sediment distributions in these river mouths. They may result in building a sill at the river mouth that partially or totally blocks the river flow, similar to an ice jam (Lindenschmidt et al., 2019). This blocking may lead to flooding of the areas around the river mouth and to a degradation of water quality in the closed estuary. This phenomenon is frequent on open-ocean shores (e.g. Thom et al., 2020). It usually occurs in wave-dominated environments, which are scarce in the Baltic Sea and are represented, for example, by the Narva River (Laanearu et al., 2007).

- Offshore wind farms (+) can be affected by coastal processes if they are close to the coast, e.g. through currents and sediment transport. Coastal currents may lead to wake effects and scouring and problems with the stability of pillars and the sediment distribution in the lee of the wind turbines. The interaction between the foundation and the surrounding soil is a major source of uncertainty in estimating the safety margins of support structures (Smilden et al., 2020).

- There is a large influence of coastal processes on shipping (+) routes close to the coast and in intracoastal waterways: changing currents and the generation of shallows and sand spits into fairways, either naturally or forced by different coastal engineering structures (Davis and Barnard, 2003), may result in re-location and the need for dredging of fairways.

- Coastal processes may affect the distribution of chemical contaminants (?) and toxic heavy metals through sediment translocations and the modification of habitats. Coastal erosion contributes significantly to the inflow of substances to the sea (including toxic chemicals), and wave-driven alongshore transport may carry such substances to great distances. The concentrations of toxic metals in the eroding cliff are mostly low (Kwasigroch et al., 2018), but due to the large amounts of eroded sediments, the total load of metals introduced in this way is significant (Bełdowska et al., 2016a). Additionally, episodes of erosion occur several times a year, leading to large loads of toxic substances in a relatively short time. Metals introduced to the environment in this way are often bioavailable (Kwasigroch et al., 2018).

- Chemical munition (?) dump sites are located far from the coasts, but current systems may affect the distribution of leaked substances. Conventional munition dump sites can however be located in shallow water at a close distance to the shore, i.e. in Kiel Bight. As degradation products and trace metals originating from munitions have been detected in the sediments, coastal processes may enhance the spreading of those contaminations to adjacent areas or increase their bioavailability (Gębka et al., 2016; Bełdowski et al., 2019; Maser and Strehse, 2020).

- Coastal processes have no impact on the generation but a significant impact on the distribution and accumulations of beach wrack (Suursaar et al., 2014) and litter (+) on the shoreline (Esiukova, 2017; Haseler et al., 2020; Urban-Malinga et al., 2020).

- There is a very strong impact of coastal processes on coastal management (+). Coastal processes like erosion, sediment translocation, accretion, etc. are primary drivers for coastal management (Hapke et al., 2016), which includes the provision of coastal defences against erosion and inundation by engineering and planning.

Sand and gravel extraction from nearshore areas creates an intrinsic danger to the shoreline by removing sedimentary material in the affected area and increasing the wave energy reaching the shoreline. Mining of sand or gravel is usually considered acceptable in terms of its effect on the shoreline dynamics if the extraction site is well offshore from the closure depth. For example, mining in Polish waters (Uścinowicz et al., 2014) was performed at a depth of 15 to 30 m, and several operations in Tromper Wiek, NE of the island of Rügen, at depths from 14 to 21 m (Kubicki et al., 2007). As these sites had a depth more than twice the closure depth in the open Baltic Sea (Soomere et al., 2017), it is natural that no impact was reported on the coastal processes in the vicinity. Several operations providing sand for beach nourishment at Palanga, Lithuania, used sand extracted from the Baltic Sea floor at a depth of > 50 m (Pupienis et al., 2014). Similarly, no direct impact on coastal processes was reported in 1997 after extraction of approximately 320 000 m^3 of sand from a site located about 25 km off Wustrow, Germany (Krause et al., 2010). However, negative impacts on the coastal sediment budget cannot be excluded (Diesing et al., 2006).

5.2.2 Knowledge gaps

Today, there are major gaps in the understanding of the functioning of sedimentary compartments and the wave-driven mobility of sediment between these cells in the eastern Baltic Sea. A major knowledge gap is the scarcity and low accessibility of data about changes to the coastline (Muis et al., 2020). They are crucial for the validation of modelled sediment fluxes and for understanding and forecasting coastline changes. Modelling with much finer resolution (about 500 m alongshore) is necessary to properly identify the structural features of sediment transport over long interconnected sedimentary systems. To resolve both rapid and slow phases of coastal evolution, it is necessary to combine high-resolution scanning techniques with detailed bathymetric data and to develop and validate methods for approximate estimates of underwater sediment transport. Further questions are as follows.

- *Coastal processes and hypoxia.* What effects do coastal processes, i.e. currents, erosion processes and sediment translocations, have on coastal hypoxia?
- *Coastal processes and acidification.* What effects do coastal processes have on acidification? What is the impact of coastal erosion on alkalinity and acidification? It is assumed that weathering in the northern basins and rivers may contribute to an increase in alkalinity. What contribution may coastal processes have on alkalinity, acidification and the carbon system in general?
- *Coastal processes and marine ecosystems.* To which extent and how are coastal marine ecosystems impacted by coastal processes?
- *Coastal processes and fisheries.* How do coastal processes have an impact on coastal fisheries, e.g. gill nets?
- *Coastal processes and chemical contaminants.* How do coastal processes affect the release and distribution of chemical contaminants from rivers and sediments?
- *Coastal processes and Dumped military material.* Do coastal processes affect dumped military material, e.g. by current systems or sediment transports? Are there any effects expected at the dump sites and how strong could they be?

5.3 Hypoxia

Oxygen (O_2) is one of the central biogeochemical elements on Earth and is primarily produced in seawater by phytoplankton, but its concentration is also strongly affected by the gas exchange through the sea surface. In most parts of the world ocean, seawater is a source of oxygen; it is estimated that 50 %–85 % of the atmospheric oxygen is produced in the oceans (NOAA, 2021). Oxygen can be carried to non-productive deeper layers by processes like convection, downwelling and diffusion, so that many parts of the deep ocean are rich in oxygen (Jahnke and Jackson, 1992). Respiration by heterotrophic organisms (bacteria, protists, micro- and macrozooplankton, larger animals) and nitrification (the microbial process in deeper water layers to produce nitrite and nitrate from ammonium) are the sinks for oxygen in the water column. Poor ventilation and enhanced respiration in deeper water layers may lead to hypoxia, which is defined as the approximate oxygen concentration too low to allow the existence of complex multicellular life ($< 2\,\mathrm{mL\,L^{-1}}$), or anoxia, denoting the complete absence of oxygen with the concomitant microbial production of hydrogen sulfide ($\mathrm{H_2S}$).

Hypoxia in the Baltic Sea (as in other highly productive and stratified regions of the world ocean) is a common phenomenon but has increased considerably in the deep basins of the Baltic Sea (mainly in the Bornholm, Gdansk and Gotland basins) over the course of the past century (by a factor of 10 since the beginning of the 20th century; Carstensen et al., 2014). A hypoxic area of roughly 32 % of the Baltic Proper was estimated in 2019 (Hanson et al., 2020). This in principle goes parallel with the industrialization and eutrophication of the Baltic Sea (Zillén et al., 2008; Conley et al., 2009; Carstensen et al., 2014). Thus, eutrophication has been identified as the foremost cause of this development. However, the decreasing nutrient inputs in recent decades and years have not yet resulted in a re-oxygenation because of legacy nutrient pools, i.e. nutrient pools which are temporarily accumulated in the sediments and released to the water column slowly (McCrackin et al., 2018b).

Major Baltic inflows (MBIs), i.e. irregular inflows of saline, oxygen-rich deep water through the Kattegat and belts and sounds into the deep basins of the western and central Baltic Sea, do not have any long-term positive impact on the oxygen conditions in the deep layers, as the enhanced salinity (and density) of these waters increases stratification and drastically reduces the vertical exchange between surface and deep waters. Recent studies show that oxygen consumption rates after MBIs have significantly increased during the last decades, causing hypoxic conditions to prevail or even deteriorate (Meier et al., 2018). Thus, saltwater inflows generally contribute to a reduction of oxygen concentrations in the deep basins (Meier et al., 2017).

In addition to the deep basins, many coastal waters in the Baltic Sea increasingly suffer from temporal or even permanent anoxia or hypoxia (Conley et al., 2011; Jokinen et al., 2018). The main causes for coastal hypoxia are nutrient releases from the surrounding land, seasonal thermal stratification and reduced water circulation in coastal embayments.

Climate change affects the extent of hypoxia in the water column. Oxygen deficiencies have increased in the deep basins and in coastal waters over the past decades (Carstensen et al., 2014; Caballero-Alfonso et al., 2015). Climate warming has contributed to this trend through lower O_2 dissolution in water, increased respiration rates and intensified stratification. Eutrophication with subsequent extensive biomass production and remineralization has been identified as the primary driver (Meier et al., 2019). Sea level rise is also expected to contribute to hypoxic areas, through the potential intensification of saltwater inflows and subsequent stronger stratification. It may be a considerable factor in the future (Meier et al., 2017, 2021b).

For more on hypoxia and the role of oxygen in the marine ecosystem of the Baltic Sea, see Kuliński et al. (2021).

5.3.1 Impacts of hypoxia on other factors

- Hypoxia is a direct consequence of eutrophication and water column stratification. Such conditions lead to the partial separation of enhanced organic matter production in the surface from its remineralization in the deep water layers and surface sediments. This enhanced respiration in the deep basins lowers O_2 concentration (hypoxia) but at the same time increases CO_2 concentration, which contributes directly to acidification (+) (Melzner et al., 2013; Kuliński et al., 2021). On the other hand, total alkalinity (a measure of seawater buffer capacity) is generated during an anaerobic organic matter remineralization. Although most of those anaerobic reactions are reversible when conditions change back to oxic, processes like denitrification and pyrite and vivianite formation are permanent sources of alkalinity, which counteract acidification (Kuliński et al., 2017, 2021; Gustafsson and Gustafsson, 2020). In the end, the relevance of these processes and their net effect on ocean acidification in the Baltic Sea (deep basins and coastal waters) remain unclear.

- Hypoxia and anoxia have a strong impact on marine ecosystems (+). The biogeochemistry and redox state of the system are strongly affected through feedbacks on the nitrogen and phosphorus cycles with strong implications for the pelagic and benthic ecosystems, e.g. the occurrence and massive blooming of nitrogen-fixing, filamentous cyanobacteria, and implications for higher trophic levels, e.g. cod (Vahtera et al., 2007; Dippner et al., 2008).

- Oxygen plays a significant role in the nitrogen and phosphorus biogeochemistry. Nitrogen is removed by processes such as anaerobic ammonium oxidation (anammox) and denitrification and, alternatively, recycled through dissimilatory nitrate reduction to ammonia and nitrification. Hypoxia may alter nutrient dynamics by affecting the coupling of these pathways and further exacerbate the effects of eutrophication (Gustafsson et al., 2017; Savchuk, 2018). There is a feedback on internal *nutrient cycling* (+), i.e. the internal release of phosphorus from anoxic sediments. Hypoxia in this case would act as a driver for eutrophication, leading to favourable growth conditions for N_2-fixing cyanobacteria in summer when free bioavailable nitrogen is depleted in the surface waters. This is an important feedback mechanism, strongly affecting the biogeochemistry of the Baltic Sea, with repercussions on the food web structure. This feedback mechanism is sometimes called the "vicious circle", as the additional cyanobacteria biomass is respired mainly in deeper waters, thereby increasing the oxygen-free zones and subsequently the phosphate release in the deep water (Vahtera et al., 2007).

- Coastal aquaculture (?) may be affected by local hypoxia and in turn may also create hypoxic areas by sedimented unused fish food which is then respired (Díaz, 2010).

- Hypoxic zones affect fisheries (+) through the impairment of fish production. The most substantial impacts are demonstrated for cod, where low oxygen has negative effects on egg production and survival (Köster et al., 2017). Furthermore, oxygen is considered to affect the growth and condition of the eastern Baltic cod both directly and via regulation of the availability of benthic food (Casini et al., 2016a; Neuenfeldt et al., 2020).

- Changing oxygen concentrations in bottom waters alter the redox conditions, which in turn may lead to remobilization of contaminants accumulated in sediments and influence their bioavailability. A re-colonization of hypoxic bottoms by benthic animals can lead to increased release of "archived" contaminants (+) in the sediments by bioturbation (Thibodeaux and Bierman, 2003; Granberg et al., 2008), but it is unclear how this transport compares to other processes (Kwasigroch et al., 2021).

- Corrosion rates of dumped munitions (+) are dependent on oxygen concentration, the presence of specific ions in near-bottom water and the activity of microbial communities (Silva and Chock, 2016). Although lower oxygen concentrations inhibit corrosion rates, subsequent changes from oxic to anoxic and back to oxic conditions may accelerate corrosion, due to oxidation of hydrogen sulfide to sulfates. Therefore, periodic hypoxic events may almost double corrosion rate compared to fully anoxic conditions and enhance it by ca. 20 % to fully oxic conditions (Fabisiak et al., 2018). Additionally, hypoxia can alter the degradation process of chemical warfare agents, leading to greater persistence of degradation products in sediments (Vanninen et al., 2020). At the same time, arsenic released from agents based on this metal in pentavalent form may be remobilized from sediments in trivalent form, which is more toxic to biota (Czub et al., 2020, 2021).

5.3.2 Knowledge gaps

A realistic estimation of the anoxic and hypoxic areas in the deep basins and coastal zones is very difficult due to the lack of a highly resolved measurement grid. The current estimations are based on sporadic measurements, extrapolations and modelling and may differ by up to 20 %. It is insufficiently known which processes govern the observed frequencies of major saltwater inflows and the mixing with stagnant deep waters. Also, there is no sufficient quantification of sources and sinks in the oxygen budgets. Further questions are as follows.

- *Hypoxia – acidification.* The connection between anoxia and acidification or alkalinity is strong and should be considered in acidification studies. Is anaerobic alkalinity generation in coastal sediments an essential process in the Baltic Sea?
- *Hypoxia – aquaculture.* Does coastal hypoxia have any impact on coastal open-cage or extractive aquaculture sites?
- *Hypoxia – dumped military material.* Does hypoxia or anoxia at the dump sites have any impact on the corrosion rates of the hulls and shells, and what could be potential chemical reactions of leaked substances in the oxygen-free biogeochemical environment?

5.4 Acidification

The oceanic uptake of CO_2 goes with the price of ocean acidification (Gattuso and Hansson, 2011) and is also expected to affect coastal seas. However, the specific processes here are more complex, due to land–sea interactions such as river and drainage basin biogeochemistry and effects from anoxic water and sediments. Whether coastal seas act as a source or a sink for atmospheric CO_2 depends on an intricate balance between air–sea CO_2 exchange, terrestrial carbon loads (rivers), water exchange with adjacent basins and sediment fluxes.

The strength of acidification depends on the accumulation of acid over basic elements and the buffering capacity of seawater (alkalinity). The variation in total alkalinity concentrations is considerable in the Baltic Sea, with low total alkalinities in the Gulf of Bothnia and the Gulf of Finland and higher ones in the Gulf of Riga and the southern Baltic Sea. The variations in total alkalinity concentrations are presumably caused by the different geological structures in the Baltic Sea basins: the southern drainage basin is richer in limestone and hence alkalinity than the northern part, where granite dominates the bedrock (Hjalmarsson et al., 2008; Bełdowski et al., 2010). This shows the complex acid–base system in the Baltic Sea and the importance of riverine discharge in shaping seawater pH.

Generally, total alkalinity is lower in the Baltic Sea (especially in the Gulf of Bothnia and the Gulf of Finland) than in the open ocean, except in the direct vicinities of the mouths of the continental rivers (south and southeastern coast). Since lower alkalinity corresponds to lower buffer capacity, at first approximation the Baltic Sea can be considered more vulnerable to acidification than oceanic regions. However, recent studies by Müller et al. (2016) reveal that total alkalinity in the Baltic Sea increases. The highest alkalinity increase, observed in the Gulf of Bothnia, entirely makes up for ocean acidification caused by CO_2 increase, whereas in the central part (Baltic Proper) ocean acidification is lowered by about 50 %. Although the source of that increase is unknown so far, increase in weathering on land and anoxic alkalinity generation in sediments have been suggested.

The central role of the marine CO_2 system in biogeochemical processes in the Baltic Sea is discussed by Schneider and Müller (2018). Increased nutrient loads may increase the seasonal pH oscillations but may not inhibit future Baltic Sea acidification on longer timescales (Omstedt et al., 2012). This is further supported by a recent sensitivity study including aspects of eutrophication by Gustafsson and Gustafsson (2020).

It is not entirely clear if the Baltic Sea is or will be a net source or sink for CO_2 (Kuliński and Pempkowiak, 2011). Model calculations indicate that, before industrialization, the partial pressure of carbon dioxide in water was above atmospheric values (Omstedt et al., 2009). Seasonal variability increased after industrialization and the onset of eutrophication, making the modern Baltic Sea both a sink (in summer) and source (in winter) of CO_2 to the atmosphere. Outgassing or uptake due to air–water CO_2 fluxes depends on river loads of carbon, total alkalinity and nutrients, and the freshwater import (Gustafsson et al., 2015).

Carbon dioxide is not the only fossil fuel combustion product contributing to acidification. Acidification due to atmospheric deposition of sulfur and nitrogen oxides as well as ammonium from land and shipping peaked around 1980, with a pH decrease of approximately 0.01 pH units in surface waters, an order of magnitude less than acidification due to atmospheric CO_2. (Omstedt et al., 2015). Then again, the contribution of shipping to acidification was found to be 1 order of magnitude less than that of land emissions. Interestingly, the pH trend due to atmospheric acids has started to reverse due to reduced land emissions, although the effect of shipping is ongoing (Omstedt et al., 2015). While shipping is expected to become a major source of strong acid deposition to the Baltic Sea by 2050, the long-term effect on the pH and alkalinity is projected to be significantly smaller than estimated previously. A significant contribution to this difference is the efficient export of acidified surface waters to the North Sea (Turner et al., 2018). Despite decreasing emissions on land, soil and freshwater acidification due to fuel combustion and related atmospheric sulfur and nitrogen deposition ("acid rain") should be taken into account in coastal regions (Tranvik, 2021) to estimate how this may affect coastal acidification. More on acidification and alkalinity and their roles in the biogeochemistry of the Baltic Sea is given in Kulinski et al. (2021).

5.4.1 Impacts of acidification on other factors

- Acidification may affect the marine ecosystems (?), by disturbing the metabolism of various organisms. Still, there has been no clear evidence of the extent of in situ impacts in the Baltic Sea (Brander and Havenhand, 2012; Paul et al., 2016). Effects of lower pH on various organisms have been mainly derived from mesocosm experiments. The impact on in situ ecosystems of the different regions of the Baltic Sea is mainly low or unknown (Havenhand, 2012; Doo et al., 2020).

- It is unknown if there is an impact of acidification on aquaculture (?). There is no clear evidence for a considerable impact of moderate acidification (realistic in the near future) on the growth of blue mussels (Thomsen et al., 2010)

- The same holds true for a potential impact of acidification on fisheries (?) in the Baltic Sea, e.g. by affecting calcifying food organisms for fish larvae. Otoliths are made from calcium carbonate, and no apparent effects of lower pH have been shown (Coll-Lladó et al., 2018; Di Franco et al., 2019; Hamilton et al., 2019). There are indications that acidification may affect the auditory behaviour of fish (Simpson et al., 2011), but it is entirely unclear whether these findings can be transferred to Baltic Sea species.

- Changing pH can directly influence the speciation of dissociating chemical contaminants (?), but the extent and significance for the environment are largely unknown. Marine acidification in surface, deep and sediment layers may change how contaminants like heavy metals and aluminium dissolve in the water body and circulate in the environment, but the effects are largely unknown.

5.4.2 Knowledge gaps

There are many unknowns in the Baltic Sea, and it is not clear whether acidification in the Baltic Sea is a threat for the time being or not. A major knowledge gap is the uncertainty related to the sources and regional distributions of alkalinity, which largely determines the strength of acidification in the Baltic Sea. What is responsible for the observed trends in alkalinity in the different basins? What impact does acidification of freshwaters and soils through deposition of nitrogen and sulfur oxides have on coastal acidification? Further questions are as follows.

- *Acidification – marine ecosystems.* How are organisms and the ecosystem functions affected by acidification?

- *Acidification – aquaculture.* Which impact could acidification potentially have on open-cage or extractive aquaculture?

- *Acidification – fisheries.* Which impact could acidification potentially have on fisheries? There is evidence that otoliths may be affected by lower pH values in the surrounding waters, but observed effects on larval growth and survival rates are scarce and contrasting.

- *Acidification – chemical contamination.* Are there any impacts of acidification on chemical contaminants? Does the pH in the foreseeable changes affect the chemical speciation of organic substances and the reactivity or potential toxicity of these compounds?

5.5 Submarine groundwater discharge

Submarine groundwater discharge (SGD) is driven by overlapping land and marine drivers (e.g. precipitation, currents, tides, waves, density gradients; Taniguchi et al., 2019). Due to its complex nature, SGD includes all flow of water across the seabed to the water column, regardless of fluid composition or driving force (Burnett et al., 2003). It includes both fresh groundwater discharge derived from terrestrial recharge (e.g. meteoric, precipitation-derived, fresh submarine groundwater discharge, FSGD) and recirculated seawater (salty groundwater, recirculated submarine groundwater discharge, RSGD; Burnett et al., 2006). Usually, recirculated seawater dominates SGD.

Meteoric groundwater and salty groundwater discharge usually show different geochemical characteristics. The composition of meteoric groundwater discharge mostly depends on local hydrogeological conditions. The discharge of recirculated groundwater, which can consist of recirculated seawater or a mixture of fresh and recirculated groundwater, goes through various biogeochemical processes. Some chemical substances like nutrients, dissolved organic and inorganic carbon have concentrations several orders of magnitude higher in groundwater than in surface water. Therefore, even if the SGD rate is low, the chemical substance flux via SGD can be relatively important, as groundwater in coastal aquifers tends to be enriched in various chemical substances.

The first assessment of SGD in the Baltic Sea was made by Peltonen (2002), who estimated the fresh SGD (FSGD) to the entire Baltic Sea, using a combination of hydrological and hydrogeological methods. The amount of FSGD to the Baltic Sea, compared to total runoff, was small, around or even less than 1 % (around $4.4\,\mathrm{km^3\,yr^{-1}}$). However, this calculation does not include the recirculated water component. Krall et al. (2017) estimated SGD at Forsmark, Gulf of Bothnia, to range from $5.5\ (\pm 3.0) \times 10^3\,\mathrm{m^3\,d^{-1}}$ to $950\ (\pm 520) \times 10^3\,\mathrm{m^3\,d^{-1}}$, using Ra isotopes. These rates are up to 2 orders of magnitude higher than those determined from local hydrological models, which consider only the fresh component of SGD. Kłostowska et al. (2020) obtained similar results in the Bay of Puck, southern Baltic Sea. Recently estimated SGD rates range from 1.4×10^6 to $11.3 \times 10^6\,\mathrm{m^3\,d^{-1}}$, which are 17 to 130 times higher than the results obtained by Piekarek-Jankowska (1994), including only the freshwater component of SGD. The obtained fluxes were several times higher than the surface runoff. Additionally, local studies in the Bay of Puck suggest that SGD can be an important source of methane, dissolved organic and inorganic carbon (Szymczycha et al., 2012; Kotwicki et al., 2014; Donis et al., 2017), nutrients (Szymczycha et al., 2012, 2020b), and trace metals (Szymczycha et al., 2016). It may also have an impact on ecosystems locally (Kotwicki et al., 2014).

SGD may be a significant source of nutrients in different Baltic Sea regions and therefore affect biogeochemical processes in the coastal zone (Szymczycha et al., 2020b). It is well established that nutrient loads from land are filtered by biogeochemical processes and enter the open Baltic Sea in a modified form (Asmala et al., 2017; Edman et al., 2018). As the effectiveness of the coastal zone is important for a proper understanding of open-sea eutrophication, SGD and accompanying nutrient fluxes should be considered in models characterizing the biogeochemical process in Baltic Sea coastal areas. Still, the current state of knowledge on SGD in the Baltic Sea is limited to local studies, which have used different approaches. Therefore, it is hard to draw overall conclusions and projections for the entire Baltic Sea.

Driving forces of SGD involve topography-driven flow, wave set-up, precipitation, sea level rise and convection caused by salinity and temperature between the seawater and groundwater. As climate change is expected to affect most of the above-mentioned factors, consequently it can also be expected to affect SGD. These effects would be observed in changes in the magnitude and composition of SGD, as well as in the biogeochemistry of the subterranean estuary (mixing zone/transition zone). Climate change is expected to affect ecosystems differently in different regions of the Baltic Sea. Furthermore, it can be speculated that SGD fluxes may increase in the northern Baltic Sea, where increased precipitation and groundwater tables are projected (Christensen et al., 2021). In the southern part the opposite trend can be envisaged. Sea level rise and geostatic land movement will certainly also affect SGD, but due to a lack of SGD data, it is hard to project the direction and significance of the change.

5.5.1 Impacts of submarine groundwater discharge on other factors

There may be an indirect effect on coastal hypoxia (?) through the release of additional nutrients via SGD, but its magnitude and relevance are uncertain. Studies have indicated that nutrients transported through SGD can support benthic and water column primary production in various coastal ecosystems and inhibit hypoxia (McMahon and Santos, 2017; Adolf et al., 2019).

SGD may be enriched in dissolved inorganic carbon, $p\mathrm{CO_2}$ and have low pH and alkalinity in comparison to receiving coastal waters (Liu et al., 2014; Szymczycha et al., 2014) and thus may alter coastal water properties. Still, there is no indication that SGD in the Baltic Sea region has any effect on acidification (?), except maybe on a very local scale. However, studies on the global level reveal that SGD can reduce the $\mathrm{CO_2}$ buffering capacity of the receiving ocean and act as a local driver of ocean acidification in local regions (Liu et al., 2014, 2021).

Impacts on marine ecosystems (?) may be locally important. To date, in many coastal regions marine organisms, and their biomass, abundance, productivity, physiology and community structures, have been directly evaluated along SGD gradients. SGD can contribute significantly to reef productivity and/or calcification and alter the phytoplankton community structure (McMahon and Santos, 2017; Adolf et al., 2019). In meiofauna assemblages in the Bay of Puck, southern Baltic Sea, a significant decline in certain meiofaunal taxa (mainly nematodes and harpacticoids), as well as altered temporal patterns and a changed small-scale vertical zonation, was demonstrated (Kotwicki et al., 2014).

The impact of SGD on nutrient loads depends on the hydrogeological and biogeochemical conditions of the coastal region. In many coastal sites, SGD-driven nutrient loads (+) are significant. Nutrients as well as dissolved organic and inorganic carbon components usually have concentrations several orders of magnitude higher in groundwater than in surface water. Therefore, even if the SGD rate is low, the chemical substance flux via SGD can be relatively important, as groundwater in coastal aquifers tends to be enriched in various chemical substances. In the Bay of Puck, Poland, the estimated seasonal and annual loads of both dissolved inorganic nitrogen and phosphates via SGD were the most significant sources of nutrients (Szymczycha et al., 2020b). Thus, SGD may also be a significant source of nutrients in other coastal regions of the Baltic Sea and may affect benthic and water column primary productivity and phytoplankton community structure.

SGD may contain considerable concentrations of various substances, as they accumulate in the freshwater bodies and soils and intrude in the aquifers, where they may reach high concentrations McKenzie et al. (2020). SGD may thus be an essential input route for chemical contaminants (+) and metals to the coastal Baltic Sea. Local studies in the Bay of Puck (Poland) suggest that SGD may be an important source of methane, dissolved organic and inorganic carbon (Szymczycha et al., 2012; Kotwicki et al., 2014; Donis et al., 2017), nutrients (Szymczycha et al., 2012, 2020b), pharmaceuticals and caffeine residues (Szymczycha et al., 2020a), and trace metals (Szymczycha et al., 2016).

5.5.2 Knowledge gaps

There are currently only very few measurements in selected areas, so a projection of the significance of submarine groundwater discharges to the Baltic Sea as a whole is very difficult. A dedicated groundwater-monitoring network combined with a coupled groundwater–surface model simulating the transport, adsorption and mixing processes would help understand and evaluate the role of submarine groundwater discharges in chemical substance cycling in the coastal Baltic Sea. Further questions involve the following.

- *Submarine groundwater discharges – hypoxia.* Do submarine groundwater discharges have any impact on the generation of coastal hypoxia, e.g. through local nutrient inputs?

- *Submarine groundwater discharges – acidification.* Do submarine groundwater discharges have any impact on coastal acidification of seawater?

- *Submarine groundwater discharges – marine (coastal) ecosystems.* What are the effects of submarine groundwater discharges on coastal ecosystems?

5.6 Marine ecosystem

The marine ecosystem of the Baltic Sea is largely characterized by the physical and biogeochemical conditions of the water body, which in turn are defined by the physical settings. The marine ecosystem features the taxonomic groups which are present in the oceans, ranging from viruses to bacteria, phytoplankton, and mixo- and heterotrophic protists (flagellates, ciliates, amoebae, nano- and microzooplankton); multicellular heterotrophic organisms like crustacean plankton (cladocerans, copepods); and fish, mammals (grey seals, ringed seals, harbour porpoises), sea birds and invertebrates like ctenophores and jellyfish. Organisms dwelling on or in the sea floor (benthos) are primarily unicellular foraminifera and invertebrate multicellular bivalves, snails, worms and macrophytes (HELCOM, 2012). The Baltic Sea features a salinity continuum between near freshwater in the northeast and near ocean values in the Kattegat, resulting in a comparably low species diversity in the Baltic Sea, compared to other coastal seas (HELCOM, 2018a).

Due to its geographical location, the Baltic Sea ecosystem is subject to a strong seasonality. The seasonal cycle in the pelagic zone shows a strong growth pulse of phytoplankton in spring, as new nutrients have been distributed throughout the upper water column by thermal convection in winter, and enough light is available to trigger photosynthesis. Spring blooms are characterized by larger phytoplankton, usually diatoms. Summer is typically the phase when regenerated production dominates, i.e. when a strong stratification cuts off the nutrient supply from the deeper layers and when the microbial loop prevails with very small phytoplankton (*Synechococcus* sp., *Prochlorococcus* sp.) grazed by very small flagellates, ciliates and other microzooplankton. As nitrogen is a scarce commodity during this phase, the ecological niche opens for the nitrogen-fixing filamentous cyanobacteria, which usually bloom in late summer. As the strong summer stratification is eroded by cooling and strong winds, new nutrients can again be distributed to the euphotic zone, giving rise to autumn blooms of larger phytoplankton, mostly dinoflagellates. In the past decades, a shift of seasonality (earlier occurrences of spring and cyanobacterial summer blooms (Kahru and Elmgren, 2014) and oscillations; Kahru et al., 2018) and a shift towards a predominance of dinoflagellates over diatoms (Klais et al., 2011; Spilling et al., 2018) have been shown and related to milder winters and related ecosystem changes (Wasmund et al., 2017). There are no coccolithophorids in the Baltic Sea, which is an important group of oceanic phytoplankton, forming extensive booms in the adjacent North Sea. Their absence in the Baltic Sea is difficult to explain, but it may be related to the complex carbonate budget of the Baltic Sea (Tyrrell et al., 2008). There are also no single-celled radiolaria in the Baltic Sea, which may be related to the low salinity (Kruglikova, 1989).

The extensive blooms of filamentous nitrogen-fixing cyanobacteria are an outstanding feature of the Baltic Sea pelagic ecosystem, which are absent from most oceanic provinces (except upwelling areas) but are often found in other marginal seas and freshwater bodies. The dominance of the cyanobacteria can be attributed to the particular biogeochemistry of the Baltic Sea, which follows its unique oxygen conditions (Bianchi et al., 2000). In times of low nitrogen availability, nitrogen fixers have an advantage over other phytoplankton as they can transfer molecular nitrogen to the bioavailable form of ammonium. As they decay, this nitrogen becomes available for the rest of the autotrophic community. Bioavailable nitrogen is removed from anoxic water through denitrification, and phosphorus is released from the deep water and sediments (internal phosphorus loading). So far, there is no clear evidence for an overall significant increase or decrease in cyanobacterial blooms (Olofsson et al., 2020).

The comparably low diversity and distribution of fish communities in the Baltic Sea are largely determined by the salinity gradient. Marine species (cod, flounder, herring) are more abundant in the open waters and coasts of the southern and central Baltic sea, while freshwater species such as perch and roach are more found in the northern waters (HELCOM, 2006, 2018a). Migratory fish species like salmon, sea trout and eel, which spawn in other waters, are also present in the Baltic Sea. Fish larvae largely live from zooplankton, of which some marine and brackish copepods species as well as the fresh and brackish water Cladocera are dominant in the Baltic Sea. Fish, in turn, are food for predatory fish species, marine mammals, birds and humans.

Food production for human consumption has a substantial impact on the marine ecosystem. It has been shown that increasing fish stocks and catches in the 1980s were partly related to an elevated level of food availability for upper trophic levels due to eutrophication (Elmgren, 2021). A comprehensive assessment of Baltic Sea ecosystems under climate change is given by Viitasalo and Bonsdorff (2021).

5.6.1 Impacts of marine ecosystems on other factors

- There is a strong impact by ecosystems on hypoxia (+). This connection is a strong example for the feedback between different factors: hypoxia strongly affects ecosystems (by altering the redox conditions in the deep water and sediments and hence the microbial communities and metabolic processes, i.e. hydrogen sulfide production; Gustafsson and Stigebrandt, 2007) by denitrification and phosphorus release and thus altering the pelagic nitrogen-to-phosphorus ratio (Dalsgaard et al., 2013; Vahtera et al., 2007), e.g. by inciting cyanobacterial blooms. Hypoxia in turn is strongly affected by the pelagic ecosystem as produced and sedimented biomass from the surface layers increases oxygen demands and the hypoxic and anoxic area (Conley et al., 2009).

- There is a feedback of ecosystems on acidification (+) through primary production and respiration processes affecting the CO_2 budget in the water column (Gypens et al., 2011; Cai et al., 2011). Also, feedback mechanisms related to alkalinity are known.

- There are various food web interactions possible between the autochthonous ecosystem and the intruding non-indigenous species (+). Prominent examples are round goby (Almqvist et al., 2010), *Marenzelleria viridis* (Quintana et al., 2018) and *Mnemiopsis leidyi* (Riisgård, 2017).

- Exploitable fish stocks for fisheries (+) are part of the Baltic Sea ecosystem, so the state of the food web and ecosystem in general has a strong impact on the fish stocks (Harvey et al., 2003), through cascading effects from fish to phytoplankton (Donadi et al., 2017).

- There can be an indirect impact of the ecosystem on tourism (+), through extensive blooms of filamentous cyanobacteria and other toxic or nuisance blooms which may be washed onto beaches (Bechard, 2020), but also by the intrinsic value of intact ecosystems which can attract visitors to coastal destinations.

5.6.2 Knowledge gaps

There are large uncertainties concerning the impact of climate change on the marine ecosystems of the Baltic Sea. This refers to temperature and acidification effects on various trophic levels, starting from the microbial communities and the microbial loop all the way to higher levels. It is uncertain how salinity may change in the future, and likewise the potential consequences for pelagic and benthic communities are uncertain. Further questions involve the following.

- *Marine ecosystems – acidification.* It is known that primary production affects acidification, but do other ecosystem functions also have an effect?

- *Marine ecosystems – aquaculture.* What are the interrelations of marine ecosystems with open-cage or extractive aquaculture? The latter can be described as the exploited part of the natural ecosystem.

- *Marine ecosystems – chemical contaminants.* What roles do aquatic ecosystems play in the transfer and transformation of organic constituents between trophic levels up to organisms consumed by humans like mussels, fish or algae?

5.7 Non-indigenous species

Non-indigenous species are introduced by human activity into environments where they had previously been absent. For the Baltic Sea, it is estimated that 140 to 170 new species have established (HELCOM, 2018a; Ojaveer et al., 2017), while their ecological and economic impact varies widely. The main vectors are ship hulls (biofouling), ballast water and canals connecting previously separated bodies of water (Gollasch et al., 2000; Keller et al., 2011). Ports are known as hot spots for the distribution of non-indigenous species (HELCOM, 2018a). Temperature and salinity may be limiting or favouring factors for the distribution of non-indigenous species in the Baltic Sea (Holopainen et al., 2016). Prominent non-indigenous species, which have been shown to affect pelagic and benthic communities in the Baltic Sea, and also have economic implications, are the benthic polychaete worm *Marenzelleria* spp. (Stigzelius et al., 1997), the pelagic comb jelly *Mnemiopsis leidyi* (Haslob et al., 2007) and the demersal fish round goby, which is shortly described here.

The bottom-dweller round goby *Neogobius melanostomus* was recently recognized as an important intruder with the capacity to influence local species (Karlson et al., 2007; Järv et al., 2011; Ustups et al., 2016) and the potential to cause a regime shift in coastal ecosystems (Nurkse et al., 2016). The small fish (up to 25 cm length) is of Ponto–Caspian origin (Miller, 1986) and was first reported in 1990 from the Gulf of Gdansk (Skóra and Stolarski, 1993). Since then, it has spread to other coastal areas of the Baltic Sea. It is believed that ship ballast water was the main vector for a long-distance transport to the Baltic Sea (Kornis et al., 2012; Kotta et al., 2016); however, it has been demonstrated that round goby is capable of migrating along the coast at a speed of up to 30 km yr^{-1} (Azour et al., 2015).

The round goby is found in different types of bottom habitats, usually at depths up to 30 m (Cross and Rawding, 2009). During summer, the round gobies breed and feed in shallow coastal waters (Kornis et al., 2012). The migration range during this period is mostly restricted to distances of a few hundred metres (Ray and Corkum, 2001). Longer migrations of up to several kilometres to and from deeper waters take place in spring and autumn (Sapota, 2012). The fish is an opportunistic feeder (Skóra and Rzeznik, 2001; Kornis et al., 2012), and no statistically significant size-specific preference for the pacific mussel *Mytilus trossulus* was found (Nurkse et al., 2016). Other studies have documented that round goby prefers the shrimp *Crangon crangon* over blue mussel *Mytilus edulis* and prefers *Mytilus edulis* over herring eggs (Wiegleb et al., 2018), leaving the issue of round goby food preferences somewhat unresolved.

It was shown that round goby represents the most important prey for the medium-sized cod *Gadus morhua*, and the perch *Perca fluviatilis* almost exclusively feeds on round goby in the Gulf of Gdansk (Almqvist et al., 2010). Similarly, round goby was found to be an important fraction in the diet of perch in the Pomeranian Bay (Oesterwind et al., 2017). At the same time, Järv et al. (2011) documented that perch prefers other fish species over round goby in its diet, suggesting that round goby is rather a prey of opportunity than of choice. Therefore, it can be assumed that in some Baltic Sea regions round goby has significantly suppressed several species that used to be preferred food items for other predatory fish species in coastal ecosystems. Furthermore, it was shown that round goby has also become an important food source for the turbot *Psetta maxima* (Sapota and Skora, 2005) and birds like the great cormorant *Phalacrocorax carbo* (Bzoma, 1998; Rakauskas et al., 2013) and grey heron *Ardea cinerea* (Jakubas, 2004; Rakauskas et al., 2013). A dietary overlap between round goby and flounder (Karlson et al., 2007; Järv et al., 2011) and juvenile turbot presumably resulted in lower abundances in these species (Ustups et al., 2016).

It is presently not possible to assess detailed impacts on ecosystems, as they seem to be very specific to the ecosystem invaded (Hirsch et al., 2016). Intraspecific interactions between invasive species could potentially mediate their ecological effects (Kornis et al., 2014). There have been efforts to introduce the round goby to the consumer market ("use and reduce"). While it is well suited for the market in terms of meat quality, the main obstacle seems to be its small size (Brauer et al., 2020).

5.7.1 Impacts of non-indigenous species on other factors

- Non-indigenous species may have strong impacts on marine ecosystems (+); for example, round goby alters coastal habitats, decreasing their value as marine protection areas (Skabeikis et al., 2019). Examples are the round goby *Neogobius melanostomus* (Almqvist et al., 2010), *Marenzelleria* spp. (Quintana et al., 2018) and *Mnemiopsis leidyi* (Riisgård, 2017).

- Non-indigenous fish can either positively or negatively affect food availability and growth of commercial fish (Ojaveer and Kotta, 2015), with impacts on fishery (+) opportunities. Also, non-indigenous species can become a target for fisheries, e.g. round goby (Ojaveer et al., 2015). Also, it has been demonstrated that round goby competes for food with juvenile flatfish (Ustups et al., 2016).

- Regulations to mitigate biofouling and ballast water vectors have economic repercussions on the shipping (+) industries. A convention for the Control and Management of Ships' Ballast Water and Sediments by IMO is in force as of 2017 (IMO, 2021a) and requires the use of ballast water management systems.

- It has been shown that the non-indigenous polychaete *Marenzelleria neglecta* burrows deeper in the sediment than native species and can enhance bioturbation-mediated transport of chemical contaminants (+) to the overlying water (Granberg et al., 2008; Hanson et al., 2020).

- There may be an impact on coastal management (?) if a non-ingenious species becomes a problematic species, causing problems for other species, having a detrimental effect on the ecosystem or causing a regime shift through the introduction of a novel predator (Kotta et al., 2018). Eventually, management actions need to be taken to minimize the impacts. There are considerable impacts by non-indigenous species on biodiversity and ecosystem structure (Lehtiniemi et al., 2015). However, a complete removal of the new species is impossible once it has established itself (HELCOM, 2018a).

5.7.2 Knowledge gaps

The number of non-indigenous species in the Baltic Sea is an estimation based on monitoring, for which there is not a common strategy in all Baltic Sea basins. The impacts of single or multiple non-indigenous species on the ecosystem, food webs and food production (e.g. through the introduction of toxic algae) are complex and hard to distinguish from other factors. Further questions are as follows.

- *Non-indigenous species – coastal management.* What is the coastal management strategy to cope with non-indigenous species and their potential impacts?

5.8 Land use and land cover

Anthropogenic land use in the Baltic Sea region started at least about 6000 years before present (Gaillard et al., 2015; Smith et al., 2008). Deforestation for firewood, iron mining and agriculture has been the main factor driving land cover changes since at least 2000 years BP (Roberts et al., 2018; Lavento, 2019). Simulations by Strandberg et al. (2014) indicate that, during its maximal extent around 200 years ago, the deforestation of the southern and eastern parts of the Baltic Sea catchment may have had an impact on the regional climate, comparable to present-day greenhouse gas emissions driving climate change.

Land cover and its use are widely discussed as an important part of the Earth's carbon cycle, both as the second largest source of anthropogenic CO_2 emissions due to the ongoing large-scale deforestation of tropical areas (IPCC, 2014) and for its potential to mitigate the effects of anthropogenic CO_2 emissions through increased carbon uptake by reforestation (Sonntag et al., 2016; Law et al., 2018). However, many land-cover-driven environmental changes and the possible feedbacks from those are not clear and under debate (Gaillard et al., 2015).

During the last decades, the ongoing deforestation of the tropical and subtropical regions is accompanied by accelerated reforestation of northern mid-latitudes to high latitudes (IPCC, 2014). The projections of future land use and cover in general anticipate a global increase in cropland and a reduction in the pasture and forest extent, but they show considerable differences in the predictions of land use and cover development at continental and sub-continental scales and incorporate large uncertainties (Prestele et al., 2016).

Since the introduction of agriculture millennia ago, anthropogenic deforestation has been, at the continental scale, a major human impact on land cover (e.g. Ellis, 2011; Roberts et al., 2018). In addition to the biogeochemical feedbacks, i.e. changes in the capacity of the CO_2 sequestration through photosynthetic fixation into biomass, there are also considerable biogeophysical feedbacks on climate through the change in the reflectivity of the land surface (albedo). Dark surfaces (e.g. forests, waters) absorb the incoming heat better than bright surfaces (deserts, agricultural lands). The type of land cover thus has an impact on the regional climate (Bala et al., 2007; Deng et al., 2013). Most importantly, both effects may counteract each other; for example, reforestation may contribute to a drawdown of CO_2 from the atmosphere, thereby theoretically contributing to a cooling effect. But that additional forest area may increase the dark surface and lead to a weaker albedo, thus contributing to warming. These trade-off effects are difficult to quantify (Mykleby et al., 2017). It has been assumed that reforestation as a measure for carbon drawdown and cooling, at least in the already mostly forested northern Baltic Sea region, may be of little effect (Arora and Montenegro, 2011), but recent modelling studies imply that a massive reforestation may lead to a significant lowering of summer maximum temperatures and a reduction of summer heat waves south of the Baltic Sea (Strandberg and Kjellström, 2019).

There are major uncertainties related to projections of the speed and direction of terrestrial land cover change and its ability to act as a reducer of atmospheric CO_2 concentrations. Projected land use and land cover change will have implications for the functioning and structure of terrestrial ecosystems and for the amount and nature of the ecosystem services supported by the land cover, regardless of whether we consider more deforestation or reforestation. As terrestrial land cover is a slowly changing system with long-term implications, it is crucial to investigate both short- and long-term effects.

The role of land use and land cover change as a driver of terrestrial organic matter transport into aquatic systems is not well understood (Kayler et al., 2019). While the importance of terrestrial vegetation around drinking water resources is well recognized at the local scale, the impacts on the aquatic environments at a regional to global scale are much less known and studied. Cross-system studies with a focus on matter transfer between terrestrial and aquatic environments are rare, but when conducted, they show considerable land-use-driven changes in the composition and amount of terrestrial origin dissolved organic matter transported into the aquatic systems (Ning et al., 2018; Bragée et al., 2013). Dissolved organic carbon (DOC) from the land (Humborg et al., 2015) is one of the major sources of nutrients in terrestrial surface water systems and can have considerable impacts on coastal marine environments (Ning et al., 2018).

A specific type of land use is urban complexes. With their aggregation of human activities and modifications like soil sealing, cities and infrastructure (traffic, housing, water systems, sewer systems, etc.), they are strongly affected by warming (heat island effect, heat waves) and extreme precipitation (flash floods). Coastal cities often have fronts and harbours in close vicinity to the sea, which are increasingly vulnerable to the rising sea level (Deppisch et al., 2015).

5.8.1 Impacts of land use and cover on other factors

- There is evidence that land use and cover may have an impact on the regional climate (+), through biogeochemical and biogeophysical effects (Strandberg et al., 2014; Mahmood et al., 2010). Albedo, i.e. the reflectance of the land surface, affects the amount of energy reflected back into space and the fraction that is converted to warming. Bright surfaces such like agricultural lands reflect more energy than dark surfaces as forests and waters (biogeophysical effect). Thus, the fraction of land cover may affect regional warming (Strandberg et al., 2014, Strandberg and Kjellström, 2019). There is also evidence that an increase in CO_2 concentrations leads to an increase in vegetation (biogeochemical effect), at least in regions where water is not a limiting factor, i.e. the northern part of the Baltic Sea basin (Smith et al., 2008). It is, however, not clear what the respective impacts of these effects are and whether reforestation as a measure to mitigate climate change can be successful (Gaillard et al., 2015).

- There is an indirect but clear relation between land use and hypoxia (+) through nutrient release from agricultural fields and associated eutrophication (Altieri and Diaz, 2019).

- There is a well-documented connection between land use and soil erosion/acidification (+); both can be accelerated or slowed down by the choice of agricultural practices, fertilizers and crops (Bolan et al., 2005; Xiong et al., 2019). Furthermore, these processes affect matter exchange between aquatic and terrestrial systems and can lead to accelerated deterioration (eutrophication and acidification) of water quality (Hornung et al., 1990).

- There can be a considerable impact of land use on submarine groundwater discharge (+). It can be expected that the type of land use and associated soils affect the quantity and quality of water seeping into groundwater and eventually reaching coastal discharge spots. However, the extent of this relationship is unknown (Rufí-Salís et al., 2019).

- Land use (other than agriculture) may have an impact on effluents (nutrients, contaminants) from soils and land surface, potentially affecting coastal or marine ecosystems (?), but this has not been assessed (Langlois et al., 2011).

- While forestry predominates in the northern part of the Baltic Sea basin, agricultural lands (+) are the dominant type of land use in the southern part of the basin, and it may be severely affected by an uncertain change in precipitation in the south. The decisions on which part of the land is dedicated to agriculture (or any other type of land use) are very much management and political decisions, which are influenced by climatic conditions (Wiréhn, 2018; Mendelsohn and Dinar, 2009). There is a strong interrelation between the type of land use and nutrient loads (+), as it strongly affects the amount of nutrients leaking to the sea, predominantly from agricultural land (Dambeniece-Migliniece et al., 2018).

- Land use indirectly affects certain branches of fisheries (+), e.g. by affecting rivers where salmon and other migrating fish spawn (Drouineau et al., 2018); see also Sect. 5.11 and 5.12.

- Land use change is a major force driving river regulations (+). Regulation of river basins and drainage works in agriculture and forestry have been major factors for changes of hydrological and water quality responses in watersheds (Wörman et al., 2010). Moreover, damming of rivers has increased the area of freshwater bodies in the Baltic Sea region (Smedberg et al., 2009; Humborg et al., 2015).

- There may be an indirect connection between land use and offshore wind farms (?) as there may be a competition for space between land-based wind farms and other types of land use. If the spaces on land become rare because of regulations and protests against extensive land use for wind farms, political decisions may be taken to build more at sea (Ladenburg, 2008).

- Fertilizers and insecticides on cultivated land may leak into the soil and sea; thus, it can be expected that change of land use has a considerable impact on emissions of contaminants (+) to the coastal sea. In addition, remobilization of toxic mercury from the soil (where it has been accumulated for decades) and transport to rivers and into the sea have been shown (Saniewska et al., 2014, 2019; Gębka et al., 2020).

- Land use is expected to have a certain impact on tourism (+) because coastal resort areas, beach developments and golf courses, among others, have high demands on areas and infrastructure, which are in competition with other types of land use (Kropinova, 2012; Cottrell and Raadik Cottrell, 2015).

- There is a clear connection between coastal land use and coastal management (+). Housing areas close to the coast, on sand spits or on cliffs that are affected by coastal erosion and sea level rise are in peril of being lost to the sea. While it is customary to also protect endangered segments of the coastline against erosion in the parts of the Baltic Sea where the coasts are sinking (Pruszak and Zawadzka, 2005), the concept of managed retreat (Hino et al., 2017) is gradually being included in planning measures, and several decisions have been made to abandon sections of shoreline (Schernewski et al., 2018). The same holds for agricultural lands and forests (Rekolainen, 1997; Nordström et al., 2015; Gopalakrishnan et al., 2019) close to affected shorelines even though the value of the unit of such areas is less than that of urbanized regions. Furthermore, land use affects terrestrial biodiversity, by degrading natural biotopes, reducing habitat and population sizes (Hansen et al., 2012), and hindering migration of species through fragmented landscapes (Oliver and Morecroft, 2014; Smith et al., 2008). Changed land cover, e.g. the replacement of permeable soils with sealed urban spaces, may lead to an increased vulnerability to flooding and inundation, with consequences for local economies, of which there is usually a high concentration in urban areas (Saniewska et al., 2014, 2018).

5.8.2 Knowledge gaps

There are major knowledge gaps concerning the speed and direction of terrestrial land cover change and what the effects on atmospheric CO_2 concentration and dissolved organic matter transport could be. Cross-system effects and feedbacks may impede afforestation efforts to enhance CO_2 drawdown. There is still insufficient knowledge of the possible environmental, system, and cross-system impacts and feedbacks to facilitate continental-scale decisions on large-scale land cover changes. Terrestrial land cover is a slowly changing system with long-term implications, so both short- and long-term effects need to be evaluated. Further questions are as follows.

- *Land cover – marine ecosystems.* What are the impacts of land cover and land use on marine ecosystems? They are spatially separated but may be connected through various land–sea interlinkages; which could they be and how do they interact?
- *Land cover – offshore wind farms.* What is the relationship between wind power generation on land, where there is an intense competition between different types of use and conflicts in regions where people live, and the designation of new offshore wind parks?

Human-induced factors

The following sections describe the factors and impacts of direct anthropogenic origin; i.e. these factors would not exist in the absence of humans. Often coastal management is an integrating activity managing the factors and impacts described below. These focus on human benefits and may be in conflict with benefits for ecosystems.

5.9 Agriculture and nutrient loads

Agriculture accounts for 40 % of global land area, 30 % of greenhouse gas emissions and 70 % of water withdrawals and has doubled the amounts of nitrogen and phosphorus in circulation (Foley et al., 2011). In the Baltic Sea region, about 20 % of the total catchment area is agriculture, varying from about 7 % of the area for Sweden and Finland to 60 % for Denmark (Svanbäck et al., 2019). In the past several decades, fertilizer use has decreased, while yield has increased due to improvements in crop varieties and agronomic practices (Lassaletta et al., 2014). There is a strong, positive linear correlation between agricultural nutrient surpluses and nutrient loads to the sea (surpluses are calculated as the sum of nutrients in fertilizer, manure, N-fixation by crops (N only) and atmospheric deposition (N only) minus removal due to crop harvest) (Hong et al., 2017).

Diffuse losses of nutrients from agriculture are a core driver of nutrient loads to the Baltic Sea (Andersen et al., 2015). For the drainage basin as a whole, about 14 % of net anthropogenic nitrogen inputs and 4 % of net anthropogenic phosphorus inputs are transferred to the sea annually (Hong et al., 2017). There is often an inverse correlation between nutrient use efficiency and agricultural nutrient surpluses (e.g. low use efficiency often results in high surpluses). Nitrogen and phosphorus use efficiency in crop production is about 55 % for both but varies greatly by country. For example, phosphorus use efficiency is $< 40\,\%$ in Russia and Belarus but $> 90\,\%$ in Germany, Denmark, Estonia, Latvia, Lithuania and Sweden (McCrackin et al., 2018b).

Livestock is a driver of nutrient cycling in the drainage basin. About two-thirds of nutrients in crops grown in the region are fed to livestock animals (not humans). In addition, substantial amounts of nutrients for livestock are imported in the form of soy. There is a positive relationship between the density of livestock and nutrient surpluses. Nutrients in manure are not always used efficiently in crop production because of increased specialization and separation of crop and livestock production. It is often more economical for farmers to purchase commercial fertilizers than to use nutrients in manure for crops (Wang et al., 2018; Svanbäck et al., 2019). Model studies suggest that redistributing manure nutrients, together with improving agronomic practices, could meet 54 %–82 % of the remaining nitrogen reduction targets (28–43 kt N reduction) and 38 %–64 % of phosphorus reduction targets (4–6.6 kt P) under the Baltic Sea Action Plan (McCrackin et al., 2018a).

It is not known how fertilization practices, crops grown and land use will change in response to climate change. However, it appears plausible that changes in temperature and precipitation patterns could change the types of crops grown in the region, with potential changes in fertilizer practices and diffuse nutrient losses as well as riverine runoff and the magnitude of nutrient loads attributable to agriculture. Trends in nutrient loads to the coastal Baltic Sea are much the opposite of the increasing global trends (Beusen et al., 2016). External nutrient loads peaked around 1980, and total waterborne and airborne N and P loads decreased by 42 % and 56 %, respectively (Savchuk et al., 2012).

Large amounts of phosphorus are stored in the sediment and deep waters, which are released in anoxic conditions (Puttonen et al., 2016). This phosphorus surplus in the large basins in combination with depleted available nitrogen at the surface gives nitrogen-fixing cyanobacteria a competitive advantage over other phytoplankton, resulting in extensive cyanobacterial blooms in late summer, still exacerbating the oxygen situation in the deep basins (Reed et al., 2011). Nitrogen from rivers does not effectively reach the central Baltic Proper due to coastal denitrification and turnover. The cyanobacterial blooms in this area, however, are fuelled by additional phosphorus from land sources and internal loading (Voss et al., 2005a).

The effects of climate change on nutrient loads are highly uncertain. Climate models suggest that the north of the Baltic Sea region would be wetter and the south would be unchanged or drier (Christensen et al., 2021; Meier et al., 2021c), so the agricultural south may experience reduced nutrient loads to the sea. Currently, there is no consistent catchment-wide model of nutrient source apportionment (HELCOM, 2018c), so it is difficult to assess where which sources predominate in different sea sub-basins. It is unknown how fertilization practices, crops grown and land use will change in response to climate change. Also unknown is the relative contribution of nitrogen from accumulated legacy sources to current riverine loads to the sea and how the accumulation and release of legacy nutrients will be impacted by climate change.

5.9.1 Impacts of agriculture on other factors

- A possible feedback by agriculture, or land use in general, on the regional climate (+) is through albedo. Agricultural areas have a higher albedo than forests and waters, so increased agricultural areas may be a cooling factor, but the extent is unknown (Gaillard et al., 2015).

- Agricultural practices, i.e. fertilization of fields, are the primary source for nutrient loads to the Baltic Sea, so there is a strong impact of nutrient loads on hypoxia (+). Increased nutrient (mostly phosphorus) loads to the large basins since the 1950s are responsible for expanding oxygen-poor or oxygen-free zones in the past decades. There is clear and unequivocal evidence for this connection (e.g. Gustafsson et al., 2012).

- Agriculture affects the carbon chemistry of the coastal sea due to carbon and nutrient loads and thus may have an impact on acidification (+) through nitrogen fertilizers and agricultural procedures (Peters et al., 2011) and the stimulation of primary production, stimulating the drawdown of CO_2 in the water column and thereby affecting acidification.

- The amounts and types of dissolved substances in the groundwater are strongly determined by agriculture, which thus strongly affects the quantity and quality of submarine groundwater discharges (+) (Szymczycha et al., 2020a, b).

- The impacts of agriculture on marine ecosystems (+) are clearly the release of excess nutrients from agricultural fields (e.g. Wulff et al., 2007). These excess nutrients are washed into the aquifers and rivers, and a large fraction end up in the sea, where they lead to eutrophication, phytoplankton blooms and, in the Baltic Sea, increased oxygen deficiency zones with extensive further repercussions for the ecosystems, e.g. extensive cyanobacterial blooms.

- Agriculture has been the dominant type of land use (+) in the southern Baltic Sea region (e.g. Ning et al., 2018).

- There is a strong effect on fisheries (+) and aquaculture (+) as nutrients are the basis of the aquatic food web, affecting fish production through multiple trophic processes. Generally, more nutrients mean more fish production. However, a too high nutrient availability contributes to eutrophication and oxygen deficiency, with negative impacts on fish growth and reproduction, e.g. for cod (Köster et al., 2017; Casini et al., 2016a). Furthermore, the composition of prey species, which may be affected by nutrients, is important for the production of specific fish species (e.g. Möllmann et al., 2005; Neuenfeldt et al., 2020).

- Agriculture is a major driver of river regulations (+). A multitude of drainage works in agricultural land have gradually led to a more rapid hydrologic response and may affect the transport of nutrients from land to sea, including Si retention by damming (Humborg et al., 2000).

- Like for land use, agriculture does affect the amount and distribution of chemical contaminants (+) through agricultural practices and use of fertilizers, veterinary pharmaceuticals and pesticides. Nutrient loads can affect chemical contaminants and heavy metals indirectly via eutrophication and organic carbon content/dynamics in the sea. Increased organic carbon in the surface water affects the air–sea exchange of airborne contaminants and transport via settling particles (Dachs et al., 2002). Increased organic carbon content and lower oxygen levels may promote the methylation of mercury present in the sediments, enhancing its toxicity and bioavailability (Avramescu et al., 2011; Bełdowski et al., 2015).

- There may be a connection between agriculture and coastal management (?) in regions where coastal infrastructure and agricultural fields compete for space. Coastal management may need to respond where agricultural fields are at stake where they are close to cliffs and other coastal features that are subject to erosion;

however, these threats are currently considered minor compared to the potential loss of infrastructure. Nutrient loads stimulate actions to mitigate the effects of eutrophication (e.g. HELCOM, 2007), affecting coastal management actions (or management actions in general). On the short-term scale, such actions include warnings about cyanobacteria blooms and increased concentrations of other adverse substances in water in swimming areas (Kowalewska et al., 2014). On the long-term scale, actions may be necessary to manage the growth of reeds or other plants that may decrease the recreational value of the beaches but at the same time reduce damage caused by coastal erosion and flooding (Osorio-Cano et al., 2019) and also act as a coastal filter for nutrient fluxes from the adjacent land (Kochi et al., 2020).

5.9.2 Knowledge gaps

It is highly uncertain how fertilization practices, crops grown and land use will change in response to climate change. Also unknown is the relative contribution of nitrogen from accumulated legacy sources to current riverine loads to the sea and how the accumulation and release of legacy nutrients will be impacted by climate change. Nutrient loads are strongly influenced by runoff and discharge, so the eutrophication status of the sea is strongly influenced by riverine nutrient loads. Diffuse losses of nutrients from agriculture are one of the core drivers of nutrient loads to the Baltic Sea. Further questions are as follows.

- *Agriculture – coastal management.* What is the relation between agriculture and coastal management? Is coastal agriculture of any relevance for coastal management and what does it look like?

5.10 Aquaculture

Aquaculture, in its broadest sense, includes all cultured breeding and commercial production of plants and animals in water, ranging from fish to bivalves, macroalgae, microbes and wetland grass. Aquaculture can be roughly divided into *fed* and *extractive* aquaculture: the former depending on external resources and the latter extracting resources from its surroundings. Aquaculture in open waters (in contrast to closed recirculating systems) has an impact on its direct environment and is in turn affected by environmental conditions.

In the Baltic Sea region, Denmark and Finland are the major producers in marine aquaculture. There is also well-developed freshwater aquaculture, primarily in Poland and Denmark. Rainbow trout (*Oncorhynchus mykiss*) is by far the most produced fish in the region, with a share of roughly 70 % of the region's total production, followed by common carp with 20 %. Other cultured fish species are European eel, sturgeon, pikeperch, pike, tench and others. Shellfish (i.e. bivalves like mussels), as another important aquaculture product, is primarily grown in Germany, Sweden and Denmark (Paisley et al., 2010; Eurofish, 2015).

Rainbow trout cage farming in brackish waters is concentrated in Åland, Åbo archipelago, the southwestern Finnish coast and the Danish straits, while freshwater cage farming is mainly located in the sheltered waters of the large and exploited rivers of northern Sweden. Land-based farms, which include traditional flow-through systems as well as the more modern closed recirculation systems, are found throughout the catchment area. Open fish farming is mainly associated with nutrient losses to the environment and has been shown to cause local eutrophication (Talbot and Hole, 1994; Diaz, 2010).

Increasing water temperatures as well as sea level rise, changed precipitation patterns and extreme weather events have been identified as the main climate impacts on open fish aquaculture (De Silva and Soto, 2009; Galappaththi et al., 2020). In the Bothnian Bay, farmers already now see longer periods of suboptimal to lethal temperatures in the upper water layers (Kankainen et al., 2020). This might promote a growing interest in warm-water-tolerant species such as perch and pikeperch but also in closed land-based systems as procedures and technology constantly evolve and become economically competitive. In general, adaptation strategies are necessary for a sustainable aquaculture in the future (e.g. Reid et al., 2019).

A poorly understood climate-related risk is the changing microbial biota in fish guts as water temperatures rise (Huyben et al., 2018) and the risk of infections and diseases (Reid et al., 2019) and parasites (Unger and Palm, 2017). Changes in salinity might also affect the biota, with possible physiological consequences for the fish. Still, none of the present or future candidates for aquaculture are expected to be affected by a decrease in salinity.

Another problem related to open-cage farming and increased water temperatures is the risk of escaping fish (e.g. Atalah and Sanchez-Jerez, 2020) For instance, escaping rainbow trout (accidentally or intentionally released for sport fishing) is a non-indigenous species that may establish permanent wild populations (Skilbrei and Wennevik, 2006; Stanković et al., 2015). This is now addressed by growing sterile fish.

For some cultivation types, a location within offshore wind farms has been envisaged. The closure of certain wind farms to traffic and fishing together with a location in open, well-ventilated sea areas seems attractive for certain types of aquaculture production (e.g. Mikkola et al., 2018).

Extractive aquaculture includes filtering organisms such as bivalves, but also macroalgae and other plants like seaweed (Critchley et al., 2019; Weinberger et al., 2020) and reed (Karstens et al., 2019). Similar to seaweed farming, mussel farming has the potential to reduce the environmental impact of marine aquaculture by acting as a nutrient sink, transferring nutrients into harvestable biomass ("mussel mitigation farming"; Petersen et al., 2014; Holbach et al., 2020). Germany and Denmark are the leading producers of blue mussel (Eurofish, 2015). Macroalgae farming has been tested, also in conjunction with fish (Wang et al., 2014). Blue mussels have been shown to be particularly sensitive to changes in temperature and/or salinity (e.g. Westerbom et al., 2002; Braby and Somero, 2006).

Reeds have a long history as backup fodder for livestock but also as roofing material around the Baltic Sea (Köbbing et al., 2013; Karstens et al., 2019). While the blue mussel is a candidate for pelagic nutrient abatement on the local scale, reeds (*Phragmites australis*) represent a catch crop for nutrient runoff and habitat enhancement in the inner littoral zone. Management of this zone, i.e. the targeted cultivation and harvest of reeds, may be an option for nutrient removal.

5.10.1 Impacts of aquaculture on other factors

- Aquaculture may be important for local hypoxia (+) in enclosed or semi-enclosed coastal regions with little water exchange, where fish cages release excess nutrients and alleviate local eutrophication and possibly hypoxia (e.g. Talbot and Hole, 1994).

- Aquaculture may have an impact on marine ecosystems (+) through local eutrophication near open-cage farms, or by escaping cultured specimens from cages into the wild. Indirectly, it could act to reduce fishing pressure on certain species if there is an aquaculture alternative and the natural populations are less exploited. Mussel farms could enhance wild declining populations by releasing a spate of mussels of precisely the same genetic heritage as the wild populations. It has recently been observed that lost mussels from the farm can establish wild colonies under the farm. Also, mussel farms could be used to clean up the seawater at a large scale (Kotta et al., 2020).

- Non-indigenous species (+) which are grown in open water cages may escape and establish stable wind populations in the new environment. In 2016, a cargo ship crashed into a Danish fish farm, releasing some 80 000 rainbow trout specimen from the cages (Reuters, 2016). It is unsure whether escaped rainbow trout are able to establish stable wild populations. Continuous escapes during routine operation may also be a problem. Efforts to mitigate this problem are to culture indigenous species preferentially or to grow sterile non-indigenous fish. Another prominent example is the escape of the pacific oyster from oyster farms, following the successful establishment of wild populations in the German Wadden Sea, with subsequent strong competition and suppression of blue mussel beds (Reise et al., 2017).

- An increase in land-based aquaculture in recirculating systems with associated land use (+) is anticipated as technology improves and becomes economic. This would require a complex energy-intensive industrial infrastructure. For an estimated 6.4 GWh energy demand per year for a production of 1000 t of market-size salmon (Nistad, 2020), this would require a massive commitment of renewable energy in a carbon-neutral production process. A back-of-the-envelope calculation yields that for this yearly production volume, roughly 3.1 ha of solar collectors or 560 wind turbines would be needed. This means additional land use beyond the ceiling of the fish factory itself.

- Nutrient release (+) to the open water is important on the local scale near fish farms through excess fodder and fish excrement (e.g. Talbot and Hole, 1994). On the other hand, blue mussel, seaweed and macroalgae farming may act to remove nutrients from the vicinity of the farms (Kochi et al., 2020; Kotta et al., 2020) and may help to counteract eutrophication by catching plankton and other small particles and improving water transparency, at least on the local scale (Petersen et al., 2014). In this way, mussel farming may deal with increased nutrient release from sediments due to hypoxia and changed nutrient runoff from land (Kotta et al., 2020). Fish farming in the Baltic Sea presently represents only 0.5 % of nutrient losses to the Baltic Sea. However, the use of recapture-based feed sources, i.e. interacting with fisheries, could be a net remover of nutrients from the Baltic Sea. Aquaculture is the extension of land-based agriculture and farming into the waters. As such, it complements and extends the benefits and detriments of food production to the waters. However, new technologies for particle collection from open cages, land-based farming and circular feeds as well as obtaining nutrients from the recipient load using blue catch crops and ecosystem management fishing products can make aquaculture a net contributor to reduced nutrient pressure. Reed management and harvest for fodder production and other uses on sheltered coastal stretches may mitigate local nutrient runoff from nearby agricultural fields.

- Aquaculture may complement fisheries (?) and theoretically ease the fishing pressure on certain species by growing them in controlled conditions or providing cultured alternatives to wild catches, thus reducing the impact of the fishing pressure on the ecosystem. However, it is assumed that aquaculture production on the global scale may not substantially displace but instead largely supplement fishery capture (Longo et al., 2019).

- There are no direct impacts of aquaculture on offshore wind farms (+). However, wind farms represent suitable locations for certain aquaculture types, as they are installed in open-water areas which ensure constant ventilation and exchange of water. These areas are banned from shipping and fishing and have a certain infrastructure, so aquaculture in wind farms may be synergistic (Buck et al., 2017; Mikkola et al., 2018).

- Some cultivated fish species are loaded with anthropogenic chemical contaminants (?) (e.g. antibiotics, pesticides, persistent organic pollutants) to a higher degree than wild populations (Cole et al., 2009).
- Aquaculture may be a source for marine litter (?) and microplastics (as the bulk of handling material and equipment is from plastics), but the scale and relevance are largely unknown (Lusher et al., 2017; Sandra et al., 2019).
- There may be an impact of aquaculture on touristic (?) activities, for instance by culinary tourism (Kim et al., 2017). Certain types of aquaculture farming (e.g. water reed, macroalgae, blue mussel) may improve the water quality and light penetration in inner coastal regions and may thus be beneficial for certain touristic activities in these protected inner coastal areas (boating, swimming, fishing, duck hunting).
- Coastal management (+) strongly affects coastal aquaculture by allocating areas for farms; conversely, the aquaculture industry is a strong coastal stakeholder and thus has a certain influence on the management of the coastal waters (e.g. Primavera, 2006).

5.10.2 Knowledge gaps

A climate-related risk that is poorly understood is the changing microbial biota in fish guts as water temperatures rise. Changes in salinity might also affect the biota, with possible physiological consequences for the fish. A further uncertainty is the impact of parasites in future aquaculture and the impacts of pharmaceuticals on the environment. Further questions are as follows.

- *Aquaculture – fisheries.* What is the economic connection between aquaculture and fisheries? Also, there may be a competition for coastal spaces.
- *Aquaculture – chemical contaminants.* What is the impact of pharmaceuticals to fight fish diseases and parasites on the environment? What is the impact on the environment and other organisms?
- *Aquaculture – marine litter.* There are considerable knowledge gaps concerning aquaculture as a source for marine litter of any kind.

5.11 Fisheries

The main target species in commercial fisheries in the Baltic Sea are cod, herring and sprat. Other target fish species include salmon, plaice, flounder, dab, brill, turbot, pikeperch, pike, perch, vendace, whitefish, eel and sea trout. Fisheries affect the Baltic Sea ecosystem primarily through selective extraction of species and physical disturbance to the seabed. The latter is most relevant in the southern Baltic Sea, where gears that come into contact with the seabed (e.g. bottom trawls) are commonly used (ICES, 2018a). Furthermore, some gears, especially gill nets, have incidental by-catch of marine mammals and seabirds, affecting these populations (HELCOM, 2017). According to EU Common Fisheries Policy (CFP), fishing should be conducted in an environmentally, economically and socially sustainable way, and catch limits should be set at levels that ensure maximum sustainable long-term yields. For the major fish stocks in the Baltic Sea, a multiannual EU management plan (EU, 2016) aims to contribute to the achievement of the objectives of the CFP. Fisheries for the major Baltic Sea fish stocks are expected to further align with the targets of these policies in the future.

One of the major scientific challenges concerning fishery impacts is the quantification relative to other human or ecosystem factors. An example here is cod, where fishing for its prey species potentially influences cod growth and condition (ICES, 2018b). However, as several other factors influence cod growth and condition at the same time (e.g. oxygen conditions, parasites from grey seals) (Casini et al., 2016b; Horbowy et al., 2016), the possible effects of fishery management actions are difficult to determine. Another example is fishing impacts on the seabed, for which little is known about the sensitivity of different organisms and communities to fishing gear disturbances, at the Baltic Sea scale. In this area, further research and data are needed to parameterize models and establish quantitative links to other pressures (e.g. anoxia) (ICES, 2018a).

Fish stocks and fisheries are also affected by climate (salinity, temperature) and eutrophication, whose effects are closely connected through the oxygen conditions in the Baltic Sea. For example, recruitment of the eastern Baltic cod is largely influenced by salinity and oxygen conditions (Köster et al., 2017), and temperature significantly affects sprat recruitment (MacKenzie and Köster, 2004; MacKenzie et al., 2007). A combination of oxygen content and temperature was found to have significant effects on egg and larva development and survival of the western Baltic cod (Hüssy, 2011). The growth of planktivorous species or life stages is also affected by climatic conditions regulating zooplankton dynamics (Casini et al., 2011; Köster et al., 2017). Furthermore, oxygen is considered to affect the growth and condition of the eastern Baltic cod both directly and via regulating the availability of benthic food (Casini et al., 2016a). Climate impacts on one species can also propagate through the food web and affect other species via food web interactions. For example, a high abundance of sprat due to favourable temperatures increases competition between sprat and herring and reduces their growth and condition (Casini et al., 2011). Möllmann (2019) provides an overview of the effects of climate change and fisheries on the fish stocks of the Baltic Sea.

A combination of high fishing pressure and unfavourable salinity and oxygen conditions for cod reduced the cod stock in the late 1980s, which released sprat from predation pressure and allowed for an increase in sprat stock in the 1990s, which was additionally favoured by suitable temperatures (Köster et al., 2003; Möllmann et al., 2008). In another example, the increase in the cod stock in the late 1970s to the highest level on record was found to be due to a combination of favourable climate and a temporary reduction in fishing pressure (Eero et al., 2011).

Eutrophication presently has negative effects on fish resources via deteriorated oxygen conditions, but some coastal species may benefit from the associated high nutrient levels. Historically, the increase in nutrient concentrations from the 1950s to the 1980s possibly improved the growth of sprat and herring (Eero et al., 2016) and may have slightly enhanced the productivity of cod (Eero et al., 2011). Fishing is considered to remove nutrients from the Baltic Sea (Nielsen et al., 2019), which is another interaction between eutrophication and fisheries.

Contaminants in fish above accepted thresholds have implications for marketing possibilities of the fish, and invasive species may interact with fisheries through food web interactions: round goby has become a new exploitable resource for some fisheries but also has negative impacts on some other native commercial species (Ojaveer et al., 2015).

5.11.1 Impacts of fisheries on other factors

- For hypoxia (?), there may be a cascading effect; for example, fishing out large predators may affect consumption at lower trophic levels. In the end, this trophic cascade may have repercussions on nutrient concentrations, eutrophication and hypoxia (Nielsen et al., 2019).

- Fisheries strongly affect the marine ecosystem (+). The withdrawal of large quantities of intermediate to top predators may cascade down to lower trophic levels in the pelagic and benthic zone and affect higher trophic levels like marine mammals and sea birds (Jennings and Kaiser, 1998; Bergström et al., 2019; Elmgren, 2021). There can be considerable detrimental effects to benthic communities through bottom trawls.

- Fisheries may directly or indirectly affect non-indigenous species (?) by altering the food web structure and opening up an ecological niche for new species, or may be a new commercially interesting species, e.g. the round goby (Ojaveer et al., 2015).

- There is no direct effect of fisheries on nutrient loads (?), but there can be feedback to coastal nutrient concentrations due to cascading effects if certain species are removed by fishing. By removing fish, fishing is considered to extract nutrients from the Baltic Sea (Nielsen et al., 2019).

- Fisheries may affect aquaculture (?) indirectly, by increasing the need to culture fish due to overfishing (Longo et al., 2019).

- There is a connection between fisheries and offshore wind farms (+) regarding the competition for space and resources in the coastal areas (Methratta, 2020). On the other hand, the bases of pillars have been shown to form artificial reefs, which can act as nursery grounds for specific fish species (Wilson and Elliot, 2009; Degraer et al., 2020).

- Likewise, a possible impact of fisheries on shipping (?) regards the competition for space.

- Fishing vessels have been a source for marine litter (+) and contamination, e.g. nylon nets, buoyancy gear, and solid and liquid waste, similar to general shipping. Abandoned fishing nets, however, are a special threat not only for fish and marine mammals (Stelfox et al., 2016) but also for birds (e.g. Merlino et al., 2018).

- Fisheries may have an impact on tourism (?). In some holiday resorts, fishermen have switched from traditional fishing to offering recreational fishing tours to tourists, selling fish (not own catches) from fishing vessels or touristic sightseeing boat tours altogether.

- Fisheries are an integral part of coastal management (+) in areas where fishing grounds or essential fish habitats potentially overlap with other uses of the coastal zone. While conflicts of this type are scarce in the Baltic Sea region, they are common in regions that use massive fish ponds at the coast (Kalther and Itaya, 2020).

5.11.2 Knowledge gaps

A major challenge is to quantify fishing impacts on ecosystems relative to those of other human or ecosystem factors. An example here is cod in the Baltic Sea, where fishing for its prey species potentially influences cod growth and condition. However, as a number of other factors influence cod growth and condition at the same time (e.g. oxygen conditions, parasites from grey seals), possible effects of fishery management actions are difficult to determine. Furthermore, little is known about fishing impacts on the seabed and the sensitivity of different organisms and communities to fishing gear disturbances. Further research and data to parameterize models are needed, and establishing better quantitative links to other factors (e.g. anoxia) is required. Monitoring systems with respect to other ecosystem components or factors need to be implemented. Further questions are as follows.

- *Fisheries – non-indigenous species.* What is the impact of fisheries on the success and distribution of non-indigenous species? Some species may be a commercial alternative to indigenous species (e.g. round goby), but how do fisheries respond to non-indigenous species?

- *Fisheries – agriculture.* What is the influence of fisheries on agriculture; i.e. what is the potential feedback on terrestrial food production?
- *Fisheries – aquaculture.* What is the connection between fisheries and aquaculture (economically through markets or directly)?
- *Fisheries – tourism.* Is there any impact of fisheries on tourism and the attractiveness of coastal areas and their traditional cultures and livelihoods, in addition to fishermen switching from fishing to organizing touristic fishing tours in fishing and touristic hotspots or selling market fish directly from fishing vessels?

5.12 River regulation and stream restoration

Many rivers in the Baltic Sea catchment basin are regulated; i.e. their natural course has been altered for power generation, municipal water supply and irrigation for agricultural purposes, flood protection, shipping and navigation (e.g. Kelly et al., 2017). Damming for hydropower generation is more common in the northern, boreal part of Europe, where a considerable fraction of electric power generation is by hydropower (up to 82 % in Norway and 77 % in Finland; Lehner et al., 2005; Humborg et al., 2015). Regulation of river basins and drainage works in agriculture and forestry has been a major factor for changes in the hydrological and water quality responses in watersheds (Wörman et al., 2010).

It has been shown that damming leads to a reduced silica transport to the sea (Humborg et al., 2000), due to diatom blooming in reservoirs and reduced weathering in the regulated rivers (Humborg et al., 2015). One option to reduce nutrient loading (in particular nitrogen and phosphorus) is to implement local remediation measures within the agricultural drainage system that utilize the “self-purification” of the stream network. Such local measures – structures built in stream channels – both limit the eutrophication in downstream inland waters and can potentially have a major role in reducing the nitrogen loading to the sea (Seitzinger, 1988; Boano et al., 2014). A general understanding is that nitrogen removal in streams is controlled by biochemistry, but stream hydromechanics impose a limit on the nitrate removal rate (Gomez-Velez and Harvey, 2014; Grant et al., 2018; Morén et al., 2018). The past few decades of research on stream hydrology and biogeochemistry provide a picture of the so-called hyporheic zone as a hotspot for stream biogeochemistry and self-purification of the stream water (Boano et al., 2014).

Stream restoration projects tend to reverse effects of previous drainage works by introducing engineered structures like cross-vanes, riffles and pools, new bed substrate or checker dams (Wortley et al., 2013). Such stream structures create localized hydraulic head drops in streams, which can increase the water flux into the hyporheic zone and, thereby, reduce both nitrate and phosphate transport (Morén et al., 2018). A recent study of the potential for reducing nitrogen export through denitrification in agricultural streams via restoration actions indicates that the effectiveness is highly heterogeneous, depending on local stream conditions. It also indicates that significant reduction in nitrogen export can be achieved through such actions if implemented widely (Refsgaard et al., 2019).

The hydrological response changes over time due to landscape changes, climate variability and global warming. The energy level available for the transport of sediment and solutes in streams is highly variable (Wörman et al., 2017), which has significant environmental implications for decadal or longer timescales. Climate change may generate higher runoff due to overall increasing precipitation, especially in the winter, with large regional differences (Graham et al., 2008; Räisänen, 2017; Christensen et al., 2021). Runoff peaks are expected to come earlier in the year in some regions and be less pronounced due to a lower snowmelt peak and a more spread-out precipitation volume across the winter. An increased runoff would generally enhance nitrogen transport and decrease retention and transformation of nitrogen in streams. Impacts of river regulations on flow regimes and temperatures may be stronger than or comparable to those by current climate change (Arheimer et al., 2017; Ashraf et al., 2016). Moreover, regulations and modifications of many rivers are not well represented in current coupled climate models (e.g. Hagemann et al., 2020).

5.12.1 Impacts of river regulation on other factors

- There is a close connection to coastal processes (+), as regulated rivers carry different amounts of sediments to the sea (Tena and Batalla, 2013), which can thus alter coastal processes and morphology in the vicinity (downstream) of river mouths of regulated rivers. Marinas at the river mouth may have a similar impact (Soomere et al., 2007). While extensive damming of major rivers is detrimental for their deltas (Li et al., 2017), many small beaches experience permanent erosion because of the regulation of rivers that fed them with sand in the past (Vitousek et al., 2017).

- River regulations may have an impact on hypoxia (?) near river mouths, through altered nutrient loads, eutrophication and increased oxygen demand and depletion.

- River loading of total carbon and alkalinity is associated with weathering processes in the drainage areas where some are rich and some are poor in limestone, affecting alkalinity and acidification (+) (Hjalmarsson et al., 2008). Differences in river concentrations of organic carbon and organic alkalinity (Kuliński et al., 2014; Ulfsbo et al., 2014) and in some drainage basins are associated with acid sulfur soils (Nordmyr et al., 2006).

- There is some evidence that regulated rivers have an impact on a drainage basin's groundwater budget (Hancock, 2002), so there is a plausible connection to groundwater discharges (?) to the sea, but the uncertainty is high.

- River regulation and damming may lead to reduced nutrient transport to the sea, especially for silica (Humborg et al., 2000), due to diatom blooming in reservoirs and reduced weathering in the regulated rivers (Humborg et al., 2015). The changed amounts and stoichiometric ratios of the nutrients entering the coastal waters may modify the coastal biogeochemistry and hence affect the marine ecosystem (+).

- There may be an impact of river regulations on land use (?) and agriculture (?). River regulation and restorations can be seen as a type of land use, and the fraction and distribution of useable land are partly determined by regulated rivers.

- River regulations substantially affect nutrient loads (+) through damming and sedimentation, changing the river's nutrient concentrations and biogeochemistry, particularly for Si (Humborg et al., 2015). Still, it has been estimated that the global riverine nitrogen and phosphorus transport has increased despite all regulation efforts (Beusen et al., 2016).

- If river passages are opened for upstream-migrating fish, there is the risk of introducing pathogens from the marine environment into protected areas. The majority of Swedish aquaculture (?) of cold-water fish is harboured from marine pathogens in shielded areas. This needs to be managed if upstream migration is facilitated.

- There is a connection of regulated rivers with fisheries (+), at least for some branches, as regulated rivers (barriers, dams, locks, modifications of the riverbed) make it difficult or impossible for some fish to migrate to their spawning grounds through the rivers (anadromous species like salmon, eel). Fish passes have been installed at many locks and barriers, but passages are significantly lower than without barriers and differ tremendously between species and types of passes (Noonan et al., 2012; Bunt et al., 2012)

- For some chemical contaminants (?) (e.g. pharmaceuticals; Lindim et al., 2016) and trace metals, riverine transport is the major transport route to the sea. Degradation of chemical contaminants during river transport depends on several environmental factors including shading, nutrient conditions, turbidity, exchange between surface water and the hyporheic zone, and the bacterial community in the sediment, and attenuation is therefore dependent on watershed characteristics and water residence time (e.g. Rieger et al., 2012; Posselt et al., 2020). It is therefore plausible that the extensive regulation of rivers in the Baltic Sea catchment impacts the attenuation of many organic contaminants and metals (Saniewska et al., 2014, 2018; Gębka et al., 2020).

- Rivers represent major pathways for microplastic emissions to the sea (Schmidt et al., 2017). In the Baltic Sea, microplastic input via rivers can be expected as well, although retention rates are unknown (Schernewski et al., 2021). River regulations may influence how much or which fraction of marine litter (?) reaches the sea. However, this is largely unknown.

- Regulated rivers change the amount and quality of water entering coastal waters so they have an impact on coastal management (+) (Coccossis, 2004).

5.12.2 Knowledge gaps

Concerning stream restoration, there is a need for more extensive observations on the water quality effects of stream restoration actions and a comparison of the effectiveness of such efforts compared to other land-based remediation plans. Furthermore, there is a need to be able to project the effects of remediation actions on nitrogen removal and other water quality objectives, especially regarding feedbacks between hydrological changes and biogeochemistry of the hyporheic zone under different conditions. Further questions are as follows.

- *River regulations – hypoxia.* Are river regulations in any way correlated with coastal and deep-water hypoxia?

- *River regulations – submarine groundwater discharges.* Are river regulations in any way correlated with submarine groundwater discharges, or do they affect groundwater in coastal regions in any way?

- *River regulations – marine ecosystems.* What impact do river regulations have on marine (coastal) ecosystems?

- *River regulations – aquaculture.* To what extent is coastal aquaculture affected by river regulations?

- *River regulations – chemical contaminants.* Is there a connection between river regulations and the release or transport of chemical contaminants?

- *River regulations – marine litter.* Is there a connection between river regulations and the release or transport of marine litter?

5.13 Offshore wind farms

Regenerative power generation is on the rise to help reach decarbonization goals. For Europe, an increase of up to 15 % in regenerative wind power generation is projected for the late 21st century (Tobin et al., 2015, 2016). Wind power installations have increased in recent years, especially in the southern Baltic Sea, and the prospects are substantial. By late 2019, 2 GW offshore wind power was installed in the Baltic Sea, and it is expected to be 9 to 14 GW by 2030 (Pineda and Fraile, 2019). WindEurope's latest scenario projects installations of 85 GW by 2050, making the Baltic Sea the second-largest basin for offshore wind in Europe (after the North Sea). Offshore wind power is expected to be competitive with other power sources in 2030, according to the ECDGE report (2019). Wind power generation of course depends on future wind conditions. Climate models do not project any consistent future trend for wind speeds in the Baltic Sea region (Räisänen, 2017; Christensen et al., 2021), except for an increase in near-surface wind speed in areas that today are covered by sea ice and which are projected to have largely disappeared in a future warmer climate (Kjellström et al., 2018). Hence, only a drastic increase in the number of wind farms can yield a considerable increase in renewable energy production, with all its potential consequences on ecosystems and potential feedbacks to the regional climate. Moreover, the variability and expected technological development in turbine effectivity are expected to be larger than the estimated climate effects (Tobin et al., 2016). Irrespective of future wind conditions, problems regarding wind wake effects are to be expected in very large wind farms, with consequences for the efficiencies of these large farms (Akhtar et al., 2021).

There are several socio-economic and psychological aspects, which may affect the development of offshore wind energy generation in the Baltic Sea. The visual impact of offshore wind energy infrastructure is a considerable hurdle shaping the social acceptance of the surrounding communities to wind energy development (e.g. Upham and Johansen, 2020). On occasions, this has triggered economic compensation demands by citizens living in coastal areas as a retribution scheme to allow the development of offshore wind energy, an issue which can (a) significantly further slow down the development of new wind energy infrastructure and (b) add additional development costs should financial compensation need to take place. In that respect, various governments across the Baltic Sea region have included compensation mechanisms within their renewable energy system support policies.

Furthermore, the so-called "viewshed effect" of offshore wind energy may have a particularly acute economic impact on coastal touristic destinations, an observation corroborated across multiple case studies in Spain (Voltaire and Koutchade, 2020), the US (Landry et al., 2012; Lilley et al., 2010; Parsons et al., 2020), France (Westerberg et al., 2013) and Denmark (Ladenburg and Dubgaard, 2007), among other jurisdictions. This may lead to significant revenue losses for tourism-dependent businesses, potentially outweighing the economic profits stemming from offshore wind farm developments and ultimately resulting in a net welfare loss for the affected coastal region (Voltaire and Koutchade, 2020). However, there may also be limited benefits (Hooper et al., 2017).

Wind energy development may enhance social acceptance and positive economic distributive impacts under more collaborative procedural and co-ownership conditions whereby individual citizens are offered the opportunity to more proactively participate in the development of wind projects (Langer et al., 2017; Pons-Seres de Brauwer and Cohen, 2020). Importantly, the aggregated "social potential" stemming from citizen-financed wind energy infrastructure development is significant under a European context (Pons-Seres de Brauwer and Cohen, 2020), and thus highly relevant (and potentially replicable) for the Baltic Sea Region.

As of October 2021, there are 18 wind parks in operation in the Baltic Sea region (including Kattegat, Belt Sea and Lake Vänern), with a total production of 2.8 GW, 3 out of operation and 11 under construction or in planning (https://de.wikipedia.org/wiki/Liste_der_Offshore-Windparks, last access: 10 December 2021; this German Wikipedia page is the only up-to-date source; page retrieved 13 October 2021). Figure 2 shows a map of the offshore wind farms in the Baltic Sea (https://www.4coffshore.com/offshorewind/, last access: 10 December 2021).

5.13.1 Impacts of offshore wind farms on other factors

- There may be a certain impact on the regional climate (+) by offshore wind farms through absorbing atmospheric energy. There is little information on the magnitude of this effect, and modelling exercises have found varying impacts on the regional climate at current densities of wind warms (Fitch et al., 2013; Vautard et al., 2014; Akhtar et al., 2021; Fischereit et al., 2021). Considerable impacts cannot be excluded in the future with an extensive development of renewable energy production to meet climate goals. Studies suggest that with climate change, the wind resource change in the Baltic Sea is not as significant as other European seas, with a majority of studies suggesting a small tendency of increasing resources in the northern part (Devis et al., 2018; Reyers et al., 2016; Hahmann et al., 2020). However, the impact of the farms on the regional climate has not been assessed in this area, partly due to the scale of the offshore wind industry being still rather small. While observational evidence is scarce, numerical studies in other regions have suggested possible impacts of wind farms on local meteorology and climate, depending on the farm size and density and turbine types. The impact from the farms on local meteorology can be seen in the formation of fog (North Sea; Emeis, 2010; Hasager et al., 2017), the change of spatial distribution of precipitation (US coast; Pan et al., 2018), cloud cover (North Sea; Boettcher et al., 2015), decrease in sensible heat flux (North Sea; Foreman et al., 2017) and local temperature (conceptual; Roy and Traiteur, 2010). Obser-

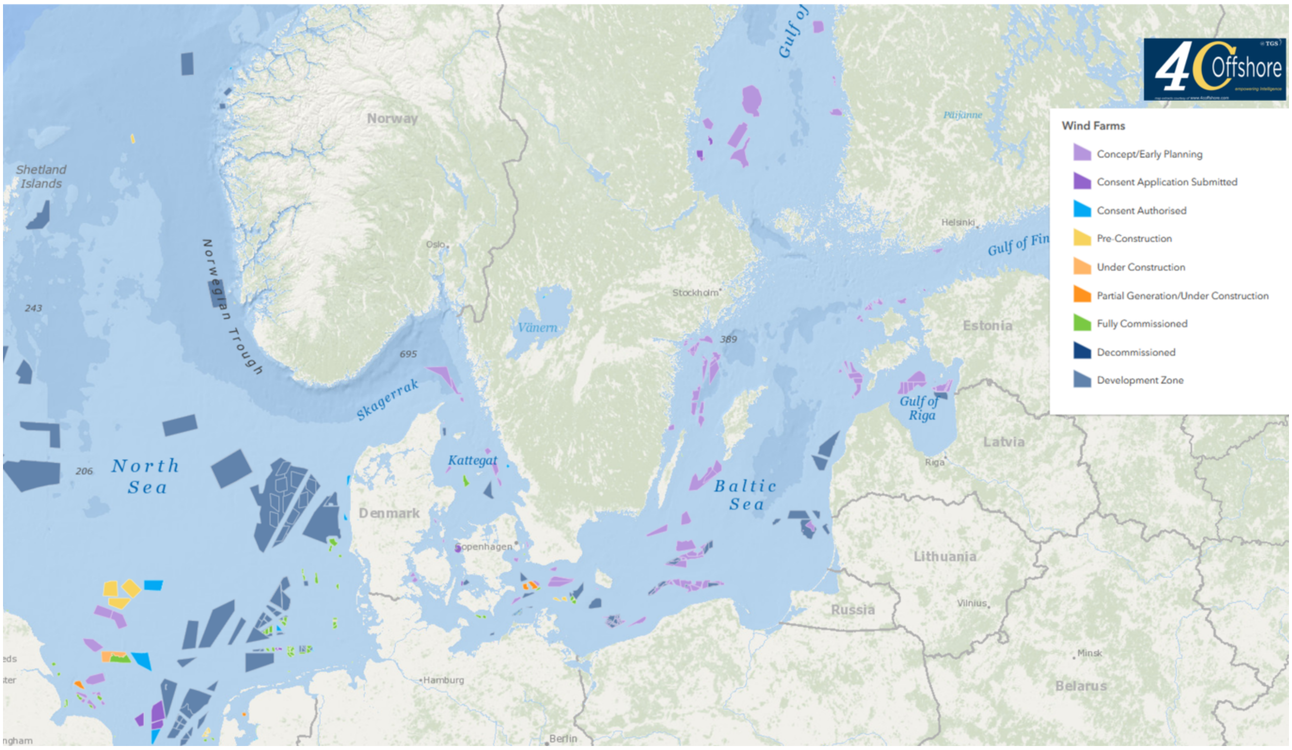


Figure 2. Offshore wind farms in the Baltic Sea (https://www.4coffshore.com/offshorewind/, last access: 10 December 2021), as of 24 June 2021, courtesy of 4COffshore.com.

vational evidence has shown that offshore wind farms may affect the local climate by modifying the marine boundary layer (Siedersleben et al., 2018). The impact is mostly assessed through temperature, and the findings are that there is only a statistically insignificant change in mean temperature, with seasonal peak values up to 0.5 °C (Vautard et al., 2014; Keith et al., 2004; Pryor et al., 2018). In contrast, Wang and Prinn (2011) and Huang and Hall (2015) found a potential cooling effect in the vicinity of the offshore wind farms due to an increase in latent heat flux. Airborne observations confirm that wind farm wakes can extend 50–70 km under stable atmospheric conditions (Platis et al., 2018; Akhtar et al., 2021). These measurements show that wakes can increase the temperature by 0.5 °C and humidity by 0.5 g kg^{-1} at hub height, even as far as 60 km downwind (Siedersleben et al., 2018).

- The impact of wind farms on coastal processes (+) depends on the vicinity to the coast. Currents may be affected by pillars, and sediment transport may be affected locally (Zhang et al., 2009; Besio and Losada, 2008). Coastal currents may lead to scouring and problems with the stability of pillars (Whitehouse et al., 2011). The disturbance to the downwind wave field heights was estimated to be minor (Alari and Raudsepp, 2012).
- There is a considerable impact of offshore wind farms on marine ecosystems (+). Noise from pile driving can cause temporary to permanent damage to marine mammals to different degrees and cause their behaviour to change in communication and travel (Southall et al., 2007). Cables during construction and electromagnetic fields can also affect the orientation of those who use geomagnetic cues during migration (Lovich and Ennen, 2013). Tougaard and Michaelsen (2018) examined the impact of the wind farm Kriegers Flak in the Baltic Sea on marine mammals (specifically two species of seals) regarding underwater noise and suggest that noise from construction and operation are without significant long-term impact on the marine mammals. Wind parks may also host fish and sessile assemblages of organisms (Andersson and Öhman, 2010) and be selective hunting areas for harbour porpoises due to high fish abundances there (absence of fishing and artificial reef conditions, shown for the North Sea; Scheidat et al., 2011). Many species of water birds have been observed to react to the presence of a wind farm, from a few hundreds of metres to a few kilometres ahead, as observed over both the Baltic Sea and the North Sea (Hueppop et al., 2006). Most of them change flying route and fly around the farm, and very few (less than 1 %) fly riskily close to the farm and end with collision, according to observation around the Nysted wind farm in the Baltic Sea

(Desholm and Kahlert, 2005). Large wind farm clusters may form a barrier effect to migrating birds, though some may fly into the space between the farms (Larsen and Guillemette, 2007). Studies for land birds affected by offshore wind farm are lacking. Potential impacts of wind wakes on hydrodynamic features of the downstream waterbody and ecosystems are discussed by van Berkel (2020).

- There is no clear connection between offshore wind farms and land use (?) except that an extension of offshore wind farms may result in a reduced number of wind turbine constructions on land.

- The same holds for the connection with agriculture (?); land-based wind farms may need to be reduced to make space for agricultural fields. It needs to be taken into account that land-based wind energy constructions need to fulfil certain regulations concerning the vicinity to housing settlements and that local communities can often contest the construction of new sites in their neighbourhoods, so that land areas for wind generation may be increasingly scarce in the future.

- There is a potential synergistic use of offshore wind farms related to certain types of aquaculture (+) in the Baltic Sea (Mikkola et al., 2018). The installation of open cages between the pillars was proposed to grow seaweed, rainbow trout or Atlantic salmon (Stuiver et al., 2016; Legorburu et al., 2018). The shared infrastructure, the placement in clean and open waters, and the exemption from fishing and shipping have been reasons for considering this type of synergetic use. There are, however, certain associated obstacles which may have so far prevented a successful application. These refer mostly to economic, legal and management-related rather than technical constraints (Buck et al., 2017; Chen et al., 2020; van den Burg et al., 2020).

- There is an array of possible impacts of wind farms on fisheries (+). Wind farms cover large areas, which are exempt from fishing, so there is competition for space. Studies have suggested that some fish species are affected by noise from foundation construction or operation (Thomsen et al., 2006). Some found evidence of injury from pile driving sounds for several fish species (e.g. Casper et al., 2012, 2013), and noises and consequent vibration produced by the turbines can negatively affect the communication and orientation signals of fish (Wahlberg and Westerberg, 2005). Their behaviours (e.g. swimming route) can be disrupted by the magnetic fields from the electrical currents in the transmission cables (Ohman et al., 2007). On the other hand, these large areas banned from fishing may act as spawning grounds for fish due to banned fishing and the functioning of windmill pillars as artificial reefs (Wilson and Elliot, 2009; Degraer et al., 2020). There is evidence for increased fish populations in the presence of wind farms (Stenberg et al., 2011; Methratta, 2020).

- Offshore wind energy infrastructure may have important disruptive impacts on the shipping (+) routes of cargo vessels (Samoteskul et al., 2014). In case of route obstruction, wind farm owners must financially compensate cargo vessel operators for detouring from their shipping routes. One such example is the Anholt wind farm in the Kattegat (Petersen et al., 2015). This represents a significantly high added cost to be internalized during the offshore wind farm development process (Samoteskul et al., 2014). Consequently, offshore wind energy infrastructure may therefore be built in areas away from recognized shipping routes and anchoring locations to avoid collision and subsequent financial compensation to vessel operators. Moreover, nearshore locations should be avoided, as this may reduce social acceptance due to the infrastructure's visual impact on the population living in coastal areas, which may have significant economic implications, particularly in coastal touristic areas with high recreational value. Alternatively, cargo vessel routes ought to be modified on a permanent basis, an action that could significantly reduce the financial cost of future offshore wind farm developments (Samoteskul et al., 2014).

- There are potential emissions of chemical contaminants (?) from all offshore activities due to increased emissions from constructions and traffic leading to disturbance of seabed sediments (release of contaminants in sediments and chemicals used in the infrastructure, leakage through lubricants, other material, e.g. metals, biocides, oils, coolants, dielectric fluids). However, there are no investigations on the magnitude of this potential contamination (Tornero and Hanke, 2016; Ytreberg et al., 2020).

- As with any offshore activity, wind farm constructions may affect dumped munitions (?), due to possible breach of munition hulls. Since wind farms are built away from official dump sites, solitary munitions or unofficial dump sites are the main risk factors. In 2017, the construction of a wind farm in the North Sea released an abandoned sea mine from the sediments that was later found floating between the piles of the GodeWind 2 farm (Schuler, 2017).

- Marine litter (?) could be generated through the maintenance and traffic related to the offshore constructions, but there are no investigations on this connection.

- Offshore wind farms may have an impact on coastal tourism (+). The so-called "viewshed effect" or "horizon pollution" (in Germany) of offshore wind farms may have adverse economic impacts on coastal touristic destinations (e.g. Ladenburg and Dubgaard, 2007) and may result in a net welfare loss for the affected coastal region (Voltaire and Koutchade, 2020). There are, however, controversial views (Hooper et al., 2017).

- Wind farm planning is a part of coastal management (+); i.e. governments and local authorities attempt to balance and manage their use and development in coastal zones. On the one hand, socio-economic effects, such as revenue losses for tourism-dependent businesses, may possibly outweigh economic benefits from offshore wind farm developments and may result in a net welfare loss for the affected coastal region (e.g. Voltaire and Koutchade, 2020); on the other hand, recent modelling results indicate that large offshore wind farms may affect the wind resources and impact power production in the future (Lundquist et al., 2019). Wind resources are limited and large wind farms may reduce the harvestable wind due to shadowing effects, i.e. power production of downwind turbines may be compromised in large wind farms (Akhtar et al., 2021).

5.13.2 Knowledge gaps

The impact of wind farms on the regional climate has not been assessed in the Baltic Sea. With increasingly extensive wind parks, the impacts on the regional weather and climate as well as on currents, stratification and marine ecosystems (including birds) need to be further investigated. It will be important to project the future contribution of offshore wind farms to energy production in the Baltic Sea region and Europe in relation to land-based structures and other producers of regenerative energy. Further questions are as follows.

- *Offshore wind farms – chemical contaminants.* Do offshore wind farms release any organic contaminants to the water?
- *Offshore wind farms – dumped military material.* Is there a connection between offshore wind farm sites and dump sites of ammunition?
- *Offshore wind farms – marine litter.* Do offshore wind farms release considerable amounts of litter to the water?

5.14 Shipping

Shipping has a significant impact on the environment, both in the water and in the atmosphere (Moldanová et al., 2021, Fig. 3). The Baltic Sea has some of the densest maritime traffic in the world, with more than 2000 ships in the area on an average day (IMO, 2021b). Today, 80 % of the world's trade is operated by sea traffic (UNCTAD, 2019), and 15 % of the global cargo traffic is via the Baltic Sea (BalticLINes, 2016). Ships carry oil, gas, containers and large freight. In the Baltic Sea, the main shipping route is from the Belt Sea in the west to Saint Petersburg and other ports in the eastern Baltic Sea. The main hazards on this route are the shallow and narrow Kadet channel between Falster, Denmark and the Mecklenburg coast, Germany, and the Danish straits. The northern part of the Baltic Sea and the Gulf of Finland and Gulf of Riga can also be affected by severe ice conditions in winter.

Air emissions from shipping are fairly well known as vessel activity can be tracked using ship-specific positioning systems like AIS (automatic identification system), and emissions as well as discharges can be estimated using modelling tools (Jalkanen et al., 2009, 2021; Johansson et al., 2013, 2017). Various pollutant streams are regulated by conventions by the International Maritime Organization (IMO MARPOL, IMO, 2021c), which sets the rules for air emissions and various discharges from ships. Antifouling and ballast water releases are governed by separate conventions outside the MARPOL framework. The reduction of air emissions has been primarily motivated by impacts on human health (Sofiev et al., 2018; Jonson et al., 2015; Brandt et al., 2013; Mwase et al., 2020; Lin et al., 2018; Karl et al., 2019; Ramacher et al., 2019; Soares et al., 2014). Ship-emitted NO_x deposition contributes to eutrophication with less than 10 % of various biogeochemical variables, but this share is 3 to 8 times larger than shipping contribution to total nitrogen input to the Baltic Sea (Raudsepp et al., 2013, 2019).

Sulfur emissions from shipping fuels (crude oil) are a particular problem for the environment and human health (Barregard et al., 2019). As of 2020, IMO has banned fuels with a sulfur content above 0.5 %, compared with a previous 3.5 % (IMO, 2021d). Efforts to reduce sulfur have led to the adoption of SO_x scrubbers, which are used to clean the exhaust gases by spraying them with water, which is released back to the sea. The wastewater release from scrubbers represents the second largest discharge from ships to the sea. The full impacts of SO_x scrubbing are currently unknown, but several countries have prohibited the use of SO_x scrubbers in port areas, anticipating potential water quality problems. As of 2021, NO_x emission regulations are planned to be in force for new ships (IMO, 2021b). This requirement is not applied retroactively for old vessels, which means that the full 80 % reduction in ship-emitted NO_x will be visible only after the whole Baltic Sea fleet has undergone a renewal cycle, which may take up to 30 years. It is possible to adapt to both sulfur and nitrogen regulatory changes by using liquid natural gas (LNG) as a shipping fuel. To date, LNG mostly consists of methane, which is a fossil fuel. Unburnt methane may also escape the ships' engines, thus leading to methane slip, making it more difficult to achieve GHG reduction targets set for international shipping (Ushakov et al., 2019).

Sewage releases to the Baltic Sea will become illegal for passenger traffic in 2023, which will reduce nitrogen inflow from ships to the sea by 90 % (Jalkanen et al., 2021). The introduction of non-indigenous species through vessel

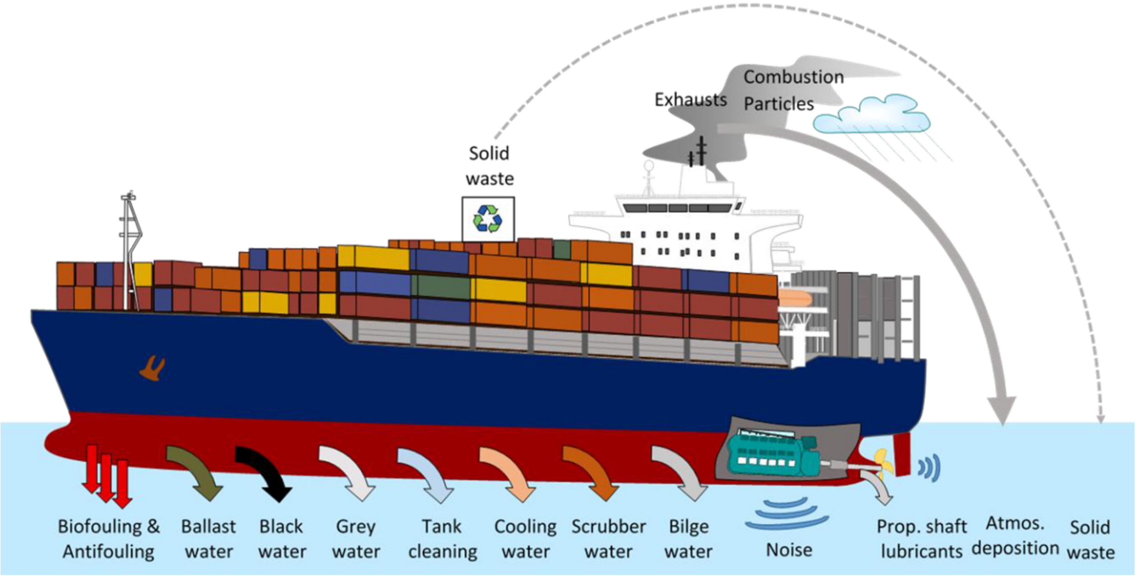


Figure 3. Different impacts of shipping on the environment. Hydrodynamic impacts such as wakes are not shown but described in the text. Courtesy of Moldanová et al. (2018), modified.

hulls can be mitigated by using antifouling paints. Organotin compounds have been banned for more than a decade (IMO, 2021e), but these and various other organometallic compounds remain in use, especially in recreational boats (Eklund and Watermann, 2018). The traffic patterns of ships and recreational boats are different: large vessels travel along designated shipping lanes, whereas small boats mainly operate in coastal waters. The maximum release of organometallic compounds from antifouling paints occurs during the summer months, when contributions from both shipping and boating are at a maximum. Estimated annual quantities of copper released to the Baltic Sea are about 282 and 57 t for ships and boats (Jalkanen et al., 2021; Johansson et al., 2020).

Oily bilge water release is allowed if the oil content is below 15 ppm and the vessel is not in coastal waters. Discharges of grey water (wash water from sinks, washing machines, etc.) and emissions of energy (noise, light, heat) to the sea are currently not regulated, but the importance of noise as pollution has been recognized (Mustonen et al., 2019; Jalkanen et al., 2018). The impact of modern military ships on the Baltic Sea environment is largely unknown.

5.14.1 Impacts of shipping on other factors

- Shipping has a considerable impact on climate (+) through the emission of combustion gases and particles/aerosols (black carbon, methane, CO_2) to the atmosphere. Shipping worldwide contributes to approx. 2 % of global GHG emissions (Selin et al., 2021), and CO_2 from shipping in the Baltic Sea is less than 2 % of global CO_2 emissions from ships (Johansson et al., 2017).
- Shipping effects on coastal processes (+) such as erosion become noticeable along shorelines in relatively sheltered coastal regions where the impact of ship-induced waves adds to the impact of natural waves. Hydrodynamic impacts of shipping in rivers, navigational channels and archipelago waterways have been known for decades (Madekivi, 1993). Shipping may generate dangerous waves and swell-like disturbances in narrow passages and rivers and even on relatively open shores with potential harm for banks, beaches and coastal infrastructure (Kelpšaite et al., 2009; Soomere et al., 2009; Zaggia et al., 2017; Scarpa et al., 2019; Ulm et al., 2020). It may cause extensive resuspension of bottom sediments (Erm and Soomere, 2006), trigger ecological disturbance and cause harm to the aquatic wildlife (Ali et al., 1999; Lindholm et al., 2001). The impact of ship-generated waves may become substantial in areas where either period or approach direction of the wave deviates from those typical of natural waves. Several parts of the Baltic Sea (most notably Tallinn Bay) with high traffic of strongly powered ships are affected by much longer waves than wind waves in the area (Soomere, 2007). Such waves cause unusually strong impacts at a certain depth that first becomes evident via intense sediment resuspension (Erm and Soomere, 2006) and later may be compensated for by sediment from the beach profile (Soomere, 2007). The increased local hydrodynamic activity may damage various structures and archaeological sites, and safety problems for navigation and users of the beach and nearby shore may arise (Parnell and Kofoed-Hansen, 2001).

- Scrubber water increases acidification (+). According to the IMO requirements, the pH of the effluent discharge must not be lower than 6.5, and the difference between inlet and released water must be less than 2 pH units (IMO, 2009). Even with these requirements, gradual acidification of ocean areas may occur with a high adoption rate of open-loop scrubbers as a means to comply with sulfur emission restrictions. Ocean acidification because of climate change and CO_2 solubility is estimated as 0.002 pH units per year (Rhein et al., 2013). In contrast, scrubber adoption is estimated to reduce pH with an additional 0.0001 pH units per year (Turner et al., 2018). Confined water areas, like estuaries and ports, may experience larger reductions (up to 0.015 pH units; Teuchies et al., 2020).

- Shipping has various impacts on marine ecosystems (+), for example, the pollution by chemical substances and antifouling agents, the release of nutrients to the water and to the atmosphere, acidification by scrubber water, and contribution to marine litter and marine noise. Shipping contributes to continuous low-frequency underwater noise, which may have adverse effects on marine life (Nedwell et al., 2004; Rolland et al., 2012; Mustonen et al., 2019). Furthermore, the leaching of organometallic compounds, especially Cu and Zn, from antifouling paints on ship hulls is high (Eklund and Watermann, 2018; Jalkanen et al., 2021; Lagerström et al., 2020) and affects organisms. Anchors and chain scour may affect benthic ecosystems at anchorages (Broad et al., 2020).

- There is a clear connection to the introduction of non-indigenous species (+) as ballast water and attachment on hulls are major pathways for the introduction of new species (Bressy and Lejars, 2014; Davidson et al., 2009).

- It has been shown that shipping is a significant source for the emission of airborne nitrogen into the atmosphere. Its contribution from ships may be less than 3 %, but its share from various biogeochemical variables may be as high as 10 % (Raudsepp et al., 2019). Direct discharge from ships to the sea includes nutrients (+) and pharmaceuticals in the form of black (from toilets), grey (other sewage) and bilge (engine and other liquid waste) water, but also as food waste (Jalkanen et al., 2021).

- Shipping may have an impact on open water aquaculture (?) farming by excluding shipping routes or endangering safe cages and potential escape of non-indigenous species to the environment by collision or swell damage. In October 2016, a cargo vessel collided with an aquaculture cage in Danish coastal waters, causing 80 000 rainbow trout to escape the closed farm, with unknown consequences for the coastal ecosystem (Reuters, 2016); similar incidents have been reported by local fishermen.

- There is a connection between shipping and fisheries (+) through competition between fishing grounds and shipping routes (e.g. Bastardie et al., 2015), the generation of underwater noise (Jalkanen et al., 2018), and the contamination of fish by heavy metals and antifouling agents (Maljutenko et al., 2021).

- There may be an impact of shipping on offshore wind farms (?) through the danger of collisions in detrimental conditions (storms, loss of manoeuvrability). The location and approval of wind farms are dependent on shipping routes. Areas for specific purposes are allocated by maritime spatial planning (HELCOM, 2013, an example for the Gulf of Bothnia).

- Shipping is a significant source of water pollution in general, also for chemical contaminants (+). This is through the release of organic contaminants and heavy metals to seawater through scrubber water and other contaminated water (black, grey and bilge water) and antifouling agents, in particular copper and zinc (Jalkanen et al., 2021; Magnusson et al., 2018; Ytreberg et al., 2020). Polyaromatic hydrocarbons (PAHs), e.g. pyrene, are carcinogenic compounds formed during combustion, of which particularly high concentrations are found along shipping lanes due to the release of bilge and scrubber water.

- Furthermore, shipping can be a source of marine litter (+), although it is not considered the main source (e.g. Graca et al., 2017).

- Shipping has an impact on tourism (+) as coastal touristic activities involve recreational boating, either on a guided basis (touristic boat trips or recreational fishing trips) or on an individual basis (recreational small-vessel leisure boating). Another dimension is the growing cruise ship sector, which has grown into a large commercial sector, providing many jobs in various branches (also in the destination harbours), but having a detrimental impact on the environment (air pollution, scrubber water, litter, marine noise) and disturbance of local communities (Urbanyi-Popiołek, 2019).

- Shipping may have an impact on coastal management (+) as some impacts on coasts and coastal structures as well as in rivers (damage through waves and swell, unprotected coastlines affected by swell) are evident (e.g. Zaggia et al., 2017; Jägerbrand et al., 2019).

5.14.2 Knowledge gaps

There are large unknowns concerning underwater noise generated by ships and its impacts on marine life. A monitoring network for underwater noise would help to get reliable data. The development and implementation of quiet ship hulls and propulsion systems and the issue of marine noise could be further implemented in IMO measures. The effects of emission abatement techniques and their waste streams (SO_x scrubbers, catalytic converters, use of gas or hydrogen as a marine fuel) could be investigated and evaluated as to their benefit or harm to the ecosystem. The climate impacts of shipping, emissions of black carbon, methane and CO_2, could be quantified and the use of biofuels evaluated. Further questions are as follows.

- *Shipping – aquaculture.* What impacts could shipping have on aquaculture?

5.15 Chemical contaminants (with an emphasis on organic contaminants)

Thousands of organic chemicals, both synthetic and naturally occurring, are released intentionally or unintentionally to the Baltic Sea environment due to human activities. It is unclear if the total anthropogenic chemical stress to the Baltic Sea is currently increasing or decreasing: in many cases, e.g. for banned chemicals that are monitored, environmental/biotic concentrations are declining, although emissions from remaining reservoirs in the technosphere and buffering by secondary sources such as soils and sediments delay their elimination (Breivik et al., 2016; Glüge et al., 2017; Abbasi et al., 2019; Sobek et al., 2016). Dioxins and dioxin-like polychlorinated biphenyls (PCBs) are for example still present in Baltic Sea fish in high levels, making sales restrictions and recommendations of maximum fish intake necessary to protect human health (Pihlajamäki et al., 2018).

Legacy pollutants, i.e. those which are banned but still present in the environment, still dominate the burden of some groups of persistent organic pollutants analysed in Baltic Sea marine mammals and birds, due to their persistence and exceptional bioaccumulation potential. However, analysis of less well-studied organic contaminants, often replacements for the legacy pollutants, indicate that levels in fish and mussels are now similar to or exceeding their predecessors (de Wit et al., 2020). The lack of control of identification and amount of emitted substances hampers characterization and quantification of combined toxic effects in the Baltic Sea (Lehtonen et al., 2017; van den Brink et al., 2018). Organic contaminants can reduce the resilience to other stressors by influencing the fitness of the organism, e.g. the key physiological mechanisms to maintain homeostasis (Noyes et al., 2009).

Direct effects of climate change include an array of processes. Changing environmental temperatures affect diffusive partitioning between environmental phase pairs such as air–water, air–aerosols, air–soil and air–vegetation, leading to a different distribution between environmental compartments, like increased volatilization from seawater to air (Macdonald et al., 2003). Increasing temperatures can enhance photo- and hydrolytic degradation as well as biodegradation of organic contaminants (Noyes et al., 2009). Atmospheric transport and air–water exchange can be influenced by changes in wind fields and, to a lesser extent, wind speeds (Lamon et al., 2009; Kong et al., 2014). Changing precipitation patterns influence chemical transport via atmospheric deposition (rain dissolution and scavenging of particles; Armitage et al., 2011) and runoff, in turn transporting terrestrial organic carbon (Gustavsson et al., 2019; Josefsson et al., 2016; Ripszam et al., 2015). As ice cover in lakes and the sea decreases, more organic contaminants may volatilize to the atmosphere (Macdonald et al., 2003; Undeman et al., 2015). The responses are complex, and several processes can act antagonistically. For example, warmer temperatures may lead to re-volatilization of organic contaminants in soils, but may also lead to increased degradation in the atmosphere and the environment in general. This latter effect, however, can be expected to be weaker than the former (Armitage et al., 2011).

Hydrophobic organic contaminants adsorb to organic carbon; hence, changes in organic carbon cycling may influence the distribution of organic contaminants (Nizzetto et al., 2012). Increased primary production in the sea influences the air–water exchange of some organic contaminants (Dachs et al., 2002). The downward transport of organic contaminants via sedimentation of particulate matter increases with increasing primary production (Nizzetto et al., 2012). The concentration of particulate organic matter in the water column reduces the bioavailability of organic contaminants as they adsorb to the particles (Borgå et al., 2010). In the Baltic Sea, eutrophication leads to hypoxia and anoxia in bottom sediments, which reduces the activity of benthic organisms and hence bioturbation (Thibodeaux and Bierman, 2003; Granberg et al., 2008). This may lead to a reduced release of organic contaminants archived in the sediments. Invasive species such as the deep-burrowing polychaete *Marenzelleria* spp. or higher abundances of the native bioturbating species *Monoporeia affinis* may cause the opposite effect (Hanson et al., 2020). Changes in marine food web structure may indirectly influence bioaccumulation (Wikner and Andersson, 2012), and changes in the light regime may affect photolysis of organic contaminants, e.g. polybrominated diphenyl ethers (PBDEs) (Kuivikko et al., 2007; Leal et al. 2013; McGovern et al., 2020).

Climate change may affect bioaccumulation in food webs directly by influencing body size, growth rates and conditions, temperature-dependent ventilation rates, or biotransformation rates (Borgå et al., 2010; Alava et al., 2017). Increasing PCB concentrations in burbot have been connected to increased organic matter concentrations (Armitage et al., 2011). In the Bay of Bothnia, low growth rates may explain the observed lack of decreasing dioxin levels in herring during the last decades (Miller et al., 2013). Organic contaminants can modulate the composition and functioning of microbial communities, and potentially also biogeochemical processes important to Earth system functioning (Vila-Costa et al., 2020).

5.15.1 Impacts of chemical contaminants on other factors

- Toxic effects of organic contaminants and metals affect all types of organisms, e.g. health conditions and reproduction and marine ecosystems (+) and biogeochemical processes in general (Vila-Costa et al., 2020).
- Chemical contaminants are ubiquitous in the environment, and many are used on purpose in agriculture (+) (e.g. pesticides, insecticides). So, the desired effects on growth efficiency and agricultural yield are accompanied by unwanted and largely unknown negative effects on organisms and the food chain (Kumar et al., 2019).
- Aquaculture (+) fish may be strongly affected by organic contaminants, sometimes more than wild fish, as they are exposed to higher concentrations of deliberately dispensed pharmaceuticals, e.g. antibiotics (Cole et al., 2009).
- Organic contaminants have a strong indirect impact on fisheries (+). Contaminants in fish above accepted thresholds have implications for marketing possibilities of the fish. High concentrations of contaminants, e.g. dioxins, affect the marketing of the fish (fatty fish cannot be marketed in Europe, although exemptions exist for Sweden, Finland and Latvia). In addition, contaminants can affect fish stocks via food web interactions. For example, a reduced level of hazardous substances has allowed the top predator grey seal population to increase in abundance. Seals are preying on fish resources, and their increased abundance has led to an increased infection of cod with the seal-associated liver worm (Sokolova et al., 2018), which may affect cod condition and cause mortality (Horbowy et al., 2016).

5.15.2 Knowledge gaps

The types and amounts of organic contaminants entering the Baltic Sea are not well characterized, and major sources and pathways through the environment and food webs are not known, even for many legacy pollutants. Methods to estimate or project use patterns and emissions are lacking for the majority of organic substances used. It is not known what the combined effect of the thousands of chemicals in the Baltic Sea is and what type of chemicals are the main drivers for the mixture toxicity. It is a great challenge to separate the effects of organic contaminants from natural variability and other stressors in the Baltic Sea and to predict effects at population or ecosystem level from observations of sublethal effects in individuals. Severe detrimental effects at the population level have been linked to specific pollutants in the past, but many ecotoxicological effects on the Baltic Sea ecosystem due to the cocktail of chemicals are largely unknown. Regularly monitored organic contaminants such as dioxins and dioxin-like PCBs are currently present in Baltic Sea fish at too high levels, making sales restrictions and recommendations of maximum fish intake necessary to protect human health. Further questions are as follows.

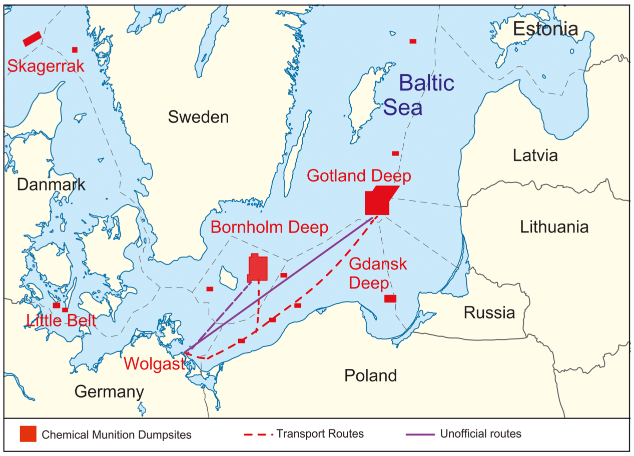


Figure 4. Chemical munition dump sites in the Baltic Sea (courtesy of Jacek Bełdowski, CHEMSEA project 2013).

- *Chemical contaminants – submarine groundwater discharges.* What is the contribution of organic contaminants released through submarine groundwater discharges and how strong is this effect?
- *Chemical contaminants – marine ecosystems.* The toxicity of organic contaminants and metals to many marine organisms is well documented in laboratory and field studies, yet there are many unknowns concerning how and to what extent organic contaminants have an impact on certain compartments of the marine ecosystem, in particular the microbial communities and thereby the potential implications for critical biogeochemical processes.

5.16 Unexploded ordnance and discarded military material

In the Baltic Sea, large quantities of unexploded ordnance (UXO) and discarded military materials (DMMs) are present on the sea floor (Fig. 4). About 160 000 mines and an unknown number of bombs, shells and torpedoes were discarded in the Baltic Sea as a result of military actions. In addition, soon after World War II, the Baltic Sea was used as a dump site for at least 40 000 t of chemical munitions (Knobloch et al., 2013). Recent studies performed at the dump sites revealed that 50 % of inspected UXO and DMM have already corroded, and their constituents have leaked to the surrounding sediments, while others are expected to do so in the next 30–40 years. Recent studies show that those substances are persistent, and their degradation products may be as toxic as their parent compounds (Czub et al., 2020). Hydrodynamic models indicate that they may spread into neighbouring areas and may be taken up by organisms. Indeed, there are reports of bioaccumulation of explosives and chemical warfare agents in organisms in the Baltic Sea (Niemikoski et al., 2017).

Hence, four scenarios are to be considered: (1) a slow release of toxicants and local contamination maintained; (2) a gradual increase in release and spread of contaminated areas; (3) a rapid release of contamination and massive pollution; and (4) a possible beaching of munitions or munition fragments and impact on tourists.

The first two scenarios depend mostly on natural conditions, and the magnitude of pollution can be assessed by existing models. In this situation, munition is only one of many stressors acting on the Baltic Sea and can be included in an overall assessment. In the third scenario, severe consequences for the entire Baltic Sea or specific areas adjacent to dump sites may result from anthropogenic intervention, which is hard to predict. The last scenario is already ongoing – periodic encounters of beach strollers with UXO or fragments of munitions, especially incendiary substances like white phosphorus, happen every year (Frank et al., 2008; Knobloch et al., 2013). The process may intensify in the case of progressing corrosion of containers or anthropogenic disturbance of munitions due to offshore activities. The first two scenarios may have an impact on fisheries, by affecting fish health and diminishing recruitment, and a limited impact on fish consumers, as they assume low contamination. The third scenario may have a detrimental impact on offshore economy, a loss of fisheries and loss of tourism. The fourth scenario may have negative implications on tourism and require high investments of coastal communities in maintaining safety on the beaches.

Degradation processes of chemical warfare agents and explosives are almost fully recognized (Mazurek et al., 2001; Söderström et al., 2018); however, not much is known about their metabolic pathways in biota.

Munition-related pollution is greatly dependent on corrosion. It is especially enhanced during anoxic to oxic transitions in the bottom water, exceeding the rates in stable oxic environments (Fabisiak et al., 2018; Vanninen et al., 2020). Therefore, the frequency of anoxic events may amplify the release of the pollutants, while oxygen-rich conditions can increase their bioavailability, due to biota return to deep dump site habitats (Czub et al., 2018).

Elongated warm periods caused by climate change can significantly affect munitions in shallow waters, where mostly conventional warfare materials were dumped. The presence of hard metal objects as substrates for colonialization in soft sediment areas can increase the local biodiversity of sessile species, and the chunks of organic compounds used as explosives can also attract primary and secondary producers as a source of nutrients. This is caused by the release of nitrates during the biodegradation of TNT and similar substances (Jessim, 2018). Higher-level organisms, e.g. nematodes, were found in the contaminated sediments, followed by various biofilm grazers.

Due to longer vegetation periods in a warmer climate, the extended transfer of carcinogenic degradation products of explosives may occur for a larger part of the year. In addition, the sympathetic effects of other pollutants, such as heavy metals, that are often associated with munitions (Gębka et al., 2016) and persistent organic pollutants (POPs) may further enhance the toxic effects of munition-related contaminants. The analysis of biomarkers for environmental stress in fish and mussels from the dump sites shows that chemical warfare agents (CWAs) and UXO act in a similar way on marine organisms; therefore the existence of other stressors can amplify the adverse effect.

5.16.1 Impacts of dumped military material on other factors

- Impacts on marine ecosystems (?) and effects beyond the local vicinity around the sources of contamination are largely unknown (Maser and Strehse, 2020). However, effects on the upper food web and consumable fish and shellfish have been shown (Maser and Strehse, 2021).

- Dumped ammunition sites can be dangerous for fisheries (+), and poisonous substances can cause fish diseases. Fisheries can be affected by fish health, diminished recruitment and consumer health. The consequences are largely unknown but may be significant. For example, the Bornholm Deep is a prominent dump site of warfare agents, and it is simultaneously the only functioning spawning area for the migrating eastern stock of Baltic Sea cod (Sanderson et al., 2008; Köster et al., 2017; Lang et al., 2018). There have been reports of fishing vessels being affected by dumped military material. In total about 200 fishermen were injured by exposure to chemical warfare agents since dumping (Sanderson and Fauser, 2015). Despite the fact that bottom trawling is restricted or not advised in chemical munition dump sites, trawl marks are present on the bottom there, some of them freshly made (Klusek and Grabowski, 2018). As conventional and chemical single munitions are located outside official dumping grounds, the risk of encounter still exists. Disturbance of munitions by trawling gear can both speed up munition casing breach and endanger crew by explosion or contamination.

- Dumped munitions may affect the development of offshore wind farms (+) as these installations need to be installed at a safe distance from dumping sites. This also holds for all offshore activities affecting the sea bottom (Appleyard, 2015).

- Chemical contaminant (+) concentrations can be affected by leaking substances from dumped ammunition at least on the local scale, as the poisons in question are largely organic substances. In addition, the sympathetic effects of other pollutants, such as heavy metals, that are often associated with munitions (Gębka et al., 2016) and persistent organic pollutants (POPs) may further enhance the toxic effects of munition-related contaminants (Czub et al., 2020).
- The management and treatment of dumped military material and unexploded ammunition may be an issue for coastal management (?) and maritime spatial planning, as allocating space for the construction of pipelines and other infrastructure needs to consider dumping sites. Actions may be necessary to cope with the consequences of leaking ammunition, which is generally offshore in deep basins, but sometimes closer to the coast (Frey et al., 2020; Maser and Strehse, 2020).

5.16.2 Knowledge gaps

Not much is known about the metabolic pathways of munition-related compounds in biota. This may lead to the underestimation of sublethal effects of those compounds. Further studies are needed to identify all the degradation products, their lifetime in the marine environment and toxicity thresholds of their metabolites. Many dump sites are unknown and may be in accessible coastal regions. Due to the scattered distribution of munitions in the Baltic Sea, further surveys and identification are needed to quantify the number of munitions that are not fully corroded and could create a source of contaminants for the Baltic Sea. Further questions are as follows.

- *Dumped military material – marine ecosystems.* How, to what extent, and when can impacts on marine ecosystems be expected?
- *Dumped military material – fisheries and aquaculture.* How substantial is the danger of released toxic substances for food production and humans?
- *Dumped military material – coastal management.* Is the fate and potential danger of unexploded ordnance in the dump sites an issue for coastal management? How is the management organized in dealing with this danger? How can modelling efforts help estimate the danger?

5.17 Marine litter and microplastics

Plastic litter has been recognized as a problem in the oceans since the 1970s, but public, scientific and political awareness has increased tremendously over the last decade. Plastic litter is generally categorized as macro- (> 25 mm), meso- (5–25 mm) and micro- (< 5 mm) litter. Larger particles (> 2 mm) can be easily sampled and implemented in cost-effective monitoring, meeting the requirements of the Marine Strategy Framework Directive (Haseler et al., 2019). Sampling, processing and analysis of smaller microplastics require a more elaborate procedure (Enders et al., 2020).

Plastic contributes the largest share of human-generated litter entering the oceans from both land and offshore sources (Derraik, 2002). Land-based litter sources include municipal, commercial, industrial, agricultural, construction and demolition activities (Barnes et al., 2009). Offshore sources encompass vessels or offshore platforms, lost containers from cargo shipping, fisheries, and marine aquaculture (Andrady, 2011; Derraik, 2002; Hinojosa and Thiel, 2009; Richardson et al., 2019).

In the Baltic Sea, litter dropped at beaches is a major source of larger micro- to macroplastics, including cigarette butts (Haseler et al., 2020). Regarding the smaller size fractions, municipal wastewater was identified as a substantial source for microplastics into the Baltic Sea (Baresel and Olshammar, 2019; Schernewski et al., 2021), especially storm water runoff including sewer overflow events, wastewater treatment plants (despite relatively good removal efficiencies) and untreated wastewater. Other potential sources of plastics that enter the Baltic Sea are marinas, agriculture, and industrial spills. Tire wear particles may form a considerable fraction of microparticle pollution in waters, but there is hardly any information on concentrations and impacts (Wagner et al., 2018). Generally, the polymers detected most frequently are the ones produced in the highest quantities, such as polyethylene and polypropylene.

The beaches of the Baltic Sea are significantly polluted with plastic particles, with reported numbers ranging from fewer than 10 to over 1000 plastic particles per kilogram dry weight (Urban-Malinga et al., 2020). An extensive survey of 190 sandy beaches across the whole Baltic Sea area yielded 4921 plastic particles > 2 mm, mostly industrial pellets (19.8 %), non-identifiable plastic pieces 2–25 mm (17.3 %) and cigarette butts (15.3 %) (Haseler et al., 2020). The Warnow estuary in the southern Baltic Sea, as an example of non-beach sediment, showed microplastic abundances (> 0.5 mm) ranging between 46 and 379 particles per kilogram dry weight, with concentrations decreasing towards the opening to the Baltic Sea (two particles per kilogram). The abundance of plastic floating on the water surface appears comparable to or lower than that in other world regions (Gewert et al., 2017; Tamminga et al., 2018; Rothäusler et al., 2019). Generally, distinct differences can be detected between areas with high versus low anthropogenic activity, with higher abundances of plastic particles and fibres close to major cities, freshwater discharges and beaches (Zobkov et al., 2019; Gewert et al., 2017). Simulations based on emission data for the Baltic Sea region indicate a relatively short average residence time of about 14 d for polymers (0.02–

0.5 mm) in the water body, assuming beaches as a sink for microplastics (Schernewski et al., 2020).

Microplastic in fish varies across the Baltic Sea and with fish species. Particles were detected in 3.4 % of demersal to 10.7 % of pelagic fish in the North Sea and southern Baltic Sea (Rummel et al., 2016), in 22 % of western Baltic herring (Ogonowski et al., 2019), and up to 1.8 % in different northern Baltic Sea fish (Budimir et al., 2018). Long-term microplastic exposure in early life stages of sea trout showed no effects on hatching rate, larvae survival or growth. Still, it generated nuclear abnormalities and chromosomal damage, indicating potential genotoxic effects (Jakubowska et al., 2020). Further data on ecotoxicological effects of microplastics on Baltic Sea biota are still rare. Methodological challenges exist, particularly for experimental studies targeting small microplastic fractions. In addition, environmental contaminants can mask microplastic-related effects.

Baltic Sea-wide investigations of microplastic-associated microbial biofilms and the potential of plastic degradation by Baltic Sea microorganisms indicate a low relevance of the interactions between microplastics and microorganisms (Kesy et al., 2019; Oberbeckmann et al., 2018). A specific enrichment of microplastics with potentially pathogenic bacteria, e.g. *Vibrio*, compared to natural particles does not occur in the Baltic Sea (Oberbeckmann and Labrenz, 2020). While some physiochemical properties of plastic beads changed significantly after exposure to bacterioplankton from the Baltic Sea (McGivney et al., 2020), the microbial degradation and metabolization of full plastic polymers are unlikely to occur in the Baltic environment at timescales relevant for human society (Oberbeckmann and Labrenz, 2020). Plastic additives or pollutants accumulating on plastic particles, such as polycyclic aromatic hydrocarbons (PAHs), are more susceptible to bacterial degradation. Evidence for PAH accumulation on plastic and subsequent degradation is still missing for the Baltic Sea.

5.17.1 Impacts of marine litter and microplastics on other factors

- The impacts of marine litter and microplastics on the marine ecosystem (?) are largely unclear as concrete data are rare. Health consequences of microplastics in higher trophic levels like fish and birds and ultimately humans are unknown to date. Large plastic particles and items like abandoned nets and lines can result in lethal entanglements or be taken up as food items as they resemble prey organisms, which then may cause starvation. It is not known what the frequency of such events is in the Baltic Sea. Ingestion of microplastics has been demonstrated for diverse marine species, ranging from zooplankton to bivalves and fish (Ivar do Sul and Costa, 2014), but ecotoxicological effects have not been shown so far. Research is hampered by methodological challenges, especially in the small microplastic range. Studies on Baltic Sea biota indicate indifferent or minor to genotoxic effects, but this is still very uncertain (Oberbeckmann and Labrenz, 2020). The same holds for open-cage and extractive aquaculture (?).

- The fishing industry (+) is affected by increasing public concern about microplastics. While microplastic uptake from other sources (e.g. plastic drinking bottles) is often neglected, the general concern is mainly focused on fish consumption. At the same time, the fishing industry is contributing to plastic pollution with lost fishing gear. There is little information on abandoned fishing gear in the Baltic Sea (e.g. Richardson et al., 2019), but it has been attributed as one of the largest sources of plastic in the Pacific (Lebreton et al., 2018).

- As any naturally occurring particles in the water column, plastic litter particles can accumulate chemical contaminants (?) that adsorb or absorb on the particle surface (Endo et al., 2013; Rochman et al., 2013). PAHs were found to accumulate on plastic particles in contrast to natural control particles (Oberbeckmann and Labrenz, 2020), but this depends on both the type of plastic studied and the chemical assessed. It has been discussed whether such contaminants can enter the food web via uptake of microplastics, but so far there is no sufficient evidence (Koelmans et al., 2016; Galloway et al., 2017). However, phthalates which had been used as plastic softeners and which are identified as endocrine disruptors have been found to leach from certain types of microplastic (Paluselli et al., 2019).

- The presence of marine litter on beaches has an impact on the tourism (+) industry. Visible pollution can devaluate a touristic region and lead to a decrease in visitor numbers in the long term. Simultaneously, tourism was identified as a major pollution source on Baltic Sea beaches (e.g. pieces from fireworks and cigarette butts) (Haseler et al., 2020; Schernewski et al., 2018).

- There is presumably an impact on coastal management (?), as plastic litter should be included in existing strategies. Removing plastics from coastal areas has been shown to be more efficient than removing them from garbage patches in the ocean (Sherman and van Sebille, 2016). Plastic monitoring and beach cleanings are successful management tools to reduce plastic loads in the marine environment (Kataržytė et al., 2020; Haseler et al., 2020).

5.17.2 Knowledge gaps

Concentrations of plastic particles in the Baltic Sea are scarce and highly variable, due to challenging and not harmonized methodologies, and data on ecotoxicological effects of microplastics on Baltic Sea biota are rare. Methodological challenges exist, in particular for experimental studies targeting the small microplastic fractions, and due to environmental contaminants masking microplastic-related effects. Also, data on PAH (polycyclic aromatic hydrocarbon) accumulation on plastic and subsequent degradation are insufficient for the Baltic Sea. While considerable plastic emissions occur in the Baltic Sea, it is not clear yet how urgent and ecologically damaging the plastic problem in the Baltic Sea is compared to other environmental problems. Further questions are as follows.

- *Marine litter – chemical contaminants.* What is the impact of the different types of marine litter? For example, how are microplastic particles degraded down to macromolecules and what is the relevance for the release of organic contaminants of different types? What are these types of contaminants and what impacts could they have on ecosystems and harvestable food organisms for human use? Which substances are the most dangerous?
- *Marine litter – marine ecosystems.* There are many uncertainties about how and to what extent marine litter affects marine organisms, ecosystems and food webs.
- *Marine litter – coastal management.* How far are marine litter and its discharge and distribution patterns a subject for coastal management?

5.18 Tourism

The Baltic Sea region is an important destination for coastal and maritime tourism (Hall et al., 2009; Agarin et al., 2010). It is estimated that the region's tourism industry employs approximately 640 000 people, based on 88 million visiting tourists creating over 227 million registered overnight stays annually (Jacobsen, 2018). Geographically, the tourism industry in the Baltic Sea region involves the sea area, the coastal zone and the catchment area. The impacts of tourism are most concrete in the coastal zone and in the Baltic Sea itself.

The cruise tourism sector constitutes a relatively small part of the shipping industry, with approximately 5 % of total maritime traffic on the Baltic Sea (Polack, 2012), but it is growing fast (Więckowski and Cerić, 2016). As a result, the Port of Helsinki was the busiest international passenger port in Europe in 2019 with a total of 12.2 million passengers (Port of Helsinki, 2020). In general, the environmental impacts of cruises on the Baltic Sea are similar to shipping; they include the release of toxic materials from ship hulls, the release of black–grey water and air pollution (Jalkanen et al., 2021), but with a scale of several thousand passengers. In addition to direct impacts on the sea areas, cruise shipping creates significant environmental impacts on the coastal zone and especially in port environments and nearby urban structures. The key environmental issues in the ports and coastal areas relate to waste management, water and soil quality, noise, and air emissions such as nitrous oxide (NO_x) and particulate matter (Simonsen et al., 2019). According to the Organisation for Economic Co-operation and Development (OECD) report (Pallis, 2015), the key sustainability management targets for the handling of waste and garbage are the development of effective policies and practices (so-called port reception facilities). According to the report, it is estimated that a cruise ship with 3000 passengers (plus crew) produces 50 t of solid waste in a week, which is considerably more than a regular ship of comparable size.

Coastal and marine environments and their attractiveness are essential for the tourism industry and so-called "sun–sand–sea tourism" (Nilsson and Gössling, 2013). In the Baltic Sea region, the coastal zone provides opportunities for a variety of tourist activities, which are concentrated in designated resort areas, spas and also urban centres along the coastal line (see Smith, 2015; Jacobsen, 2018). The main tourism activities take place during the summer season and include sunbathing and beach activities, boating, fishing and second recreational homes. Winter season activities are based on spas, skiing and ice fishing (Hall et al., 2009).

Climate change affects both summer and winter season activities. Shorter and unstable snow and ice conditions reduce outdoor activities in the winter season without necessarily providing alternatives. In contrast, summer activities and resources are expected to benefit directly from a warming climate (Hamilton et al., 2005). Furthermore, there are already indications that, compared to the Mediterranean region, more temperate summer conditions may attract increasing numbers of coastal tourists to the Baltic Sea region, especially from northern Europe (see Rutty and Scott, 2010; Grillakis et al., 2016). In conclusion, coastal and maritime tourism in the Baltic Sea region is expected to grow above the global average in the future.

However, potentially negative impacts of climate and environmental change may evoke an image problem for marketing. This may contribute to a lower recreational value or impose real health risks, like a higher probability of extremes in weather conditions (e.g. heat waves or floods; Christensen et al., 2021) or more frequent and extensive mass blooms of blue–green algae (O'Neil et al., 2012; Hogfors et al., 2014). According to Schernewski et al. (2001), for example, the poor water quality "is the main obstacle for reaching the [tourism] development goals" in Pomerania, Germany. Indeed, algal blooms have had localized impacts on summer tourism in the Baltic Sea region, as the increasing periods of blooms have already resulted in restrictions of coastal zone uses in many countries and resorts. Based on a case study by Nilsson and Gössling (2013), which covered mainly tourists from Sweden, but also from Denmark, Germany, Norway and Finland, a significant share of tourists who have experienced algal blooms have shortened or even cancelled their holidays in certain coastal destinations. Moreover, the study indicated that algal blooms had an impact on the tourist's willingness to return to the same destination where they had experienced blooms during previous visits. Thus, the impacts of algae blooms in the coastal zone can be significant.

5.18.1 Impacts of tourism on other factors

- Tourism is one of the largest economic sectors in the world. The related individual and organized land-, sea- and air-based mobility comes with the cost of fossil carbon emissions, contributing to global climate change (+) (Scott et al., 2012; Nilsson and Gössling, 2013; Terrenoire et al., 2019). It is estimated that tourism contributes to about 8 % of global GHG emissions (Lenzen et al., 2018).
- Impacts on marine ecosystems (?) by tourism are not well studied in the region. However, cruise tourism produces similar underwater noise as shipping but on a much lower scale, as cruise tourism constitutes a very small part of the overall shipping industry on the Baltic Sea (Polack, 2012). It is unclear what kind of impact the current level of cruise tourism noise has on marine life in the Baltic Sea (see Hawkins and Popper, 2017; Jalkanen et al., 2018).
- Tourism is a land use form with localized impacts on land cover (+). In particular coastal resort areas are modified to fulfil tourist and recreational requirements, such as beach developments and golf courses (Kropinova, 2012; Cottrell and Raadik Cottrell, 2015). In addition, cruise tourism, ports and related transportation channels have an impact on urban structures (Pallis, 2015).
- Coastal zone and maritime tourism cause nutrient loads (+) that are mainly based on poorly regulated resort (accommodation and other services) wastewater management and cruise ships (Schernewski et al., 2001). Wilewska-Bien et al. (2016) estimate that the annually generated food waste on board ships in the Baltic Sea contains about 182 t of nitrogen and 34 t of phosphorus.
- Offshore wind farms (+) may form aesthetically disturbing elements for visiting tourists (Veidemane and Nikodemus, 2015). As offshore wind farms, coastal tourism and yachting will grow, the probability of conflicts may increase in the future.
- Shipping (+) and cruise tourism partially use the same port facility areas in some cases, which may have a positive impact on the development of port reception facilities for the sustainable management of waste (see Pallis, 2015).
- In particular coastal tourism activities create a substantial amount of traceable marine litter (+) (Lewin et al., 2020). Based on previous studies, macro- and microplastics are the dominant types of waste, in both the coastal zone and marine area (Balčiūnas and Blažauskas, 2014; Haseler et al., 2019; Rothäusler et al., 2019). Marine litter has an impact on tourist perception and satisfaction (Lewin et al., 2020).
- Tourism is a significant factor for coastal use and change, causing both pressures and possibilities for coastal management (+). Pressures are based on overdevelopment and unregulated growth of tourism activities (Schernewski and Sterr, 2002), but tourism may also have a symbiotic relationship with coastal management, which provides safety and stability for environments of touristic activity (Haller et al., 2011; Weisner and Schernewski, 2013).

5.18.2 Knowledge gaps

In the future, it is important to monitor and control pollution loads allocated to touristic activities, including the release of nutrients, litter, chemicals and oil. Multi-stakeholder governance and coordinated collection of sustainability management indicators are needed. Monitoring data are required both for the sustainable development of the tourism sector, consisting of a large number of enterprises of different sizes, and for planning mitigation and adaptation policies in the overall catchment area of the Baltic Sea. Further questions are as follows.

- *Tourism – marine ecosystems.* How does tourism in all its variations affect the different compartments of marine ecosystems?

5.19 Coastal management

Coastal management (including marine spatial planning and marine protected area management) is an integrating factor that is used to regulate human activities in the coastal zone and thus has a strong impact on most other coastal, and many marine, factors.

With respect to the physical environment, the term "coastal management" is often used synonymously with the provision of coastal defences against erosion and inundation (Pilkey and Cooper, 2014), most frequently using engineering approaches. However, plans and decisions made by environmental managers and decision makers per se may be considerable drivers of coastal change. Sometimes, management decisions can have a direct effect, such as when an approval is given for the construction of port facilities (Pupienis et al., 2013; Žilinskas et al., 2020) or a seawall, or the effect may be more indirect, through mechanisms of land use and maritime spatial planning (Zaucha, 2014), fishery allocations (Reusch et al., 2018) or river regulation affecting sediment supply.

Ideally, coastal management should be a reasoned, achievable and sustainable long-term response to coastal use and change that protects the environment and provides for the use and enjoyment of the coast by people. It should be forward looking, identifying how future human activities will interact with natural factors (wind, waves, currents, water levels, etc.) and processes (sediment transport, erosion, deposition, etc.) by providing a framework to assess, mitigate and minimize adverse impacts while promoting positive changes. However, very frequently the actions resulting from management become factors in their own right, resulting in further, often unintended changes. For example, the implementation of plans for coastal erosion "protection", sea defences and public infrastructure (e.g. ports), can change physical factors (waves, currents, etc.) and sediment transport, resulting in new morphodynamic equilibrium conditions that may be unwanted and unpredictable. Many such situations in the Baltic Sea are described in detail in Pranzini and Williams (2013), specific examples being the use of groynes that create downdrift effects and seawalls that result in upper beach loss.

It has long been known that manipulation of one part of a system can cause effects in other parts of the system, often in unexpected ways. This "law of unintended consequences" (Mottershead et al., 2016) has meant that many coastal management actions have resulted in unanticipated outcomes, some of which have been beneficial, but the majority of which have made the problem worse, or have created new problems. Negative unintended consequences are most frequently caused by ignorance, error, immediacy (e.g. to protect human life) or basic values (Merton, 1936) (e.g. private property rights, freedom of navigation, sovereign rights). Coastal management normally relies on the best available science, but also on social and economic needs and political expediency, things that are often incompatible.

The tools now available make the assessment of coastal projects much more reliable (e.g. Bagdanavičiūtė et al., 2019). Modelling tools such as the MIKE suite (DHI) and DELFT 3D suite can effectively alert managers to cases where management actions can result in consequences that must be considered further. If a project is expected to change the fluid motions, the coastal morphology or the natural sediment transport, unintended consequences may result, and these need to be foreseen and addressed. In most parts of the Baltic Sea, due to its small size and limited fetch, waves are generally of short period and length, with sediment transport being largely confined to quite shallow waters. Therefore, even small-scale projects, such as small boat harbours, can have significant coastal impacts.

As the understanding of coastal processes improves, negative consequences of actions should become less common, and the application of simple conceptual models, along with sophisticated tools that are now available, should result in better management. A bigger challenge, however, is the resolution of the conflicts between best practice and long-held societal values and practices. Coastal management must be undertaken with specific consideration of climate change, particularly sea level rise. Vitousek et al. (2017) pose the following question: can beaches survive climate change? They conclude that "the future of the coastline will be what we engineer it to be", thereby putting forward the view that coastal management actions may be the most significant coastal driver in the future.

5.19.1 Impacts of coastal management on other factors

- Coastal management decisions have a substantial impact on coastal processes (+) by changing sediment transport pathways, erosion management and coastal constructions such as groynes, seawalls and port infrastructure. A current and emerging coastal management factor influencing shorelines is the management of sand extraction, already a problem in the southern Baltic Sea (e.g. Uścinowicz et al., 2014).

- Submarine groundwater discharge (?) may be impacted by coastal management decisions or infrastructure which could have an impact on the coastal groundwater level and the conditions and obstruction of groundwater seeps.

- Coastal management can be expected to have an impact on marine ecosystems (?) as it affects the land–sea linkages, which are important for the terrestrial and riverine loads of nutrients and pollutants.

- Possibly, non-indigenous species (?) could profit or suffer from coastal management decisions, through the management or protection of certain habitats, or the deterioration of those habitats, by coastal constructions.

- Coastal management decisions may, directly or indirectly, affect land use (?), agriculture (?) and aquaculture (?) in coastal areas.

- Coastal management can have a considerable impact on fisheries (+) and fish stocks by regulating fishing grounds and deteriorating coastal habitats of fish species (Kraufvelin et al., 2018).

- There may be a connection between coastal management and river regulations (?) at least in the estuaries (e.g. Zedler, 2017).

- Coastal management, through maritime and coastal planning, regulates the allocation of space for offshore wind farms (+) (e.g. Chaouachi et al., 2017; Sobotka et al., 2021).

- There is a considerable impact of coastal management on shipping (+) through the construction of ports and wind farms, allocation of fairways, regulations, and marine protected areas from which shipping is banned. Areas are regulated by local authorities considering the protected areas defined, for example, in the Birds and Habitats Directives (92/43/EEC and 2009/147/EC) (e.g. Andersen et al., 2020).

- Dumped military material (+) is in some cases located in the coastal zone, although it more concerns terrestrial dump sites or solitary munitions resulting from military activities. In such cases, munition may be disturbed during the construction of coastal defences. In Germany, a special programme has been initiated to locate and remediate munitions in the coastal zone (BLANO, https://www.schleswig-holstein.de/DE/UXO/uxo_node.html, last access: 10 December 2021).
- Coastal management regulations are used in the management of marine litter (?).
- Coastal management has a strong impact on tourism (+), as the tourist industry is a major stakeholder in the competition for space in the coastal area (e.g. Nordstrom et al., 2007).

5.19.2 Knowledge gaps

Coastal management uses available mechanisms (plans, laws, regulations, engagement activities, etc.) to provide for the sustainable use of the coastal and marine environment. The knowledge gaps that apply to all natural and anthropogenic factors can therefore be summarized as follows.

- What data and analyses are needed to enable coastal management to be more effective and how can the required information be obtained?
- What tools and systems (such as decision support tools) are needed to enable decision makers to provide the best possible management for a sustainable Baltic Sea?
- Recognizing that the coastal impacts in the Baltic Sea do not respect borders, how can management mechanisms be integrated across jurisdictions?

6 Discussion

The industrial revolution and the subsequent developments like the industrial production of nitrogen fertilizers (Smil, 1999) have dramatically changed the world, with massive benefits for humans and concomitant detrimental effects like anthropogenic climate change, eutrophication, overfishing, pollution and others. There is a growing understanding that the connections between these intertwined factors must be addressed. Many publications have dealt with this complex issue on a general scale (differently termed multiple or cumulative effects, stressors, pressures, drivers), mostly using statistical analysis or modelling approaches to better describe the problem, or management procedures to cope with it (e.g. Crain et al., 2008; Halpern et al., 2015; Gunderson et al., 2016; Liess et al., 2016; Elliott et al., 2020; Gissi et al., 2021). Many investigations have focused on the harvestable upper part of the food chain, e.g. fish and their food resources (Boldt et al., 2014; Andersen et al., 2017; Stelzenmüller et al., 2018). The Baltic Sea region or parts of it have been treated by various investigations (Jutterström et al., 2014; Andersen et al., 2015; Reusch et al., 2018; Andersen et al., 2020). Indices have been calculated to quantify the different effects and interrelations (e.g. HELCOM, 2018a; Korpinen et al., 2012; Blenckner et al., 2021), and the work has also been incorporated into decision support systems or general advice for decision makers (Meier et al., 2012, 2014; Hyytiäinen et al., 2021). Studies concerning the Baltic Sea have identified eutrophication, hazardous substances, non-indigenous species and fisheries (Korpinen et al., 2012; Andersen et al., 2015; HELCOM, 2018a; Andersen et al., 2020; Blenckner et al., 2021) as the most detrimental factors, but also acidification and climate change (Jutterström et al., 2014).

Looking at our DPSIR analysis of the different drivers (Table 1), and our matrix analysis (Table 2a and b), it becomes evident that the pressures caused by climate change, food production, transport, energy production, industries and tourism have the largest impacts on the Baltic Sea region. Table 2b shows the different factors considered in this analysis, sorted according to the extent they are (actively) affecting others (left column) or (passively) being affected by others (upper row). Here we see that climate change, shipping and land use/agriculture have the strongest impact, while fishing, marine ecosystems and agriculture are most strongly affected. This semi-qualitative assessment holds for the Baltic Sea region but may be different for similar regions of the world, with different foci of human activities.

Human needs and values are the ultimate drivers determining the aggregate demand of different goods and services, strongly affecting the level of production, land use and environmental footprint of economic activities in the area (Fig. 5).

The decisions of consumers living in the catchment of the Baltic Sea region are particularly important for those agricultural products (such as dairy) that are consumed locally and not much exported or imported due to high transport costs. However, for many other products (including forestry and many industries), the global demand and the competitiveness of local industries determine the level of production. In addition to their role as consumers, citizens are voters that – through their representatives in city councils, parliaments and the EU – decide on environmental policies and technology standards required from industries. It is important to note that human activities drive environmental change both globally (e.g. climate change) and regionally (e.g. pollution of the Baltic Sea). However, climate change plays a particular role as it has an integrating effect on other factors. The main message from this analysis is that climate change represents the overarching factor, affecting almost all of the other natural and human-induced factors (Table 2b). For some we know the effects reasonably well (e.g. coastal processes, agriculture, aquaculture, fisheries); for others, we know little (distribution and fate of contaminants, microplastics and dumped ammunition).

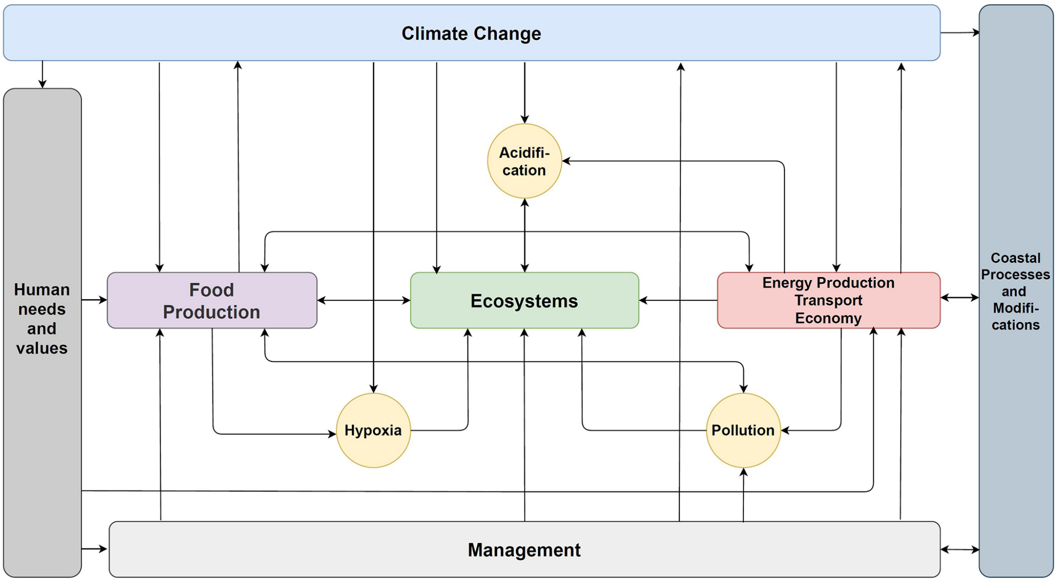


Figure 5. Schematic view of the interrelations between the different factors. Food production includes land use, agriculture and nutrient loads, aquaculture, and fisheries. Energy production, transport and economy include offshore wind farms, shipping and tourism. Coastal processes and modifications include coastal processes, submarine groundwater discharges and river regulations. Ecosystems include non-invasive species. Pollution includes contaminants, dumped military material and marine litter. Management includes technological approaches (Marcus Reckermann).

Food production on land and in the sea has severe consequences on the ecosystems, through nutrient loads and resulting eutrophication and hypoxia, but also on the climate, due to the conversion of forests to agricultural fields. More nutrients are distributed on the fields than crops can take up and convert into biomass. Artificial fertilizers are used in excess and incentives to adjust fertilizer inputs to plant needs are few. Livestock, i.e. pigs and cattle, excrete highly useable fertilizers, but this manure is mostly not used for fertilization, and use efficiencies differ largely between countries. The excess nutrients are largely washed to the sea where they have resulted not only in excessive algal growth, decay and oxygen consumption but also in increased fish stocks and catches. Fish stocks and fisheries have profited from the fertilization of the Baltic Sea in the mid-20th century (Adjers et al., 2006; Eero et al., 2016), and catches increased dramatically 8-fold over the course of the 20th century (Elmgren, 1989, 2021), mainly because of enhanced fishery methods and infrastructure, but also because of a heavily fertilized Baltic Sea. Fishing pressure and climate-related changes are presumably the main reason that some commercially used fish stocks broke down in the late 1980s (Dippner et al., 2008), but we do not know the effect of reduced nutrient loads on this breakdown, for which a reduction occurs concurrently. The efforts of nutrient abatements and regulations in the Baltic Sea, mainly though HELCOM, have been a success story (Reusch et al., 2018). Nutrient loads have been reduced since the 1980s (Gustafsson et al., 2012), but legacy nutrients (those that are hidden in the sediments and are released under certain circumstances) remain a problem, especially phosphorus (McCrackin et al., 2018b).

Offshore wind power production will presumably increase in the future, as the demand for renewable energy is growing in the effort to mitigate climate change, and extensive sea areas will be dedicated to wind power generation. A quick back-of-the-envelope calculation demonstrates this: to replace an average fossil fuel power plant of 2 GW, an area of about 15 km × 15 km must be assigned as a wind farm, assuming the currently largest wind turbines of 10 MW with a rotor diameter of 100 m and an estimated distance of 1 km between the individual turbines. This will be a challenge for marine spatial planning, increasing the political pressure to establish dual or multiple uses, e.g. with food production (aquaculture). Still, there are potential problems with efficiencies as large wind farms may experience self-shadowing effects and affect the micro-climate and potentially downstream ecosystems (von Berkel et al., 2020). Impacts on ecosystems may also be positive as the artificial reef effect may be beneficial for fish and eventually also for fisheries, even though fishing is banned from the wind farm areas. Underwater noise may be a problem for marine mammals or fish mainly during the construction phase. There is very little knowledge on marine noise impacts on marine mammals and other organisms. Offshore energy production also affects terrestrial land use as the energy produced offshore needs to be transferred to consumers over large distances (large power lines over land or in soils).

Gas and oil extraction (not treated in Sect. 5) is rather minor in the Baltic Sea, compared to other marginal seas like the neighbouring North Sea. Oil and gas production and transportation may have severe implications in the case of permanent spills and accidents (Hassler, 2011). Precautions include the use of double-hull tankers, safer shipping lanes and navigational aids (Moldanová et al., 2018), and possibly smart ship routing (Soomere and Quak, 2013). There are oil and gas fields in Polish and Russian (Kaliningrad region) territories, and oil terminals exist in the Russian part of the Gulf of Finland and in the Baltic states, so the Baltic Sea is a transfer region for oil and gas tankers to the markets of the world. Gas pipelines also cause environmental and political concerns (Nordstream 1 and 2; Heinrich, 2018), transferring gas from Russia to Germany. The Baltic Pipe Project (2021) planned for 2022 intends to provide the infrastructure for transporting gas from Norway to Denmark and Poland (Górski, 2020). Overall, the impact of oil pollution in the Baltic Sea so far is considered to be relatively low (Kostianoy and Lavrova, 2014; HELCOM, 2018a), and the number of oil spills has decreased over the past 20 years, presumably through monitoring and aeroplane and satellite surveys (HELCOM, 2018a), but the increasing volumes of surface oil transport gradually increase the relevant risk.

Maritime transport of goods not only affects the climate through the combustion of fossil fuel but also has many direct consequences for marine life and water quality. It was shown in the past that regulations work slowly but efficiently (e.g. double-hull tankers, ballast tank regulations, antifouling regulations), so a transfer to more sustainable shipping can be expected in the future. The release of chemical contaminants is also highly regulated, but the vast diversity of the different substances makes a thorough monitoring difficult, let alone the many unknown effects and reactions between the different substances, how they affect organisms and how a warmer and wetter environment affects concentrations and pathways and transfers and transformations between land, atmosphere and sea. Impacts on food webs and consequences for human marine food resources need to be constantly assessed and monitored as many new substances are released into the environment.

Marine litter originates from all human activities: offshore platforms, shipping, lost containers, fisheries, aquaculture, agriculture, municipal waste and tourism. A large fraction is carried to the sea by riverine runoff. The effects on the environment at least for the large size fractions are visible and well documented, but the effects of the micro- and nanosized particles down to colloid and molecular scales are largely unknown, as is the effect of their constituents on biota and the food chain. The toxicity to biota along the food chain up to humans and how microplastic particles remain inert over a long time horizon remain unclear. Degradation rates for some polymers are very slow, so that microbial degradation will presumably not be a big help in removing microplastics from the waters.

A legacy of human activity for which we do not know how serious potential impacts may be is the ammunitions of chemical warfare or dumped or unexploded ammunitions from World War II. These hazardous materials were deliberately dumped into the sea during or after the war. It is not known how dangerous these materials are beyond the very vicinity of the dump sites: is the dilution effect of any leaking toxic substances sufficient or are ecosystems and people living at the coasts and upper food levels including consumable fish seriously affected in the near future? Many containments are expected to corrode in the coming years and decades, so this is a large unknown threat with high damage potential. Whether we look at marine litter, microplastics, warfare agents or chemical contaminants, we see a low interference with other factors (including climate change) but a strong and direct impact on ecosystems (which are largely unknown) and on humans as the top consumer of marine products (Table 2b).

Climate change directly affects atmospheric and marine properties such as air and water temperature, precipitation, runoff, salinity, sea ice, sea level, and acidification (Table 2b). It affects the food production sector, as the growth of crops on land is temperature and water dependent, and in the sea, temperature is a significant growth factor for cultured fish and shellfish. Fish stocks are dependent on climate-sensitive availabilities of food organisms and stratification (Möllmann, 2019). In some cases, climate change affects different factors, which work antagonistically, and the net effect is not apparent. Sea level rise, for example, is expected to have a strong impact on the southern coasts and ecosystems of the Baltic Sea. Salinity (Lehmann et al., 2021) is an essential factor for marine life in the Baltic Sea, and many species live in narrow tolerance bands. Hence, it is vital to know how salinity will change in the future. It may increase through intensified inflows (as sea level rise would widen the passages in the Danish belts and sounds), but conversely, it may be reduced by increased runoff. Currently it is unclear which effect is prevailing (Meier et al., 2021a).

Certain regional factors may exert a feedback on the climate. Anthropogenic greenhouse gas emissions have been confirmed to be responsible for most of the warming of the past decades (Bhend, 2015), but apparently they cannot explain the warming completely (Barkhordarian et al., 2016). Other regional factors have been discussed, such as the decreased concentrations of aerosols in the atmosphere (Hansson and Bhend, 2015) and land cover changes (Gaillard et al., 2015). Regulations to reduce air pollution in the 1980s led to reduced aerosol concentrations in the air, and thus to a lower cooling effect through blocking of incoming insolation (Hansson and Bhend, 2015, Barkhordarian et al., 2016). Aerosol reductions are a strong candidate to contribute to the observed warming (or more precisely, to a reduced cooling effect on the regional scale; von Storch et al., 2021). This would mean that a successful mitigation effort to reduce dangerous human impacts would act to increase another one (climate warming). This once again shows how interwoven natural and human-induced impacts are and how they can work antagonistically on different factors.

Socio-economic factors such as population growth, urbanization, technological development, lifestyle and values play a significant role in developing the Baltic Sea and its coastal regions, more than the direct effects of the changing climate, but they are closely interwoven with it. A decision on land use may be primarily a socio-economic one, but it will be influenced by climate change and its impacts. Land cover also includes urbanization and sealed surfaces in urban areas. These have a high relevance for flooding as they exacerbate the flood risks in urban areas. The same meteorological event may have a low impact where soils can absorb water and distribute it downstream and via the natural aquifers, but it may turn into a catastrophic event for human infrastructure if the drainage systems below the sealed surfaces are too weak. Hence, extreme events may be exacerbated by human infrastructure. This is similar in the case of regulated rivers, where storm floods may run up higher and natural flooding areas are either embanked or sealed.

All these different factors and interactions create the need for management and policies, at their different facets. The different human claims to exploiting marine resources like fisheries, aquaculture, shipping and wind farms must be managed and balanced by preservative efforts (protective regulations, marine protected areas; Belgrano et al., 2021). While the goal of management is sustainability, it follows the needs of society (e.g. food production, energy and other resources from the sea, transport, coastal infrastructure and protection, tourism, inspiration), at the same time avoiding environmentally detrimental consequences. Coastal management needs to balance different opposing stakeholder interests and is a political rather than a scientific process in which scientists actively participate. The human benefit has been at the centre of most efforts, which is evident in concepts like “blue growth” (economic benefits from the sea) and “ecosystem services”, which perceive nature as a “service provider” for human welfare and development, rather than worth protecting for its own sake (e.g. Omstedt, 2020).

Marine protection can be justified by the need to secure the future provision of marine ecosystem services to benefit future generations. In this light, “ecosystem-based management” and “marine protected areas” also represent anthropocentric concepts, and the ultimate goal of management can be described as providing a fair intergenerational distribution of ecosystem services (and avoiding spoiling the resource). The UN Decade (2021–2030) of Ocean Science for Sustainable Development (e.g. Pendleton et al., 2020) provides an example where future coastal management may be heading, also in the Baltic Sea (see also United Nations, 2021).

The large sectors that provide goods and services to humans (food, energy, transport, recreation) have the most direct impact on the Baltic Sea environment. From a scientific point of view, it is not possible to render a verdict on the most harmful impact on the environment, as this is largely not a scientific but a social construction. Different stakeholders, e.g. scientists, coastal dwellers, people who make a living from the sea, local policy makers or environmental activists, may all have different conceptions. This is also the case between the different riparian countries (Lundberg, 2013; Martinez et al., 2014; von Storch, 2021). Science can provide the facts as far as possible to help establish and support management options.

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