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**Multiple drivers of environmental changes and their interactions in the Baltic Sea region**

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1. Synthesis and conclusions

**1. Introduction**

Antropogenic climate change has been regarded as a major driver for changes in the environment, which we have experienced since the industrial revolution and which we anticipate in the future. The IPCC has been the leading worldwide gremium to assess and document the currently available knowledge. On the regional scale, regional assessment reports have been written, talking the IPCC example to the regional scale. For the Baltic Sea region, two great assessment reports were published in 2008 and 2015, and the third is published here in a journal format. An outcome, especially of the second assessment, was, that, for the Baltic Sea region, a multitude of factors impacts on the environment, including climate change, and its effects *“are not straightforward and are difficult to distinguish from other human drivers such as atmospheric deposition, forest and wetland management, eutrophication and hydrological alterations*” (Humborg et al., BACC II, p 307). In this paper, we examine a number of different human drivers impacting on the coastal environment of the Baltic Sea region, and we assess what is currently known on the impact of climate change on these drivers, but also how they influence each other, as far as possible. The coastal zone, in this respect, is defined as the land areas, which have an impact on or are impacted by the coastal sea, and, vice versa, the sea areas that are affected by the land or have an impact on the land. The Baltic Sea is a coastal ocean, so coastal issues can be viewed here like under the magnifying glass.

The notion that the state and function of physical and living environments depends on different interacting factors, is old. Humboldt stated in 1807: *“In this great chain of causes and effects, no single fact can be considered in isolation. The general equilibrium obtaining in the midst of these disturbances and apparent disorder is the result of an infinite number of mechanical forces and chemical attractions which balance each other; and while each series of facts must be examined separately in order to recognize a specific law, the study of nature, which is the main problem of general physics, demands the gathering together of all the knowledge dealing with modifications of matter.”* (Humboldt and Bonpland 1807). More recently, this notion has evolved into larger, now generally accepted and used concepts e.g. “biosphere”, “biogeochemistry” (Vernadsky 1925, Lapo 2001) and “ecosystem” (Tansley 1935).

At least since the Neolithic Revolution e.g. the transformation from a hunter to a farmer subsistence, humans have shaped the earth´s surface, also in the Baltic Sea region (Lavento 2019). With industrialization and its related technological developments e.g. the Haber Bosch process to make nitrogen available for fertilzers (Erisman et al. 2008) and the general application of hygienic standard procedures (Cavaillon and Chrétien 2019), the human population has increased in such a way that it has become a dominant factor in shaping the environment (Lewis and Maslin 2015).

Here, we use the term “climate change” in the sense that it describes the human induced changes to climate. Although the natural climate variability is high in the Baltic Sea region, we can now detect a significant signal of anthropogenic warming in the region (Bhend 2015). The term “driver” here means any human-induced impact on the environment, which leads to a change in the state of the system. Indeed the term “global change” (or, “regional change”) better depicts 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.

Climate and other human-induced drivers are regionally very different, and the warming with its direct and indirect consequences (e.g. sea level rise, hydrological changes) sits “on top”, possibly affecting all natural processes, and may impact other drivers. Here we make an inventory of different human drivers including climate change, and how they interact. Some drivers may be completely independent from the warming; others may directly or indirectly be influenced by the warming. However, it should be mentioned that the list of drivers treated in this paper cannot be complete and should be updated continuously.

Feedbacks within the complex regional Earth system (e.g. the atmosphere, land surfaces, water bodies, biosphere, biogeochemistry, geology) may be complicated and difficult to disentangle, more so when human behavior (i.e. the anthroposphere) is involved (Gaillard 2013, 2015). The different drivers of change may affect each other, synchronously or cumulatively, creating negative or positive feedback effects. While the direct impact of an 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 with 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 like mono-cultural agriculture). In some cases, the local climate itself can be impacted by human-induced changes in the environment (e.g. albedo changes due to fortification or desertification, Gaillard 2015). Therefore, we are facing a complex system of effects and feedbacks between climatic and non-climatic drivers. Moreover, politically motivated management decisions, which have no or little natural scientific groundings, may have stronger impacts than natural ones and may be even more unpredictable than those (e.g. Lidskog and Elander 2012). Some projects have attempted to include human behavior into scenarios (e.g. BalticApp).

Complex analyses and modelling exercises have been performed to characterize the interactions between the different drivers (e.g. Crain et al. 2008, Liess et al. 2016, Robinson et al. 2018, Stelzenmüller et al. 2018, Gissi et al. 2021). The intention of this paper is to make a simple and rough inventory of drivers and connections, covering the above aspects as far as possible; information on individual drivers will have to be limited and just of overview character. The use of this paper, thus, should be to serve as an easily accessible introduction to this topic, with an emphasis on the Baltic Sea region, while most aspects can be transferred to similar marginal sea regions of the world. We would like to elaborate the relationships of the different factors with climate change on the one hand, and between the different factors on the other hand. As humans are heavily involved, socio-economic issues have a strong relevance on most “drivers” and connections described here. We emphasize on the marine realm but include the coastal zone with relevance for the sea, the “coastal continuum”. This kind of analysis and approach is particularly important for estuarine management that „requires an excellent understanding of the interacting, interrelated and interdependent sub-systems comprising ecological, societal and management complexity“(Elliott et al. 2020). So, we refer to factors in the sea, impacted by those from the atmosphere and the catchment.

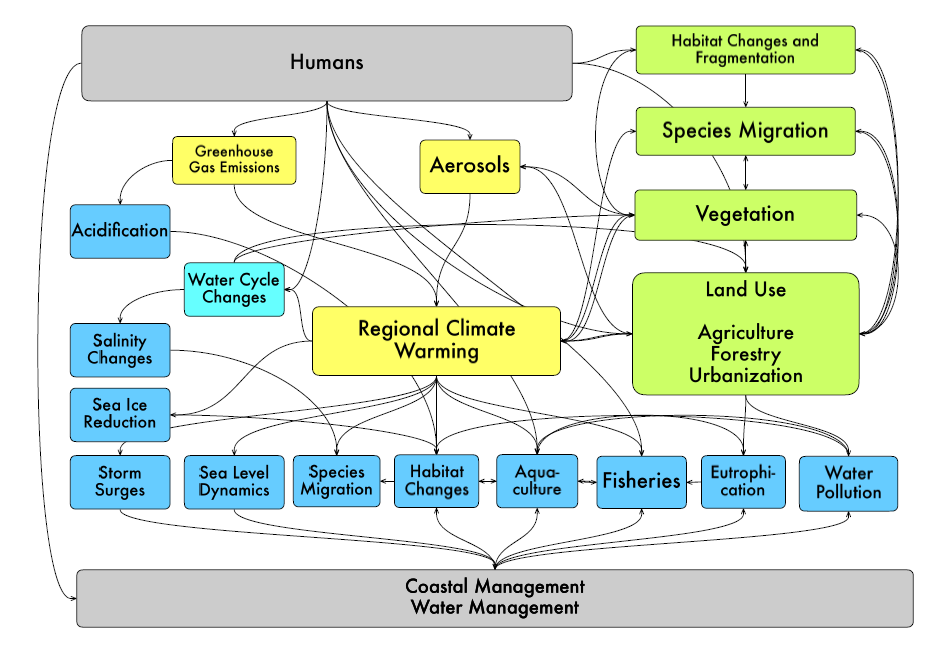


Fig. 1 Sketch of different factors in the regional Earth system and some of their possible interlinkages (from Baltic Earth Science Plan 2017, modified). For the sake of simplicity and accessibility, the sketch does not show all the parameters presented in this paper.

**2. Definitions of terms**

The tems *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 that each of the individual drivers, either immediately or (more frequently) over a longer time, which may not be the case for all combination 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 of the environmental changes (EEA 1999). However, a clear separation of these terms is often difficult. The term “climate”, for example, as such describes the state of long-term meteorological conditions, which have an influence on the environment. “Climate”, thus, in the DPSIR context, is a *state* but can also be a *pressure*, e.g. on phytoplankton growth, through cloudiness or temperature, if we define climate as the integration of all these single factors. “Climate change”, in our context, refers to anthropogenic climate change and is a *driver* and a *pressure*. It can also be a *response*, as the regional climate can change in response to anthropogenic factors like land cover (which is a DPSIR *state* and the result of a combination of natural and land-made land use, which is a DPSIR *driver*), or aerosols (Gaillard et al. 2015; Hansson and Bhend 2015). Thus, the concept of DPSIR causal links is useful but only insufficiently describes the roles and complex interrelations between the different factors (Gari et al. 2015). The changed condition of a *driver* can be the result of a *response*. We here refer to the general, integrative term *factor* to describe that they can be sometime *drivers*, sometimes *states* or *responses*, also to avoid confusion with the general use of these terms, which are less well defined.

Rather, we simply classify our parameters into two groups, loosely following Boldt et al. 2014 (Table 4): Environmental parameters which had been present also in the absence of 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-inigenous species. Then we have the pure human drivers: Offshore wind farms, shipping, fisheries, organic contaminants, dumped milititary material, marine litter and microplastics, underwater noise, tourism, agriculture, aquaculture, river regulations and coastal management. A clear separation is sometimes difficult (e.g. for land cover and land use, or underwater noise which had been there before humans appeared on the scene) but this is not relevant in this context.

The term *environment*, we here define in an integrative manner as the non-living, 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 like infrastructure at coasts or at sea, or agriculture.

**3. The impact matrix and descriptions of drivers and connections**

Core of our simple analysis is a matrix in which we try to give a qualitative (is there evidence for a connection or impact) and semi-quantitative (how strong is the impact) overview over the different connections between the drivers.

The text will give a brief characterization of the current knowledge of the drivers, and their interrelations, following the matrix. We try, as far as possible, to present evidence, i.e. references from the scientific literature, for individual links between drivers. However, we will also mention links which have not (yet) been confirmed in the scientific literature but deem plausible, not to rule out a connection which has not yet been described.

To allow a simple and comprehensive approach to the problem, we have established the matrix in which we show at a glance the impacts of the various factors on each other. The table is read as follows: The first column and the first line contain the different factors. The grade of interconnection is rated between one and three crosses (strong xxx, intermediate xx, weak x), as well as none (-) and unknown (?). This classification follows loosely the system of confidence levels of IPCC (2010), which integrates the more detailed evidence and agreement levels, but is kept simpler. Of course, this can only be a rough categorization and remains subjective to a certain degree, but we have tried to back our appraisal with references. Thus, the number of crosses refers to the strength of the interconnection according to the literature, but also reflects the amount of evidence, as we assume that a strong interlinkage is also reflected by strong evidence in the literature. Conversely, a weak relationship between factors is probably not the subject of many publications.

Thus, for the sake of simplicity we integrate the evidence and agreement levels into a simple 3-grade classification of “confidence” *(similar to EN Clime): strong, intermediate, weak*, augmented with the terms “no connection” and “unknown”. The latter may be an interesting one as it describes a connection, for which there is no evidence in the literature, but a connection cannot be excluded plausibly, and it may be worth looking at these question marks.

We have sorted the different factors to reflect, as much as possible, the DPSIR categorization in drivers (climate to shipping) and pressures (coastal processes to marine litter). The different factors and their connection with others, as well as to climate, are discussed in the text. The table is not comprehensive and many factors are obviously missing but it can be expanded with time.

**4. The region**

The Baltic Sea region has been subject to dramatic environmental changes since the last glaciation (BACC I). It has been strongly impacted by human activities since the withdrawal of the glaciers. Fishers, gatherers and hunters inhabited the coasts of the early Baltic Sea already 11,000 BP, and neolithic cultures practiced crop cultivation and animal husbandry around 6,000 BP. Deforestration and changes in forest composition have been documented since around 4,000 BP (Gaillard BACC II p463). Over the centuries, the human impact on the environment extended to more detrimental effects like pollution due to iron production (Lavento 2018). Now, the Baltic Sea drainage basin covers about 20% of the European continent, with roughly 90 Million people living in the catchment (ref). 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 sandy coasts and graded shorelines. A number of rivers enter the Baltic Sea, some of them with catchments covering more than one country, (HELCOM-BSEP163) draining nutrients and pollutants from the surrounding land areas into the Baltic Sea. Eutrophication has for many years been identified as a major threat to Baltic Sea, which has resulted in the implementation of the HELCOM Baltic Sea Action Plan (HELCOM xxx). Nowadays, a mix of natural and anthropogenic forces affects the environment, calling for management decisions to warrant both a stable ecological health and economic use (Jutterström et al. 2014).

*Map with drainage basin, rivers and country borders*

The natural variability in the region is very strong. In climatology, a 30 years period is generally needed to detect climate variations (WMO, reference), but for the Baltic Sea region, 90% of the variation already shows within a 15-year period (Omstedt et al. 2004). However, the anthropogenic climate signal is just beginning to emerge from the background noise (Bhend et al. 2015, BACC II). The natural variability in the region is very strong, and the anthropogenic climate signal is just beginning to emerge from the background noise (Bhend et al. 2015, BACC II). Parameters directly related to temperature, like ice extent or the seasonality of biota, show the most robust signals in climate-related changes (BACC I, BACC II). … For many other climate parameters, including; precipitation, wind, runoff and salinity, the signal is still small compared to the variability, precluding any conclusions about emerging trends.

In the following, we make a short description of the current state of knowledge of the various factors of regional change and their interrelations with climate and other factors, followed by a bullet list which refers to the matrix, trying to very briefly discuss the various impacts of the factor in focus on the other factors. We also make reference to the HELCOM Holistic assessment 2011-2016, and also to the ongoing EN Clime assessment work from which a comprehensive fact sheet will be produced. HELCOM has done pioneering work in describing the different drivers and stressors, and this paper is intended as a complement and addition of perspectives to the HELCOM work.

**5. Drivers of regional change**

**a. Regional climate change (Kjellström, Räisänen, Meier)**

Future global climate change depends largely on the sensitivity of the climate system in combination with the radiative forcing imposed by changing greenhouse gases, aerosol particles, land use etc. On regional scales, climate change depends both on regional and local climate forcing factors and on changes in the large-scale circulation of the atmosphere and oceans. The latter can be a result of long-term global change but natural variability on decadal/centennial time scales is also of major importance in this context (Hawkins and Sutton, 2009). All of the above-mentioned factors are associated with uncertainties that make detailed predictions of future climate conditions difficult. The most widely used approach to deal with these difficulties is the use of large ensembles of climate model projections (e.g. IPCC, 2013). A large number of simulations in such ensembles yield a spread that may be used to address the uncertainties: use of different climate models reflect uncertainties in the sensitivity of the climate system; use of different scenarios reflect uncertainties in the future forcing conditions; and use of a large number of simulations reflects uncertainties in natural variability.

As the future is highly uncertain, scenarios for the future are designed to represent a wide range of forcing conditions. In the scenarios assessed by the AR5 (IPCC 2013), four different Representative Concentration Pathways (RCPs) are considered: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The numbers indicate the radiative forcing (in W m-2) at the end of the 21st century, relative to that of preindustrial conditions.

The large spread between different simulations reflects the combined uncertainty between global climate sensitivity, regional response and natural variability. Strong future changes are projected for the climate in the Baltic Sea region. Wintertime changes in the **air temperature** climate are one of the strongest climate change signals in Europe, with approximately 2-6°C for winter (December-February, IPCC, 2013). These numbers are ensemble means with the lowest number (2°C) associated to the weakest forcing (RCP2.6) and the highest one (6°C) with the strongest forcing (RCP8.5). Results from individual climate simulations show a larger spread with 3-10°C for RCP8.5 and -2 to + 4°C for RCP2.6. It is especially pronounced in the northernmost parts of the region as a result of the feedback process involving retreating snow and ice conditions in a warmer climate leading to lower albedo and more efficient heat exchange between the atmosphere and the surface. In summer, strong warming is also projected in the south by many climate models as a result of feedback processes involving decreasing soil moisture. Corresponding ensemble mean numbers for summer (June-August) are 1-5°C, again with large spread between individual members for each scenario. Still, it is clear from the scenarios that a continuing warming is almost certain.

For **precipitation** and wind, the uncertainties are still 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. Also for **wind**, projections for the future vary considerably, so that no clear trend can be identified. (Räisänen 2017, Christensen and Kjellström 2018)

The regional climate change in the Baltic Sea region is strongly dependent on variability and change in the large-scale atmospheric circulation in the North Atlantic and European sector. One prominent feature of this variability is the North Atlantic Oscillation (NAO) with its two modes with either stronger or weaker zonal winds. The positive NAO phase with stronger zonal winds is associated with mild wintertime conditions and high precipitation over parts of the Baltic Sea region. Contrastingly, the negative phase with weaker zonal circulation is associated with relatively colder conditions and less precipitation. Long-term changes in the phase of the NAO may therefore act either to reinforce warming on the regional scale, when there is a shift from a negative phase to a positive phase, or to attenuate it, when a positive phase is replaced by a negative one. 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 (e.g. Deser et al., 2012; Maher et al., 2019).

**Sea water temperatures** have already begun to increase, both at the surface and in deep waters of the Baltic Sea (Lehmann et a. 2011, Elken et al. 2015, Mohrholz et al. 2006), and are projected to increase further. According to the results from 48 scenario simulations, volume averaged water temperatures at the end of the century will be 1.3 to 2.2 °C (RCP 4.5) and 3.0 to 4.2 °C (RCP 8.5) higher, compared to the ensemble mean water temperature for the historical period (Meier et al 2020). The increase in SST is projected to be largest in the northern Baltic Sea during early summer, very likely due to the ice-albedo feedback causing earlier warming during the melting season. As the surface layer is expected to experience a stronger warming than the deep layer, the strength and possibly persistence of the seasonal thermocline would increase, leading to reduced vertical nutrient fluxes from the bottom into the biologically productive surface mixed layer. In addition to the ice-albedo feedback, also a decrease in thermal convection (Hordoir and Meier, 2012) might contribute to the earlier warming in the northern Baltic Sea. All available scenario simulations for **sea ice** suggest a drastic decrease in sea-ice cover in the future (Luomaranta et al. 2014, Meier et al. xxx, 2015). However, even the extreme scenarios do not suggest a complete disappearance of sea ice in the northernmost part of the Baltic Sea.Due to a projected increased freshwater supply from the catchment area by about 1 to 21% at the end of the century, surface and bottom **salinity** is projected to decrease by about 0.6 g kg-1 in the ensemble mean with a large spread among the ensemble members (Saraiva et al., 2019). A reduced overall salinity would cause a reduced stratification between surface and deep layer in the Baltic Sea causing improved ventilation of the bottom layer and in some sub-basins such as the Gulf of Finland, with a hypothetical increase in bottom oxygen concentration (Meier et al. 2011b). Hence, warming and freshening of the surface would have contrasting effect on stratification. It remains to be seen which effect is stronger. Assuming a negligible impact of global mean sea level rise which is relatively small in the Danish straits at the entrance to the Baltic Sea (Mitrovica et al. 2001), there would be no drastic changes in the intensity and frequency of **Major Baltic Inflow***s*(Schimanke et al. 2014).

**Impacts****of the regional climate on other anthropogenic drivers**

The term “driver” is defined in a simple way as something affecting or being affected by another force. In this respect, climate can be the force affecting other drivers, e.g. land use. On the other hand, (regional) climate may be affected by other drivers, e.g. land use or shipping. So we will try to describe this two-way dependency, wherever this is plausible and has been described in the literature.

* Climate change affects the air and water temperature as well as precipitation, so there is a clear impact on **land use** and **land cover (\*\*\*)**. Growth conditions on land and the vegetation zones are affected by changing temperatures and precipitation patterns (***ref***), but also by political or management decisions, which in turn may or may not be influenced by climate change (***ref***). Higher temperatures and CO2 concentrations in the atmosphere lead to a thriving vegetation, but declining water availability, presumably in the southern parts of the region, sets limits to this (BACC II ref). There is evidence that **land use and cover** can have an impact on the regional climate, through geophysical and biogeophysical effects. Albedo, i.e. the reflectance of the land surface has an effect on the amount of energy reflected back into space and the fraction, which is converted to warming. Bright surfaces like agricultural lands reflect more energy than dark surfaces as forests and waters. Thus, the fraction of land cover may have an effect on the regional warming (Strandberg et al. 2014, Strandberg and Kjellström 2019. There is also evidence that an increase in CO2 concentrations leads to an increase in vegetation (biogeophysical effect), at least in regions where water is not a limiting factor, i.e. the northern part of the Baltic Sea basin (BACC I). The decisions which part of land is dedicated to agriculture is very much a management and political decision, which in turn can 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 to water availability and soil type (***ref***). So, any changes in temperature and precipitation may lead to the need for better adapted crops as a response (Fronzek and Carter 2007). Still, socio-economic considerations may be still more important in defining the type of agricultural land cover than climatic ones (ref. BACC I p224).
* Inland shipping and water managementhave resulted in **river regulations** since centuries, and the hydrology of many catchment basins, including the Baltic Sea, is heavily modified. Increasing droughts with lower river water volume at certain times of the season may have an impact on 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 (*References*)
* **Coastal management (\*\*\*)** as the process of reactively mitigating problems in the face of multiple uses of coastal spaces and services is strongly challenged by climate change (Sanchez-Argilla 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 changed 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 (DiSegni 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 only (Czajkowski et al., 2015) and coastal biotopes are under pressure as well (Harff et al., 2017; Vitousek et al., 2017; Vousdoukas et al., 2020).
* 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 wind farms are, at least partly, a politics (management) response to mitigate climate change. With increasing mitigation activities worldwide, we can expect a considerable increase in offshore wind energy production. 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, the number of wind farms can be expected to increase in the future due to a politically driven shift to renewable energies and the limited space and low acceptance on land. 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 of the magnitude of this effect (… *references*).
* There is a wealth of evidence that **shipping (\*\*\*)** is heavily impacted by climate change. Perils at sea for ships are all climate sensitive, ranging from storms, waves, currents, ice conditions, visibility to sea level affecting navigational fairways. Winter navigation is less impeded as a drastically decreasing winter sea ice cover is projected, but as strong ice winters 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 shipping is impacted by floods and depth changes of rivers, 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 SOx concentrations in air emissions by large ships involve the scrubbing, i.e. the stripping of the contaminated combustion air with sea water. 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)

There is good evidence that climate change has a strong impact on coastal processes (\*\*\*), though sea level rise on coastal erosion (Defe o et al., 2009) and the translocation of sediments through erosion, currents and accretion (Slott et al., 2006). A considerable reduction of sea ice increases erosion rates at soft shores (Orviku et al., 2003; Over eem et al., 2013; Farq uharson et al., 2018). Due to the large variability in observations and projections, there is no clear indication for potential changes in storm frequencies, severity and tracks in the Baltic Sea region, except for changes to a few modelled storm-driven aspects such as water level extremes (Pindso o and Soomere, 2020) and potential sediment transport patterns (Soomer e and Viška), so their impact on coastal processes remains speculative.

* Climate change changes precipitation and runoff patterns from agricultural fields and thus largely determine 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 and the south drier (BACC II). 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. However, there is currently no consistent, catchment-wide model of nutrient source apportionment (BSEP 153), so it is difficult to assess which sources dominate in different sea sub-basins. 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 (**ref**, Juris). Climate-related changes in the Baltic Sea like warmer temperatures, changed stratification patterns and altered ecosystems and biogeochemical pathways may change the fate of nutrients in the sea (*Meier et al, Ecosupport, BalticApp*).
* **Submarine Groundwater Discharge (?)** has only recently been considered as a potential factor to affect coastal waters. There is not much evidence that there is a direct impact by climate change on the quantity and quality of these submarine discharges, but looking at the driving forces of SGDs, this is highly plausible. Driving forces of SGD involve topography-driven flow, tidal pumping, wave set-up, precipitation, sea level rise and convection caused by salinity and temperature between the seawater and groundwater. Changed groundwater levels (lowering in dry seasons, or rising at times of strong precipitation) may be the effect of changed precipitation patterns and higher temperatures leading to stronger evaporation. As climate change is expected to affect most of the above-mentioned drivers, consequently it can also be expected to effect SGD. The magnitude and relevance of these changes, however, remain largely speculative. *Refs*
* **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. Climate affects salinity and temperature, which in turn affect the reproduction and growth of several fish species (MacKenzie and Köster 2004, MacKenzie et al. 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 are regulating zooplankton dynamics (Casini et al., 2011; Köster et al., 2017). Climate effects are also closely connected to the effects of eutrophication, which in combination determine the oxygen conditions in the Baltic Sea, affecting the organisms and fish production in several ways. 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 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 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 little direct evidence. Shipping through ballast water or attachment to hulls or the disappearance of physical barriers (e.g. though the construction of canals between separated water bodies) has been identified as a major vector 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 changed climate can provide favourable growth conditions in the target region, e.g. though changes in the composition of prey (Möllmann et al. 2005), temperature and salinity. 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. Still, a northward migration of land (Smith et al. 2008) and marine species like fish have been observed and are expected for the future (McKenzie et al. 2007, Holopainen et al. 2016).
* Direct effects of climate change on **contaminants (\*\*)** include an array of processes. Changing environmental temperatures affect diffusive partitioning between environmental phase-pairs such as air-water, air-aerosols, air-soil, air-vegetation, leading to a different distribution between environmental compartments, like increased volatilization from seawater to air (Macdonald et al., 2003). 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, Macleod and Cousins, 2014). Changing precipitation patterns influence chemical transport via atmospheric deposition (rain dissolution and scavenging of particles, Armitage, Quinn and Wania, 2011) and runoff, transporting terrestrial organic 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). A reduced ice cover in the coastal zone allows 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 (Beldowska, Jedruch et al. 2016, Beldowska and Kobos 2016). As a result, a greater load of Hg can be remobilized from sediment to benthic organisms (Bełdowska 2015 (Beldowska 2015, Beldowska, Jedruch 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 the reduction of toxic metal emissions, as compared to colder winters (Beldowska, Saniewska et al. 2014, Beldowska 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 advanced corrosion of hulls. This process may also 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 a good ventilation of dumping sites can be expected to enhance corrosion rates (Silva and Chock 2016). Also, warming can significantly affect munitions in shallow waters, which were mostly used as dumpsites for conventional warfare material. There, ammunition shells as hard metal objects as substrates for colonialization 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 (Szubska 2020).
* There is no evident direct impact of climate change on **marine litter** or **microplastics (?)**, but there may be a connection via increased temperature- and photolysis dependent degradation and dissolution rates of microplastics, and on the distribution due to changed currents.

**b. Sea level (Zorita)**

The Baltic Sea, as a semi-enclosed marginal sea, is influenced by both the North Atlantic and its neighbouring landmasses. Its location at mid-to-high latitudes, its energetic atmospheric circulation and seasonal presence of sea ice may affect long-term sea level projections (**Reference**). In addition, future trends in Baltic Sea sea-level will be mostly influenced by melting of land-ice in Antarctica and other remote regions, and very little by the melting of neighboring land-ice in Greenland (Mitrovica et al. 2001). Vertical land movement has had a strong impact on the past evolution of relative sea level in this region, and currently it represents a source of uncertainty for the estimation of future coastal sea level rise. To understand sea level variability and its projections, we need to look at different factors.

In general, the interannual variability of Baltic Sea sea level is driven by the sea level in the Eastern North Atlantic (Börgel et al. 2018). However, the spatial distribution of sea level within the Baltic basin is modulated by other regional factors, the most important of which is the atmospheric circulation (Graewe et al. 2019). Strong westerlies usually cause higher sea levels in the North and North-East of the basin and more weakly in the south (Hünicke and Zorita, 2006). Also, persistent areas of lower or higher atmospheric pressure cause the sea level to rise or fall there (barometric effect). In addition, winds are also related to the advection of heat through the atmosphere and consequently to modify atmosphere-ocean heat fluxes. These may also warm or cool the water column and thus change the water density and sea level.

Baltic Sea sea level will also be affected by the warming of the global ocean. Although the Baltic Sea is rather shallow and the thermal expansion of the Baltic water column would cause a rather limited sea-level rise, water masses from the North Atlantic will protrude into the Baltic Sea as they warm and expand.

Another important driver for the rising level of the world oceans is the melting of glaciers and of polar ice sheets. Much more uncertain is the contribution of the polar ice sheets, since the total rate of melting is caused not only by surface melting but also by the flow of solid ice into the ocean. This flow is affected by subtle regional factors, like topography and ocean temperature (especially in Antarctica). Models of ice sheet dynamics are still not sophisticated enough to provide an accurate picture under different warming scenarios. Currently, the future rates of polar ice melting have been estimated by meta-analyses of expert judgment, rather than strictly by physical models (Bamber et al. 2019).

The melting of the Greenland ice sheet will barely have consequences for the Baltic Sea sea level, whereas the most important factor by far will be the melting of the Antarctic ice sheets. This somewhat counterintuitive phenomenon is due to the self-gravitational effect between ice masses and water masses of the ocean. When land-ice dissapears, its gravitational pull of the surrounding water masses disappears as well, causing sea level to fall nearby and rise further away. Regarding the Baltic Sea, the melting of the Greenland ice sheet and the gravitational effect cancel each other, whereas for the Antarctic ice sheet, both reinforce each other (Mitrovica et al. 2001).

Putting together both the thermal expansion of ocean water and the global meting of land ice sheets, an absolute Baltic Sea sea-level rise was estimated to an average of 80 cm, using the pessimistic of greenhouse gas emission scenario RCP8.5, with a very likely range between 30 and 160 cm by year 2100 (Grinsted et al. 2015). However, the absolute sea level rise must be combined with the large vertical movement of the land, caused by postglacial rebound of the land crust in northern and central Scandinavia, to obtain projections of coastal sea level changes. In the Bothnian Bay, the rising velocities attain magnitudes in the order of +10 mm/year, whereas at the southern Baltic Sea coast the land sinks slowly at rates in the order of -1 mm/year (Richter et al. 2012). These values have to be added to the projected rise of absolute sea level. Consequently, even in the high RCP8.5 scenario, coastal sea level continues to sink north of about 60°N throughout the 21st century, whereas it will continue to rise south of this latitude, or flip from sinking to rising at some point in the 21st century.

Finally, a driver of sea level that may potentially play an important role is the salinity of Baltic Sea waters. Today, the Baltic Sea is a brackish sea with rather low salinities of a few units in the north and northeast, reflecting the riverine input. In contrast, in the Skagerrak at the exit to the North Sea, salinity is at approximately 33, close to the oceanic mean value. Lower salinities and strong westerly winds cause higher sea levels in the eastern and northern basins by about 20-30 cm (**Reference**). Should salinity change in the future (due to more evaporation caused by warmer temperatures or due to more precipitation), or should the strength of the westerly winds also change, the sea level gradient can accordingly respond to that change. In extreme scenarios of future climate change, average Baltic Sea salinity could drop by about 35% (Meier and Kauker, 2003), resulting in a sea level increase by a few centimeters. However, climate model projections of precipitation and wind change are regionally not robust so that they must be considered highly uncertain. Wind strength may increase or decrease (Shepherd, 2014). Precipitation is projected to increase in the northern Baltic Sea region and decrease at mid latitudes, but climate models do not generally do not agree on the amplitude of these changes nor on the latitude separating increases and decreases. Nevertheless, some authors locate this line between 45°N and 60°N (Collins et al. 2013, Kjellström et al. 2018).

**Impacts of sea level on other anthropogenic drivers**

* There is avery strong impact by sea level change on **coastal management (\*\*\*)** and defense structures, and generally on the management of low-lying coastal regions, so that a “do nothing” approach eventually is inappropriate (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. It is interesting to compare different management approaches between different countries, and between the southern and the northern regions, which have different urgencies towards sea level rise (high, rocky coasts and land uplift in the north; low sandy coasts, soft cliffs and a slight land subsidence in the south) **(refs)**
* Rising sea levels may have an impact on **offshore wind farms (?)**, but they are probably not affected directly by sea level rise as there is presumably a sufficient safety margin calculated for storm surges within the life span of a structure; **References?**
* Impacts by sea level change on **shipping** (\*) include for example partial loading of vessel cargo capacity if water level is low. Shallow passages may also get deeper and wider in the future, depending on the balance of sea level rise, changes in rainfall, flooding and postglacial rebound of seabed, especially in the northern parts of the Bothnian Bay. Harbors and docking terminals will need to be adapted to variable higher water levels. **(refs)**
* Sea level rise may have an impact on **nutrient loading (\*)**, at least the internal loading of phosphate, through potentially increased salt water inflows in the future with rising sea levels, increasing the hypoxic areas in the deep water and the associated phosphate release, to a considerable extent in the high (+1m) scenarios (Meier et al. 2017).
* With increasing sea level rise, **coastal processes (\*\*\*)**, i.e. erosion and accretion processes, are expected to increase considerable at vulnerable coasts. In general, coasts are expected to be subject to stronger changes through increasing sediment translocations with rising sea level. **(refs)**
* A changed sea level and associated larger cross section in the Danish straits may have an impact on the volumes of future Baltic inflows of high saline waters; this may have an impact on **hypoxia (\*)** in the large basins through stronger salt-water inflows and associated stronger stratification in the deep basins (Meier et al. 2016). 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.
* There may be an effect of rising sea levels (and geostatic land rise) on **submarine groundwater discharge (\*)**. However, it is hard to project the direction and significance of the change due to missing data and investigations **(refs).**

**c. Coastal processes (Soomere)**

About half of the shores of the Baltic Sea are sedimentary and thus susceptible with respect to different hydrometeorological loads. The other half 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 (http://www.emodnet-geology.eu/). Many shore segments exhibit rapid retreat rates that may have large impacts on the coastal infrastructure and cause extensive loss of land.

While the most massive (alongshore and cross-shore) sediment transport in the nearshore (surf and swash zones) takes usually place during extreme wave events, the most rapid shoreline changes (both erosion and accumulation) occur when high waves attack the shore in unusual location under relatively large angles. This happens during high storm surges when waves impact on unprotected sediment.

The hydrodynamic forces particularly effectively reshape the shore when no ice is present and sediment is mobile (Orviku et al., 2003; Ryabchuk et al., 2011). No ice means no protection against severe waves and high water levels. Storm surges are much higher during ice-fee time than on the shore of even partially ice-covered water bodies. Particularly dangerous are thus situations when strong waves reach unprotected and unfrozen mobile sediment during extreme storm surges in higher sections of the shore that is out of reach of waves during usual water levels (Orviku et al., 2003).

Technically, the major supplier of energy to the nearshore and the driver of sediment transport are surface waves. Even quite small waves contribute to sediment transport processes. The most intense alongshore and cross-shore sediment transport usually occurs place during very strong wave storms. However, most of the erosion of shores occurs during short time intervals when high waves approach the shore from an unusual and unfortunate angle and attack the unprotected sediment during short term elevated average water level events. The properties of this energy supply and the resulting wave-driven transport in large parts of the Baltic Sea shores are described in (Soomere and Viška, 2014; Kovaleva et al., 2017; Björkqvist et al., 2018) and generalised to the entire Baltic Sea context in (Hünicke et al., 2015; Harff et al., 2017a,b).

Such events are infrequent in the Baltic Sea that host highly intermittent wave climate. On the one hand, as little as 1% of the total annual energy arrives within the calmest 170–200 days. On the other hand, 60% of the annual energy arrives within 20 days with relatively high waves and as much 30% of the energy within 3–4 most stormy days (Soomere and Eelsalu, 2014).

A simple consequence from this kind of intermittency of wave fields, anisotropy of wind patterns, and the complicated geometry of the shoreline is that the evolution of the Baltic Sea shores is a step-like process. A few events of rapid changes (when strong waves arrive from a specific direction during high water level events) occur on the background of very slow changes (that cover most of year and require high-resolution measurements to detect; Eelsalu et al., 2015).

An important consequence is that the properties of single storms and the timing of storms in sequences become decisive in the evolution of the coast.

Potential changes in the intensity and/or direction of wave-driven processes at the shore impact many parts of the society. The potential additional sedimentation of fairways and river mouths or and erosion of shores at built environments have direct economic consequences. The loss of stability of beaches may ruin communities that offer recreational services. Unexpected changes in the transport system may lead to, e.g., intense cross-shore transport of very fine sediment to vulnerable areas such as spawning areas, with substantial consequences to fish stock.

Changes to the sediment flux from rivers may have both positive and negative impact on the functioning of the shores. Reduction of ice cover and shorter time under freezing temperatures will lead to more wave energy to the surf and wash zone and apparently cause more intense sediment displacement. Modelling of the related changes is a great challenge.

In essence, many Baltic Sea shores should be very vulnerable because of small amount of sand on these young coasts that usually suffer from fine sediment deficit but are mostly open to quite large hydrodynamic loads. Still a number of beaches of the Baltic Sea are explicitly or implicitly stabilized by the (mis-) match of the directions of predominant strong storms and geometry of the shoreline: they are relatively infrequent hit by storms and may have stable sections in bay heads. As waves in the Baltic Sea are relatively short, the surf zone is narrow and wave run-up phenomena less powerful than on the open ocean shores. Postglacial rebound in some parts of the sea additionally stabilizes the affected beaches. As a consequence, many Baltic Sea beaches with very small amount of sand are in a fragile 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).

**Impacts of coastal processes on other anthropogenic drivers**

* Coastal erosion can affect **land use (\*\*)** close to the coast, beaches and land use close to endangered cliffs; accretion can generate new sand spits and on a long time scale the morphology and its associated land use are subject to change. **(refs)**
* Similarly, it can be significant for **agricultural (\*\*)** fields and forests very close to the sea or a cliff endangered by coastal erosion. **(refs)**
* Coastal processes can possibly have an impact on **river (?)** mouths and estuaries, and the associated sediment distributions in these river mouths... **(refs)**
* There is obviously a very strong impact of coastal processes on **coastal management (\*\*\*)**; coastal processes like erosion, sediment translocation, accretion etc. are the primary driver for coastal management, which is the provision of coastal defenses against erosion and inundation by engineering and planning. **refs**
* **Offshore wind farms (\*)** can be affected by coastal processes if they are lose 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 (*ref*), and the sediment distribution in lee of the wind turbines (**ref**)
* There is a large influence of coastal processes on **shipping (\*\*)** routes close to the coast, currents, the generation of shallows and sand spits into fairways, resulting in re-location and the need for dredging of fairways (**ref**)
* Coastal currents have an effect on the distribution of land-borne **nutrients** **(\*)** (e.g. near coast currents in the Pomeranian Bay, distribute Oder plume very close to the Pomeranian coast to the east, hardly any mixing with open bay waters (TRUMP, **ref**)
* Coastal current systems may possibly have an influence on local **hypoxia (?)** in coastal embayments… **(refs?)**
* There may be an impact of coastal erosion, especially of limestone on alkalinity and **acidification (?)** in some regions, but then maybe this is a complete river-borne effect… **(???is that so? Refs?)**
* Apparently, **submarine groundwater discharge (\*\*)** can be defined as a coastal process, and it is very much impacted by other coastal processes like topography-driven flow, tidal pumping, wave set-up, sea level rise and currents **(ref).**
* There may be an impact of coastal processes on coastal fish habitats and **fishing (?)** grounds… **(explain and refs)**
* Coastal processes may an have impact on **non-ingenous species (?)** that have chosen coastal habitats as their new home **(??marenzelleria, round goby… refs).**
* Coastal processes may have an impact on the distribution of **contaminants (?)** through sediment translocations and the modification of habitats. Coastal erosion contributes significantly to the inflow of substances to the sea (including toxic chemicals). The concentrations of toxic metals in the eroding cliff are mostly low (Kwasigroch et al. 2016), but the total load of metals introduced in this way is significant, due to the large amounts of eroded sediments (Beldowska, Jedruch et al. 2016). Additionally, episodes of erosion occur several times a year, leading to the introduction of large loads of toxic substances in a relatively short time. Metals introduced in this way to the environment are often bioavailable (Kwasigroch, Beldowska et al. 2018).
* **Chemical munition** dumpsites are located far from the coasts, but current systems may affect the distribution of leaked substances. Conventional munition dumpsites can however be located in shallow water at close distance to the shore, ie. In Kiel Bight. As degradation products and trace metals originating from munitions were detected in the sediments there, it is likely that coastal processes may enhance spreading of those contamination to adjacent areas or increase their bioavailability (Gebka, Beldowski et al. 2016, Bełdowski, Szubska 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 **marine litter (\*)** on the shoreline. Refs)
* **Is there any sand extraction in the Baltic Sea? Is this of any relevance for the coasts?**

**d. Nutrient loads to the Baltic Sea (McCrackin)**

Globally, nutrient loads to coastal areas are increasing despite increased retention along the land-to-sea pathway (Beusen et al. 2016). Trends in the Baltic Sea region are much the opposite of global trends. Since external nutrient loads peaked around 1980, total waterborne and airborne N and P loads decreased by 42% and 56%, respectively (Savchuk et al. 2012). Current nutrient reduction plans (e.g. under the Baltic Sea Action Plan) do not consider climate change and, therefore, additional reductions in land-based nutrient loads could be needed to reach environmental goals for the sea.

Sources of nutrients transported to the sea by rivers varies by country and nutrient type (e.g. nitrogen or phosphorus, BSEP 153). In Finland, for example, agriculture is largest source of phosphorus and natural background sources are the largest source of nitrogen. For Poland, agriculture is the largest source of nitrogen while point sources are the largest source of phosphorus.

Regardless of near-term nutrient reductions, symptoms of eutrophication will be present in the Baltic Sea for the next several decades, due to slow response times (Savchuk 2018). However, recent evidence suggests that conditions in the sea are improving (Andersen et al. 2017) even though the sea as whole was recently assessed as not achieving environmental targets (HELCOM 2017). Thus, there will continue to be a loss of social welfare as long as the sea remains eutrophied (Ahtiainen et al. 2014). The extent to which the countries around the Baltic Sea can meet the nutrient load reductions specific under the Baltic Sea Action plan is not known.

Next to the external loads through atmospheric, river and diffuse sources, internal loads of phosphorus play a particular role in the Baltic Sea. Large amounts of phosphorus are stored in the sediment and deep waters, which are released in anoxic conditions (**ref**). 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 booms in late summer, still exacerbating the oxygen situation in the deep basins (**ref**)

The effects of climate change on nutrient loads are highly uncertain. Nutrient loads depend on runoff and riverine discharge. Climate models suggest that the north would be wetter and the south would be drier (BACC II, Meier et al., this volume). Currently, there is no consistent, catchment-wide model of nutrient source apportionment (BSEP 153), so it is difficult to assess where which sources predominate in different sea sub-basins. 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. 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 is a driver of nutrient loads to the Baltic Sea.

**Impacts of nutrient loads on other anthropogenic drivers**

* The envisaged and enforced reductions of nutrient loads related to the BSAP may have a feedback on **agricultural (?)** practices, in the effort to sustain high crop yields at lower uses of fertilizers. **ref**
* Likewise, a feedback effect of nutrient load reductions on **river regulations (?)** is thinkable, but highly speculative… **ref**
* Nutrient loads stimulate actions to mitigate the effects of eutrophication (e.g. BSAP), so they affect **coastal management (?)** actions (or management actions in general, depends on the definition, is this coastal management…). **ref**
* There is a very strong impact of nutrient loads on **hypoxia (\*\*\*)**. Increased nutrient loads to the large basins since 19xx are responsible for the expansion of oxygen-poor or -free zones since the past decades. There is clear and unequivocal evidence for this connection (*Ref*)
* Nutrient loads can have an impact on **acidification (\*)** through stimulation of primary production, stimulating the drawdown of CO2 in the water column and thereby affecting acidification **(add correct explanation, references, other effects?)**
* There is also a strong effect on **fisheries** (\*\*) 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, too much nutrients contributes to oxygen deficiency, with negative impacts on fish growth and reproduction, e.g. for cod (Köster et al. 2017; Casini et al. 2016). Furthermore, the composition of prey species, which may be affected by nutrients, is important for production of specific fish species (e.g. Möllmann et al. 2005; Neuenfeldt et al. 2019).
* **Non-indigenous species (?)** may also be affected by nutrient loads by the same mechanisms stated above for fish in general. Cascading effects may stimulate of hamper the establishment of non-indigenous species. **Refs?**
* Nutrient loads can affect organic **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. (**refs**). Increased organic carbon content and lower oxygen levels may promote methylation of mercury present in the sediments, enhancing its toxicity and bioavailability (Avramescu, Yumvihoze et al. 2011, Beldowski, Miotk et al. 2015).
* Nutrient induced hypoxia may impact **dumped munitions** via the reduction of arsenic V to soluble and much more toxic arsenic III (Szubska 2020), and modify degradation patterns of mustard gas, leading to more persistent degradation products (Vanninen, Östin et al. 2020).

**e. Hypoxia** (*tbd*)

Text pending…

**Impacts of hypoxia on other anthropogenic drivers**

* There is a feedback on internal **nutrient loads** (\*\*), i.e. the internal loads from phosphorus. There is the mechanism of phosphate release from anoxic sediments, so hypoxia in this case would act as a driver for eutrophication, leading to enhanced cyanobacteria blooms (**ref, how strong is this effect.**) This is an important feedback mechanism strongly impacting the biogeochemistry of the Baltic Sea, with repercussions on the food web structure, leading to favorable growth conditions for nitrogen fixing cyanobacteria in late summer when there is free bioavailable nitrogen is depleted in the surface waters. This is sometimes called the “vicious circle” as the additional cyanobacteria biomass to a large extent sediments and increases the oxygen free zones in the deep water. **(refs)**
* In anoxic seawater, total alkalinity is generated and therefore increases the CO2 buffer capacity and may damp **acidification** (Thomas et al. 2009, Edman and Omstedt, 2013).
* Hypoxic zones affect **fisheries** (\*\*\*) though the impairment of fish production. Strongest 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 impact growth and condition of the Eastern Baltic cod both directly and via regulating the availability of benthic food (Casini et al., 2016, Neuenfeldt et al., 2019).
* Is there a plausible or demonstrated impact of hypoxia on **non-indigenous (?)** species? **(refs)**
* A re-colonization of hypoxic bottoms can lead to increased release of "archived" **contaminants (\*)** in the sediments (by bioturbation), 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 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 speed up corrosion. Additionally, hypoxia can alter degradation process of chemical warfare agents, leading to greater persistence of degradation products in sediments (Vanninen, Östin 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 (Szubska 2020).

**f. Acidification and the carbon cycle (Anders Omstedt)**

The atmospheric CO2 concentration at the beginning of the industrial era (1750) was about 277 ppm (parts per million). In 2017 it had reached 405 ppm (Quéré et al., 2018), and is continuously increasing. This illustrates an imbalance in the global carbon cycle due to strong human impact caused by fossil fuel burning, industry and land use change. In the global carbon budget, averaged over the 1959-2017 period, 82% of the total emissions were due to fossil carbon dioxide emissions and 18% by land-use change. Of the total emissions, 45% remained in the atmosphere, while 24% and 30% were taken up by the ocean and the land, respectively (Quéré et al., 2018). The global fossil emissions have increased by a factor of three from the 1960s to 2008-2017.

The oceanic uptake of CO2 goes with the price of ocean acidification (Gattuso and Hansson, 2011). Ocean acidification was only recently accepted as a real threat to oceanic environments as it was previously thought that marine waters act as strong buffers e.g. by calcium carbonate. However, during the past two decades, there has been increasing concern and new observations illustrating declining pH values in the ocean (IPCC, 2013, 2019). Ocean acidification will change the carbonate chemistry of the ocean, resulting in a wide range of effects (Gattuso and Hansson, 2011), and the estimation of the potential damage and calculation of costs is a contentious issue (World Ocean Review, 2015).

Marine acidification is also expected to affect coastal seas. However, the specific processes there are more complex, due to land-sea interactions such as river and drainage basin biochemistry, effects from anoxic water and sediments. Whether coastal seas act as source or sink for atmospheric CO2 depends on an intricate balance between atmospheric exchanges, rivers, in- and outflows and sediment fluxes.

The strength of acidification depends on the accumulation of acids over basic elements. This is illustrated in Figure AO1, showing how changes in CO2 concentrations and total Alkalinity (AT) drive the acid-base balance. The total alkalinity change is considerable in the Baltic Sea, with low total alkalinities in the Gulf of Bothnia and the Gulf of Finland. Higher total alkalinities can be found in the Gulf of Riga and the southern Baltic Sea. The large differences in total alkalinity reflects that rivers entering the southern part of the Baltic Sea are draining areas rich in limestone, therefore having higher AT than rivers entering the northern part of the Baltic Sea, where granite dominates the bedrock (Hjalmarsson et al 2008).

The Baltic Sea carbon budget illustrates the strong influence from the surrounding drainage basin and the North Sea (Kulinski and Pempkowiak, 2011). For the period 1980-2014, Gustafsson et al. (2017) estimated the net carbon loads from land and atmosphere to the Baltic Sea were mainly lost to the North Sea (90%), while only 6% was lost to the sediments and 4% was net accumulated. In the budget calculations by Gustafsson et al. (2017), the net atmospheric CO2 flux worked as an uptake to the Baltic Sea in contrast to the budget estimates by Kulinski and Pempkowiak (2011), where they estimated an outgassing of CO2.

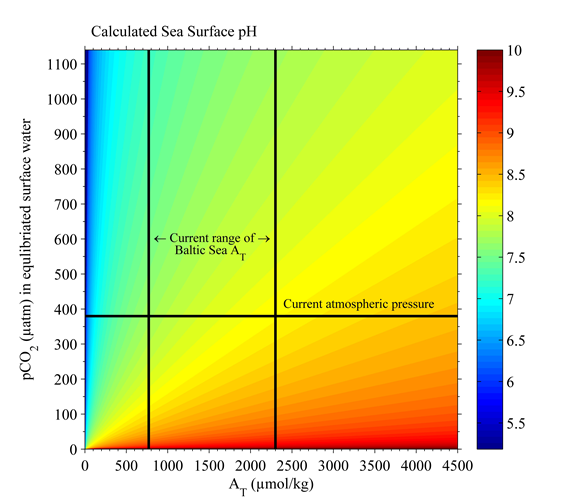


Fig. AO1. The figure illustrates how the water becomes more acid (low pH values, blue range) wth increasing concentrations of CO2 and at low total alkalinities. At high alkalinities, the water gets less acid (high pH values). Redrawn from Omstedt et al 2010.

Several studies are available on the net CO2 flux between the atmosphere and the Baltic Sea. For example, Baltic Sea model calculations by Omstedt et al. (2009) indicate that, before industrialization, the partial pressure of carbon dioxide in water was above atmospheric values, with a net release of CO2 to the atmosphere. Seasonal variability increased after industrialization and the onset of eutrophication, making the modern Baltic Sea both a sink and source of CO2 to the atmosphere.

Based on monitoring data from 1993-2009, Wesslander et al. (2010) estimated that the Gotland and Bornholm basins released CO2 to the atmosphere but the Kattegat was taking up CO2 from the atmosphere. In a model sensitivity study, Gustafsson et al. (2015) showed how outgassing or uptake due to air-water CO2 fluxes depended on river loads of carbon, total alkalinity and nutrients, as well the freshwater import. Lansø et al. (2017) examined the importance of short-term variability of the air-sea exchange in an atmosphere model study, illustrating the need for better estimates of CO2 fluxes when calculating net exchange in coastal seas with complex geometries.

The river loading of total alkalinity is associated with weathering processes in the drainage areas where some are rich and some poor in limestone (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 sulphur soils (Nordmyr, L. et al., 2006).

The central role of the marine CO2 system for biochemical processes in the Baltic Sea is discussed by Schneider and Müller (2018). The relative importance of the factors affecting acidification is difficult to disentangle as variability is often large (Wootton et al. 2008). Several time scales need to be considered when analyzing observations and evaluating future changes. For example, modelling exercises indicate that an increased nutrient load may not inhibit future Baltic Sea acidification on centennial time scales (Omstedt et al. 2012). This is futher supported by a recent sensitivity study including aspects of eutrophication by Gustafsson and Gustafsson (2020).

Omstedt et al. (2015) examined the effects of historical atmospheric depositions of sulphate, nitrate, and ammonium from land and shipping on the acid–base balance in the Baltic Sea. Modelling considered the 1750–2014 period, with strongly increasing carbon dioxide concentrations, SOx, NOx, and NHx emissions, and nutrient loads from land and ships. The present results indicate that Baltic Sea acidification due to the atmospheric deposition of acids peaked around 1980, with a pH decrease of approximately 10–2 in surface waters. This is one order of magnitude less than the acidification due to increased atmospheric CO2. The contribution of shipping to acidification is one order of magnitude less than that of land emissions. However, the pH trend due to atmospheric acids has started to reverse due to reduced land emissions, although the effect of shipping is ongoing.

Shipping is expected to become a major source of strong acid deposition to the Baltic Sea by 2050, while 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).

**Impacts of acidification on other anthropogenic drivers**

* It is unknown if there is an impact of acidification on **fisheries (?)** in the Baltic Sea, e.g. byaffectingcalcifying food organisms for fish larvae. The generation of otoliths which are from calcium carbonate has been shown to be affected by lower pH (Coll-Lladó at al. 2018, Di Franco et al. 2019, Hamilton et al. 2019), but it is completely unclear if these findings can be transferred to Baltic Sea species.
* Changing pH can directly influence speciation of dissociating **organic compounds (?)**, but the extent and significance for the environment is largely unknown. Marine acidification in surface, deep and sediment layers may change how contaminants like heavy metals and aluminium may disolve in the water body and circulate in the environment.

**g. Submarine groundwater discharge** (Beata Szymczycha)

Submarine groundwater discharge (SGD) is a young subject area within coastal hydrology, and has received increased attention over the past decades due to growing concerns over its role as a potential source of contaminates to the coastal ecosystem. Understanding the multi-disciplinary nature of SGDs requires collaboration among oceanographers, marine scientists, geochemists and hydrogeologists (Jiao and Post, 2019). In ocean research, any subsurface water is considered groundwater, but traditional hydrogeologists reserve the term groundwater for the water that originates from a terrestrial aquifer, which excludes recirculated seawater (Jiao and Post, 2019). Therefore, oceanographers and hydrogeologists are approaching the problem from different ends, and the different terminology sometimes led to confusion when SGD rates from different methods were compared (Burnett et al., 2006). Recently, the scientific community agreed on a SGD definition, which is 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 and recirculated seawater (Burnett et al., 2006). Usually, recirculated seawater dominates SGD.

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 small, the chemical substances flux via SGD can be relatively important, as groundwater in costal aquifers tends to be enriched in various chemical substances.

SGD has been investigated in the Gulf of Finland (Viventsowa and Voronow, 2003); the Gulf of Bothnia (Krall et al., 2017); the Eckernförde Bay (e.g. Schlüter et al., 2004 and Scholten et al., 2012); the Bay of Gdańsk and the Bay of Puck (e.g. Szymczycha et al., 2012, Kotwicki et al., 2014 and Donis et al., 2017). The first assessment of SGD significance 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 km3 yr-1). This proposed minor importance of SGD as a source of freshwater was most likely why the scientific community has acknowledged SGD (both FSGD and recirculated SGD (RSGD)) as an insignificant factor affecting the ecosystem of the Baltic Sea.

However, it is crucial to underline that the above-mentioned calculation is based on hydrogeological methods and modeled without validation by offshore sampling. Therefore, it relates only to FSGD and does not include the recirculated water component. Krall et al. (2017) estimated SGD at Forsmark, Gulf of Bothnia to range from 5.5 (± 3.0) · 103 m3 d-1 to 950 (± 520) · 103 m3 d-1, using Ra isotopes. These rates are up to two orders of magnitude higher than those determined from local hydrological models, which consider only the fresh component of SGD. Kłostowska et al (under review) obtained similar results in the Bay of Puck, southern Baltic Sea. Recently estimated SGD rates range from 1.4 · 106 m3 d-1 to 11.3 · 106 m3 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 surface runoff.

Additionally, local studies in the Bay of Puck suggest that SGD is an important source of methane, DOC, DIC (Szymczycha et al., 2012; Kotwicki et al., 2014; Donis et al., 2017), nutrients (Szymczycha et al., 2012; under review) and trace metals (Szymczycha et al., 2016). The ecological impact of SGD on coastal surface sediments was also assessed. Generally, meiofauna assemblages in the Bay of Puck, reflected in significant decline of particular meiofauna taxa (Kotwicki et al., 2014).

Recently, a study was conducted on annual variability of nutrient loads, concentrations and cycling by SGD in the Bay of Puck (Szymczycha et al., under review). The estimated seasonal and annual loads of both dissolved inorganic nitrogen and phosphates via SGD to the Bay of Puck were the most significant source of nutrients. It can be assumed that SGD will also be a significant source of nutrients in other Baltic Sea regions, and therefore affect biogeochemical processes in the coastal zone. 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 accompanied nutrients fluxes should be considered in models characterizing the biogeochemical process in Baltic Sea coastal areas.

The current state of knowledge related to SGD in the Baltic Sea is limited to local studies in which different approaches were used to identify and quantify SGD. Therefore, it is hard to draw overall conclusions and projections for the entire Baltic Sea.

The great challenge is to measure SGD in different areas of the Baltic Sea using similar approaches and methods. In order to understand the effects of SGD, a dedicated groundwater-monitoring network of multi-level observations is required in Baltic Sea coastal areas, together with offshore sampling. The next step would the development of a coupled groundwater-surface model that stimulates the reactive transport process of Ra and Rn, including release of the aquifer, adsorption and its mitigation and mixing in the sea (Jiao and Post, 2019). With such models, the generation and fate of SGD tracers can be better understood, and would enable a proper evaluation of role of SGD in chemical substances cycling in the Baltic Sea.

Understanding the present and future impacts of SGD and the accompanied chemical mass fluxes on coastal biogeochemistry and ecosystems functioning along the coastline is crucial to develop an effective coastal management. Driving forces of SGD involve topography-driven flow, tidal pumping, 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 drivers, 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 will differently effect ecosystems in different Baltic Sea regions. Thus, it can be speculated that SGD fluxes may increase in the northern Baltic Sea, where increased precipitation and groundwater tables are projected, while in the southern part, the opposite trend can be envisaged. Sea level rise and geostatic land movement will additionally affect SGD. However, due to a lack of SGD data, it is hard to project the direction and significance of the change.

**Impacts of submarine groundwater discharges on other anthropogenic drivers**

* Are there any indications that SGDs may have a considerable effect on local **sea level (?)**
* Is submarine groundwater discharge in any way important for **coastal management (?)** or coastal structures?
* Isthere any impact on **coastal processes (?)**, maybe locally near submarine seeps?
* Locally, **nutrient loads (\*)** andconcentrations can be affected by SGD. Nutrients as well as dissolved organic and inorganic carbon components have concentrations several orders of magnitude higher in groundwater than in surface water. Therefore, even if the SGD rate is small, the chemical substances flux via SGD can be relatively important, as groundwater in costal 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 source of nutrients (Szymczycha et al., under review). It can be assumed that SGD will also be a significant source of nutrients in other Baltic Sea regions, and therefore affect biogeochemical processes in the coastal zone.
* There may be an indirect effect on **hypoxia (?)** through the release of additional nutrients via SGDs, but its magnitude and relevance for coastal or deep water hypoxic zones is entirely uncertain.
* Is there any local effects on **acidification (?)** How is the acidity or alkalinity of groundwater? *References*
* SGDs may be animportant input route for **organic 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, DOC, DIC (Szymczycha et al., 2012; Kotwicki et al., 2014; Donis et al., 2017), nutrients (Szymczycha et al., 2012; under review) and trace metals (Szymczycha et al., 2016).

**h. Non-indigenous species** with special reference to the round goby (Juris Aigars)

Non-indigenous species usually are introduced into environments where they previously had been absent by human activity. For the Baltic Sea, it is estimated that 140 to 170 new species have established themselves (Helcom state of the Baltic, Ojaveer et al. 2016), 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, Gollasch et al. 2010). Ports are known as hot spots for the distribution of non-indigenous species (HELCOM). Temperature and salinity may be limiting ore favoring 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* ssp. (Stigzelius et al. 1997), the pelagic comb jelly *Mnemiopsis leidyi* (Haslob et al. 2007), and the demersal fish round goby.

The bottom-dweller round goby *Neogobius melanostomus* (Pallas, 1814) was recently recognized as important stressor with capacity to influence local species (Karlson et al., 2007; Järv et al., 2011; Ustups et al., 2016) and a potential to cause regime shift in coastal ecosystems (Nurkse et al., 2016).

The round goby is of Ponto-Caspian origin (Miller 1986) and was first reported in 1990 from the Gulf of Gdansk (Skóra and Stolarski, 1993). Since then the round goby has spread to other coastal areas of the Baltic Sea. It is believed that main distribution vector accounting for long-range transport is ship ballast waters (Kornis e al., 2012, Kotta et al. 2016). However, it has been demonstrated that the round goby is capable of expansion 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 few hundred meters (Ray and Corkum, 2001). Longer migrations of up to several kilometers to and from deeper waters take place in spring and autumn (Sapota, 2012).

The round goby is an opportunistic feeder (Skora 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 the 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 perch *Perca fluviatilis* almost exclusively feeds on round goby in the Gulf of Gdansk (Almqvist e 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 in its diet prefers other fish species over round goby, suggesting that round goby is rather a prey of opportunity than of choice.

Therefore, it can be assumed that in some Baltic Sea areas, round goby has significantly surpressed 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 become an important food source also for turbot *Psetta maxima* (Sapota and Skora, 2005), and birds like the great cormorant *Phalacorocorax carbo* (Bzoma, 1998; Rakauskas et al., 2013) and grey heron *Ardea cinereal* (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 predict detailed effects of the round goby as the impacts seems 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).

**Impacts of non-indigenous species on other anthropogenic drivers**

* There may be an impact **on coastal management (?)** if a non-ingenious species becomes a problematic species causing problems for other species or having a detrimental effect on the ecosystem and eventually, some management actions need to be taken to minimize the impacts. However, a complete removal of the new species is not possible once it has established itself (http://stateofthebalticsea.helcom.fi/pressures-and-their-status/non-indigenous-species/).
* Regulations put into effect to mitigate biofouling and ballast water vectors will 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 (Ballast Water Management Convention, http://www.imo.org/en/OurWork/Environment/BallastWaterManagement/Pages/BWMConventionandGuidelines.aspx) and requires the use of ballast water management systems. Further, the leaching of organometallic compounds, especially those of Cu and Zn are high (Eklund and Watermann 2018, Jalkanen et al. 2020, Lagerström et al. 2020).
* There may be indirect effects on **nutrient** concentrations **(?)** (not **loads**) if the invasive species changes the ecosystem or microbial community with the effect of changed microbial turnover or nutrient regeneration rates through trophic cascades. There may be a similar effect on **hypoxia (?)**
* Non-indigenous fish can either positively or negatively affect food availability and growth of commercial fish (Ojaveer and Kotta 2014), with impacts on **fisheries** (\*\*) opportunities. Also, non-indigenous species can become a target for fisheries, e.g. round goby (Ojaveer et al. 2015). Also, it has beendemonstrated that round goby competes for food with juvenile flatfish (Ustups et al. 2016).
* It has been shown that non-indigenous polycheate *Marenzelleria neglecta* burrows deeper in the sediment than native species and can enhance bioturbation-mediated transport of **organic contaminants (\*)** to the overlying water (Granberg et al. 2008). …
* Impacts on **biodiversity** and **ecosystem structure** (Lehtiniemi et al. 2015)

**i. Land Use and Land Cover (Poska,** Reckermann**)**

Anthropogenic land use changes in the Baltic Sea region go back to 6000 years before present (Smith et al. 2008). Deforestation for firewood, iron production, and crop areas has been the main factor driving land surface changes (Lavento 2019). There is some indication that major deforestation had some impact on the regional climate until about 2500 years BP, but not recently (Gaillard et al. 2015).

Land cover as a driver of environmental changes is well recognized when addressing the global and regional challenges related to the mitigation of anthropogenic CO2 fluxes. It is widely discussed as an important part of the Earth´s carbon cycle, both as the second largest source of anthropogenic CO2 emissions due to the ongoing large-scale deforestation of tropical areas (IPCC 2013), and for its potential to mitigate the effects of anthropogenic CO2 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 accelerating reforestation of northern mid to high latitudes (IPCC 2013). 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 show considerable differences in the predictions of land use and cover development at continental/sub-continental scales, and incorporate large uncertainties (Prestele et al 2016). The political efforts to mitigate climate change are aimed to decrease the deforestation rates in tropical regions, and further increase the reforestation pace at mid and high latitudes (UN-REDD (Reducing Emissions from Deforestation and Forest Degradation) program (UNFCCC 2014); European Union renewable energy Directive (2018/2001/EU)), in order to decrease the land cover related CO2 emissions and to increase the amount of carbon sequestered by terrestrial land cover.

Since the introduction of agriculture millennia ago, anthropogenic deforestation was, at continental scale, a major human impact on land cover (e.g. Ellis 2011, Roberts et al 2018). Next to the biogeochemical feedbacks, i.e. the sequestration of CO2 though photosynthetic fixation into biomass, there are also biogeophysical feedbacks on climate through the reflectivity of the surface (albedo). Dark surfaces (e.g. forests, waters) absorb the incoming heat better than bright surfaces (deserts, agricultural lands). The type of land cover may thus have an impact on the regional climate (ref). Interestingly, both effects may counteract each other, e.g. reforestation may contribute to a drawdown of CO2 from the atmosphere, thereby theoretically contributing to a cooling effect; but that additional forest area may have a weaker albedo, increasing the dark surface and contributing to warming. These trade-off effects are difficult to quantify (Mykleby et al 2017), but it has been assumed that reforestation as a measure for carbon drawdown and cooling, at least in the Baltic Sea region, will probably be of little effect (Arora and Montenegro, 2011). However, this is under debate. In modelling studies, Strandberg and Kjellström (2019) showed there may be a cooling effect, with massive reforestation leading to a significant lowering of summer maximum temperatures and a reduction of summer heat waves south of the Baltic Sea.

There are major uncertainties related to projections of the speed and direction of terrestrial land cover change and its ability to provide the service as a reducer of atmospheric CO2 concentrations. Projected land use and land cover change will have implications for the functioning and structure of terrestrial ecosystems, and on the amount and nature of the ecosystem services supported by the land cover, regardless if 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 little understood (Kayler et al 2019). Cross-system studies with a focus at matter transfer between terrestrial and aquatic environments are rare, but when conducted, they show clear signals of considerable impacts (Ning et al 2018, Bragee et al 2013). While the importance of terrestrial vegetation around drinking water resources is well recognized at the local scale, the impacts of land use and cover change on the aquatic environments at regional to global scale are much less known and studied. Dissolved organic carbon (DOC) from 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).

**Impacts of land use and cover on other anthropogenic drivers**

* As stated above, there is clear evidence that land use and cover can have an impact on the regional **climate (\*\*)**, through geophysical and biogeophysical effects. 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). **Agriculture (\*\*\*)** is the dominant type of land use in the southern part of the basin, and it suffers from a projected decrease in precipitation in the south. The decisions which part of land is dedicated to agriculture is very much a management and political decision, which in turn can be affected by climatic conditions (**ref**).
* Land use change is a major force driving **river regulations (\*\*).** Regulation of river basins and drainage works in agriculture and forestry have been major drivers 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 is a plausible connection between coastal land use and **coastal management (\*)**. Housing areas close to the coast, on sand spits or on cliffs which are affected by coastal erosion and sea level riseare in peril to be lost to the sea. The same holds for agricultural lands and forests close to affected cliffs. **(references?)**
* 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. **References?**
* **Impacts on erosion/sedimentation processes (how?, refs) (jukka)**
* 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. There is an indirect but clear relation between land use and **hypoxia (\*\*)** through nutrient release from agricultural fields and associated eutrophication. **References**
* **? Acidification ??? (is there a connection between land use and acidification? Does land use have any impact on alkalinity?**
* There can be a considerable impactof 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 to groundwater and eventually reaching coastal discharge spots. However, the extent of this relation is unknown. **Reference?**
* Land use indirectly affectscertain branches of **fisheries (\*)**, e.g. by affecting rivers where salmons and other migrating fish spawn (see the section on river regulations) **(ref)**
* Fertilizers, plant pharmaceuticals and insecticides on cultured land may leak to the soil and sea, thus, it can be expected that land use has a considerable impact on **contaminants (\*\*)** in the coastal sea.Aremobilization of toxic mercury from the soil (where it has been accumulated for decades) and transport to rivers and into the sea has been shown (Saniewska, Beldowska et al. 2014, Gebka, Beldowska et al. 2019, Gebka, Beldowska et al. 2020, Gebka, Saniewska et al. 2020).
* Furthermore, land use also affects **biodiversity**, **migration** capabilities for bottom dwellers on land (fragmented landscape), and **soil erosion** (Smith et al. 2008).
* Changed land cover e.g. the replacement of permeable soils with sealed urban spaces may lead to an increased vulnerability for flooding and inundation, with consequences for economic goods, of which there is usually a high concentration in urban areas

(Saniewska, Beldowska et al. 2014, Saniewska, Beldowska et al. 2018).

**j. Agriculture (McCrackin)**

Agriculture is a strong driver of earth system changes. Agriculture accounts for 40% of global land area, 30% of greenhouse gas emissions, 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 area for Sweden and Finland to 60% for Denmark (Svanbäck et al. 2019). In the past several decades, fertilizer use has decreased, while yield have 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).

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). Use efficiency is calculated as nutrients removed in crop harvest divided by the sum of manure and fertilizer added. 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 Russian and Belarus but > 90% in Germany, Denmark, Estonia, Latvia, Lithuania, and Sweden (McCrackin et al. 2018).

Livestock are 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 in the landscape. It is often more economical for farmers to purchase commercial fertilizers than to use nutrients in manure for crops (Wang et al. 2017, Svanbäck et al. 2019). Model studies suggest that redistributing manure nutrients, together with improving agronomic practices, could meet 54–82% of the remaining nitrogen reductions 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. 2018).

Global population growth will likely increase demand for food products. Increased wealth in countries like China will likely increase demand for livestock products (Yu et al. 2016). It will be challenging to reduce nutrient loads from agriculture and increase food production if farm structures and practices changes remain unchanged. 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.

**Impacts of agriculture on other anthropogenic drivers**

* A possible feedback by agriculture, or land use in general, on the regional **climate (\*)** may be though 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).
* Agriculture is a major driver for **river regulations (\*\*).** A multitude of drainage works in agricultural land has gradually led to a more rapid hydrologic response and probably a corresponding increase of the nutrient transport from land to sea. (**Ref**)
* There may be a connection between agriculture and **coastal management (?),** in regions where coastal infrastructure and agricultural fields are in competition for space. Also, coastal management may need to respond where agricultural fields are at stake where they are close to cliffs and other coastal features which are subject of erosion. **(Ref)**
* Agricultural practices, i.e. fertilization of fields, are the primary source for **nutrient loads (\*\*\*)** to the Baltic Sea, so there is a strong and direct relationship. **(more, refs)**. Likewise, agriculture and the increase in **hypoxia (\*\*\*)** are strongly related via nutrient loads and eutrophication. **(more, refs)**.
* Agriculture strongly affects the carbon chemistry of the coastal sea due to carbon and nutrient loads, and thus has an impact on the soil **acidification (?)** andeventually that of seawater. **(Refs)**
* 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 (\*\*). (Refs)**
* There may be at least partly an indirect influence on **fisheries (?)** by agriculture. This can be through nutrient releases and eutrophication, which may be beneficial (more food for fish) or detrimental, but the connection is not documented well. **(Refs)** Likewise, there could be an indirect connection to the appearance of **non-indigenous species (?)** through nutrient release, eutrophication and changed growth conditions. **(Refs)**
* Like for land use, agriculture does affect the amounts and distribution of **organic contaminants (\*\*)** through agricultural practices, using fertilizers, pharmaceuticals and insecticides for animals and plants. **(Refs)**

**k. Aquaculture (Kiessling)** *pending*

**l. Fisheries (Margit Eero)**

Fisheries influences the Baltic ecosystem primarily through selective extraction of species and physical disturbance to the seabed. The latter is mostly relevant in the southern Baltic Sea, where the 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 bycatches of marine mammals and seabirds, affecting these populations (HELCOM, 2017).

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, pike-perch, pike, perch, vendace, whitefish, eel and sea-trout. Fisheries removals are generally recorded in the form of fisheries statistics. Additionally, biological information on the catch (size/age structure, weight of the fish) are collected for the commercially important fish stocks. For several key fish species in the Baltic Sea, long time series of monitoring data and fisheries statistics are available, which have allowed describing the development of fishing pressure over multiple decades, in some cases since the beginning of the intensified fishing in the 1950s-1960s (Eero et al., 2008; Eero, 2012).

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, multiannual EU management plan is in place (EU, 2016), which aims to contribute to the achievement of the objectives of the CFP. Fisheries for the major Baltic fish stocks are expected to further align with the targets of these policies in future.

Fish is a valuable food and fisheries, together with related industries, are locally an important source of income and employment in the Baltic region, especially in small coastal communities. Therefore, sustainable use of marine resources should be ensured, as also stated in the global policy goals (United Nations, 1982). The goal for ecosystem-based approach for fisheries management is to simultaneously consider conservation, economic profits as well as social equity. In the Baltic Sea, there are tradeoffs between reaching these goals, and there are competing interests between different users of major fish stocks, which is related to food web interactions between species. For example, management strategies prioritizing overall profit would favour economically more valuable species, such as cod, which may cause conservation as well as equity issues concerning fisheries targeting other species (Voss et al., 2014).

F Both natural and human-induced processes, including species interactions influence the status of the fish stocks. To be able to identify most appropriate management actions under given ecosystem conditions, i.e. apply a holistic ecosystem based approach to fisheries management, requires knowledge of pressure‐state links in the ecosystem. One of the major scientific challenges in relation to fisheries impacts, is to be able to quantify fishing impacts relative to those caused by other human or ecosystem drivers. An example here is cod, where fishing for its prey species potentially influences cod growth and condition (ICES, 2018b). However, as a number of other factors influence cod growth and condition at the same time (e.g., oxygen conditions, parasites from grey seals) (Casini et al., 2016; Horbowy et al., 2016), the possible effects of fisheries management actions are difficult to determine. Another example is fishing impacts on the seabed, where 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 evidence to parameterize models is needed, as well as establishing better quantitative links to other pressures (e.g. anoxia) (ICES, 2018a).

Fish stocks status and resulting fishing opportunities are besides fisheries affected by climate (salinity, temperature) as well as eutrophication, which effects are also closely connected through affecting 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 the recruitment of sprat (MacKenzie and Köster, 2004). A combination of oxygen content and temperature has been found to have signiﬁcant effects on egg/larva development and survival of the Western Baltic cod (Hüssy, 2011). 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 impact growth and condition of the Eastern Baltic cod both directly and via regulating the availability of benthic food (Casini et al., 2016). 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).

A combination of several drivers is often responsible for larger changes in fish abundances. For example, 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 is record was found to be due to a combination of favourable climate and a temporary reduction in fishing pressure (Eero et al., 2011). These examples demonstrate how combinations of different forcings can have synergistic effects and consequently large impacts on population dynamics.

Eutrophication has presently negative effects on fish resources via deteriorated oxygen conditions especially in deeper basins. In contrast, some coastal species may benefit from the associated high nutrient levels. Historically, the increase in nutrient concentrations from the level before the 1950s to 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). By removing fish, fishing is considered to remove nutrients from the Baltic Sea (Nielsen et al., 2019), which is another interaction between eutrophication and fisheries driver.

Hazardous substances in the Baltic Sea interact with fisheries as well. Contaminants in fish above accepted thresholds have implications for marketing possibilities of the fish. In addition, contaminants can affect fish stocks via food web interactions. For example, 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).

Invasive species is another driver interacting with fisheries through food web interactions. An example here is round goby, *Neogobius melanostomus*, which both has become a new exploitable resource for some fisheries, but also has negative impacts of some other native commercial species (Ojaveer et al, 2015). Importantly, it has been found to increase bioaccumulation of sediment-related toxins in food chain, and thereby increase risks for fish consumers (Ojaveer et al, 2015 and references therein).

**Impacts of fisheries on other anthropogenic drivers**

* Fisheries is an integral part of **coastal management** (\*) in areas where fishing grounds or essential fish habitats potentially overlap with other uses of the coastal zone. *What is the nature and extent of these impacts?*
* There can be a connection between fisheries and **offshore wind farms (\*)** regarding the competition for space in the coastal areas. *Are there examples, references?* 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 *(examples, references)?*
* Likewise, a possible impact of fisheries on **shipping (\*)** regards the competition for space. Fairways and shipping lanes can be prohibited for fishing; these areas are exempt for fishing due to shipping traffic but can help the recovery of fish stocks (similar to wind farms). *References?*
* *Is there any impact of fisheries on* ***coastal processes (?)*** *What is the impact of coastal fishing gear like gill or trawl nets on sediments, sediment re-locations and coastal dynamics? Are there any indications to that effect?*
* There is no direct effect of fisheries on the **nutrient loads** (?) but it 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 remove nutrients from the Baltic Sea (Nielsen et al., 2019).
* Also for **hypoxia** **(?)**, there may be a cascading effect, e.g. fishing out large predators may affect consumption at lower trophic levels, and in the end have repercussions on nutrient concentrations, eutrophication and hypoxia*. Any evidence?*
* Fisheriesmay directly or indirectly affect **non-indigenous species (\*\*)** by altering the food web structure and opening up an ecological niche for new species *(reference?)*, or may be a new commercially interesting species, e.g. the Round Goby (Ojaveer et al, 2015). *Other examples?*
* There have been reports by 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 dumpsites, trawlmarks 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.
* Fishing vessels have been a source for **marine litter (\*\*)** and contamination, e.g. nylon nets, buoyancy gear, solid and liquid waste, similar as general shipping. Abandoned fishing nets, however are a special threat not only for fish, marine mammals (Stelford et al. 2016) but also for birds (e.g. Merlino et al. 2018).

**m. River regulation and stream restoration (Wörman)**

Many rivers in the Baltic Sea catchment basin are regulated, i.e. their natural course has been altered for power generation, municipal water supply, irrigation for agricultural purposes, flood protection, shipping and navigation. Damming for hydropower generation is more common in the northern, boreal part of Europe, where a considerable fraction of electric power generation (up to 82% in Norway and 77% in Finland) is by hydropower (Lehner at al. 2005, Humborg et al. 2015). Regulation of river basins and drainage works in agriculture and forestry have been major drivers for changes of the hydrological and water quality responses in watersheds (Wörman et al., 2010). Nilsson et al. (2005) describe how the majority of the world’s river basins are regulated. Such river regulations affect the river hydrograph, sediment transport and local erosion (Kumar and Schei, 2011). The dam structure and associated damming can cause permanent flooding with increased green house gas emissions from the flooded terrestrial-carbon pool, river fragmentation, higher sedimentation rate in the reservoir, retention of solute pollutions and risk for eutrophication in the reservoir.

A multitude of drainage works in all agricultural land has gradually led to a more rapid hydrologic response over the last centuries, and probably a corresponding increase of the nutrient transport from land to sea. Traditionally, there has been an understanding that the stream network topology has the major importance for the hydrological response of a river basin – this effect is due to the so-called geomorphological dispersion affecting both water flow and solute responses (Rinaldo et al., 1991; Rodriguez-Iturbe et al., 1997). However, more recently there has been a growing understanding that spatial heterogeneity of in-stream channel properties, such as those affected by drainage works, play an additional important role for hydrological responses – the associated phenomena are termed hydraulic and kinematic dispersions (Saco and Kumar, 2002). Consequently, numerous drainage projects in agricultural land during several centuries has gradually implied a more rapid flow response (Åkesson et al., 2016) with consequences also for the water quality response in streams and river basins (Riml and Wörman, 2015). Also, the interaction between the stream flow and shallow groundwater immediately below the stream water – the hyporheic zone – is highly important for filtering the stream water (Boano et al 2014) and, thus, for the water quality of estuaries.

It has been shown that river regulation and damming leads to a 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). 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 – limit the eutrophication both in downstream inland waters and can potentially have a major role for 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 recently it has been found that stream hydro-mechanics impose a limit on the rate at which nitrate is removed in the reactive zones of streams (Gomez-Velez et al., 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 the stream water (Boano et al., 2014). Restoration actions in streams can offer an important contribution to a system of management plans to reduce nitrogen and phosphorus loadings to inland waters and the Baltic Sea.

Stream restoration projects tend to reverse effects of previous drainage works by introducing engineered structures like cross-vanes, riffle-and-pools, new bed substrate or checker dams (Wortley et al., 2013). It can be shown how stream structures such as those mentioned above 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). An engineering design approach is based on many, in practice, uncertain and variable factors that can also be difficult to control by engineered structures.

Nevertheless, a recent study of the potential for reducing nitrogen export through denitrification in agricultural streams through restoration actions tentatively indicate that the effectiveness is highly heterogeneous, depending on local stream conditions, but also that significant reduction in nitrogen export can be achieved through such actions if implemented wide-spread (Riml et al., 2019).

The hydrological response changes over time due to landscape changes, periodicity of climate as well as global warming. The energy level available for transport of sediment and solutes in streams is highly variable (Wörman et al. 2017), which has significant environmental implications for decadal or longer time-scales. Climate change is generally expected to result in higher runoff, since the increase of precipitation is higher than evapotranspiration, but regional differences are large (Ref). 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 (Ref). An increased runoff would generally enhance nitrogen transport and decrease retention and transformation of nitrogen in streams. River regulation and (current) climate change may have similar impacts on the flow regime (Ashraf et al. 2016)

**Impacts of river regulation on other anthropogenic drivers**

* There is a clear impact of river regulations on **land use (\*\*)** and **agriculture (\*\*)**. The fraction and distribution of useable land is partly determined by regulated rivers. … **(refs)**
* Regulated rivers change the amount and quality of water entering coastal waters so they have an impact on **coastal management (\*\*)**. Likewise, there is a close connection to **coastal processes**,asregulated rivers carry different amounts of sediments to the sea, which can thus alter coastal processes and morphology in the vicinity (downstream) of river mouths of regulated rivers. **(refs)**
* River regulations have a strong impact on **nutrient loads (\*\*\*)** through damming and sedimentation, changing the river´s nutrient loads and biogeochemistry, in particular for Si (Humborg et al. 2015). Still, it has been estimated that the global riverine nitrogen and phosporus transport has increased despite all regulation efforts (Beusen et al. 201). River regulations may have also an impact on **hypoxia (\*)** near river mouths, through altered nutrient loads, eutrophication and increased oxygen demand/depletion. **(refs)**
* The river loading of total carbon and alkalinity is associated with weathering processes in the drainage areas where some are rich and some 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 sulphur soils (Nordmyr, L. et al., 2006). ***Impact of river regulations on acidification/alkalinity? (Refs)***
* ***Do regulated rivers have an impact on a drainage basin´s groundwater budget and thus also on groundwater discharge (?) to the sea?***
* 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). **Do fish passes make a difference? (Refs)**
* For some **organic contaminants (?)** (e.g. pharmaceuticals, Lindim et al., 2016) and trace metals, riverine transport is the major transport route to the sea, so it is plausible that theymay be distributed or scavenged differently in regulated rivers than in natural ones.(Saniewska, Beldowska et al. 2014, Saniewska, Beldowska et al. 2018, Gebka, Beldowska et al. 2019, Gebka, Beldowska et al. 2020, Gebka, Saniewska et al. 2020).
* Also for **marine litter (?)** (how much through rivers) and microplastics, river regulations may have an influence on how much or which fraction reached the sea. The question is whether litter is effectively held back if rivers are dammed…. (Refs)

**n. Coastal management (Parnell)**

When considering drivers of coastal change, we normally think of waves (of different types), water levels, coastal currents and sediment availability and their relationship to erosion or accretion. We rarely think of coastal management *per se* as a driver of coastal change. Coastal management is not merely the provision of coastal defences against erosion and inundation (Pilkey and Cooper, 2014), concentrating specifically on hard engineering (such as groynes, seawalls, revetments and offshore structures), soft engineering (renourishment, beach dewatering, dune stabilization) and planning (managed retreat, limiting development, reclamation). 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.

Coastal management should be forward looking, identifying how future human activities will interact with natural drivers (wind, waves, currents, water-levels etc.) and processes (sediment transport, erosion, deposition etc.) by providing a framework to assess, mitigate and minimise adverse impacts while promoting positive changes. However, very frequently the actions resulting from management attempts to use the coast become drivers in their own right, resulting in further, often detrimental, changes. The implementation of plans for coastal erosion ‘protection’, sea defences, public infrastructure (e.g. ports), coastal development areas, and public space and amenity creation, can change the physical drivers (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).

Many attempts to reactively mitigate coastal problems, undertaken with the best intentions but with limited understanding of processes, have resulted in negative impacts. Specific examples include 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’, first formalised by Locke in 1691 (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 (Merton, 1936) ignorance, error, immediacy (e.g. to protect human life), or basic values (e.g. private property rights, freedom of navigation, rights to use resources, sovereign rights).

An example of good coastal management conflicting with basic values is the case of hard protection (such as a seawall) constructed to protect private property from coastal erosion. It is well understood that building a seawall which protects property effectively degrades the beach (passive erosion; Griggs, 2005) when the system is in sediment deficit, causing a loss of public amenity. This results in a conflict between private property rights and public or environmental rights. Until such issues are resolved, managed retreat (Cooper, 2003) as a management response to coastal erosion is difficult or almost impossible.

The tools available now make the assessment of coastal projects much more reliable. 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. For every coastal project, a simple sediment budget (Figure 1), applied within an appropriately sized coastal compartment (for example a bayhead confined beach) should be applied. Where a project changes any of the sediment transport pathways over the active beach profile, unintended consequences may result and need to be addressed. Similarly, if a project will change the fluid motions, the coastal morphology or natural sediment transport (Figure 2), further investigations are required. In most 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.

Coastal management actions can become drivers of coastal change. 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 fewer mistakes being made. A bigger challenge, however, is 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 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.

**Impacts of coastal management on other anthropogenic drivers**

* Coastal managementmay have an impact on **land use (\*)** i.e. the use of coastal land stripes by coastal constructions and management measures **(which, refs)**. The same holds for **agriculture (\*)** on very narrow coastal stripes. **Are there any references and is this a considerable effect?**
* There is a clear connection between coastal management on **river regulations (\*\*)**. Rivers enter the sea and river mouths, and estuaries are very much the subject of regulation and coastal management **(refs, is that correct, or a matter of definition?).**
* Coastal management, if defined as also the management of useable coastal space and maritime spatial planning, is also responsible for the allocation of space for **offshore wind farms (\*\*\*)**. **(refs)**
* There is a considerable impact of coastal management on **shipping (\*\*)** through the design and management of ports and coastal fairways, the construction of ports, wind farms, allocation of fairways, regulations, and marine protected areas banned from shipping**.** These are regulated by local authorities considering the protected areas defined e.g in the Birds and Habitat directives (92/43/EEC and 2009/147/EC).
* Coastal management decisions are bound to have a strong impact on **coastal processes (\*\*\*)** through the control of sediment translocations, a reduction or enhancement of erosion etc., through coastal constructions like groynes, levees etc. **(Refs)**
* **Submarine groundwater discharge (?)** maybe 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 have a considerable impact on **fisheries (\*\*)** and fish stocks by regulating fishing grounds and deteriorating coastal habitats of fish species **(Refs)**
* 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. **(Refs)**
* **Are management decisions concerning organic contaminants (?) part of coastal management or is that another type of management?**
* **Dumped military material (\*)** is in some cases located in the coastal zone, although it concerns rather terrestrial dumpsites 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)
* **Impact on Marine litter (?) possibly if regulations concerning litter and regulations are part of coastal management…**
* **Is there any sand extraction in the Baltic Sea? Is this of any relevance for the coasts?**

**o. Offshore Wind Farms**(Xiaoli Guo Larsén, Tom Cronin, Cris Pons-Seres de Brauwer, DTU Wind Energy Department)

Power generation prospects for the late 21st century have been estimated for Europe to increase up to 15%. (Tobin et al. 2015, Tobin et al. 2016). Offshore wind power potential is substantial in the Baltic Sea and the business started taking off in recent years, with most farms being built or planned in the southern part due to higher market values. To Oct 2019, 2 GW offshore wind is installed in the Baltic Sea and it is expected to be 9 GW or even 14 GW by 2030 (Pineda and Fraile 2019). The WindEurope’s latest scenario projects installation of 85 GW by 2050, making the Baltic Sea the second-largest basin for offshore wind in Europe. The modeling of market and grid show that the offshore wind power in the best sites can be competitive in 2030, according to the report ECDGE (2019). For the Baltic Sea region, there is no robust trend for wind speed, and scenarios fail to show any consistent future trend (Meier at al., this volume, Christiansen and Räisänen 2017), except for an increase in near-surface wind speed in areas that today are covered by sea ice which will be gone in a future warmer climate (Kjellström et al. 2018).

Hence, the energy production per unit is uncertain and 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 potentially feeding back to the regional climate. Moreover, the variability and expected technological development in turbine effectivity is projected to be larger than the estimated climate effects (Tobin et al. 2016).

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. 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 (Larry et al. 2020), an issue which can a) significantly further slowdown the development of new wind energy infrastructure, and b) add additional project 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 “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), 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, 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).

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 the 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 (Pons-Seres de Brauwer and Cohen 2021).

In the Baltic Sea region (including Kattegat, Belt Sea and Lake Vänern), there are currently (November 2020) 19 wind parks in operation with a total production of 2.2 GW, 2 out of operation and 4 under construction or in planning ([*https://de.wikipedia.org/wiki/Liste\_der\_Offshore-Windparks*](https://de.wikipedia.org/wiki/Liste_der_Offshore-Windparks)*).* Fig 1 shows a map of the offshore wind farms in the Baltic Sea (<https://www.4coffshore.com/offshorewind/>).

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*Fig. 1. Offshore wind farms in the Baltic Sea (https://www.4coffshore.com/offshorewind/)*

**Impacts of offshore wind farms on other anthropogenic drivers**

* There may be a certain impact onthe regional **climate (x)** by offshore wind farms through absorbing atmospheric energy. There is little information of 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. 2013). 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 gentle tendency of increasing resource in the Northern part (Devis et al. 2018; Reyers et al. 2016; Hahmann et al. 2020). The impact of the farms on the climate change has however not been assessed in this area, partly due to the scale of the offshore wind industry is still rather small. While there is short of observational evidences, numerical studies over other regions have suggested possible impact from of wind farms on local meteorology and climate change, 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 (Hasager et al. 2017, North Sea), change of spatial distribution of precipitation (Pan et al. 2018, US coast), cloud cover (Boettcher et al. 2015, North Sea) and local temperature (Roy and Traiteur 2010, conceptual). The impact of climate is mostly assessed through temperature, and the findings are rather consistent: there is only statistically insignificant change in mean temperature, though it could be up to 0.5°C in seasonal peak values (Vautard et al. 2014, Keith et al. 2004, Pryor et al. 2018). *(… further references, Naveed).*
* There is no connection between offshore wind farms and **land use (?)** except possibly indirectly that an extension of offshore wind farms may result in a reduced construction of wind farms on land. The same holds for the connection with **agriculture** **(?)**; land-based wind farms may need to be reduced to give space for agricultural fields. *references*
* Wind farm planning can be defined as part of **coastal management (\*\*)**, i.e. governments and local authorities attempt to balance and manage the use along the coastal zones. Socio-economic effexts like revenue losses for tourism-dependent businesses, possibly outweighing economic profits from offshore wind farm developments and resulting in a net welfare loss for the affected coastal region, have been discussed (e.g. Voltaire and Koutchade 2020).
* Offshore wind energy infrastructure may have important disruptive impacts on the **shipping** **(\*\*)** routes of cargo vessels (Samoteskul, Firestone, Corbett, & Callahan, 2014). In case of route obstruction, wind farm owners must financially compensate cargo vessel operators to detour from their shipping routes. One such example is the Anholt wind farm in the Baltic Sea (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 (so as to avoid collision and subsequent financial compensation to cargo vessel operators) while simultaneously avoid nearshore siting, as this may reduce social acceptance due to the infrastructure’s visual impact on the population living in coastal areas, an effect that can have significant economic implications particularly in coastal touristic areas with high recreational value (see social acceptance section below). 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).
* 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. Coastal currents may lead to scouring and problems with the stability of pillars (?). *references*
* 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 a 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 evidences 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 behaviors (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 groundings as artificial reefs. There is evidence for increased fish populations in the presence of the wind farms (Leonhard et al. 2011).
* Noise from pile driving can cause temporal to permanent damages to marine mammals to different degrees, and cause their behavior changes in communication and travel (Southall et al. 2007). Cables during construction and electromagnetic field can also affect the orientation of those who use geomagnetic cues during migration (Lovich and Joshua 2013). Recently, 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 the **underwater noise (\*\*)**. Their study suggests that noise from construction and operation are without significant long-term impact on the marine mammals. Are wind parks selective hunting areas for harbor porpoises due to artzicicial reefs and high fish abundances?? *(ref ,Michael, Anita)?*
* There are potential emissions of **organic and other contaminants (?)** from all offshore activities due to increased traffic leading to disturbance of seabed sediments (release of contaminants in sediments and chemicals used in the infrastructure, leakage through lubricants, other material etc., e.g. metals, biocides, oils, coolants, dielectric fluids. However, there are no investigations on the magnitude of this potential contamination. *references*
* As any offshore activity, windfarm construction may have an impact on **dumped munitions** (?), due to possible breach of munition hulls. Since windfarms are built away of official dumpsites, solitary munitions or unofficial dumpsites are the main risk factors. In the North Sea, the construction of a windfarm in 2017 released an abandoned seamine from the sediments, and was later found floating between the pylones of the GodeWind 2 farm (https://gcaptain.com/wwii-mine-found-floating-near-german-offshore-wind-farm/)
* **Marine litter (?)** could be generated through the maintenance and traffic related to the offshore constructions. *references*
* Many species of **water birds** have been observed to react to the presence of a wind farm, from a few hundreds of meters to a few kilometers 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 the 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). There lacks studies of the offshore wind farm effect on land birds.
* Wind wake effects on atmosphere, boundary layer processes, stratification, nutrient distribution, primary production, ecosystems, food web structure? (Schrum, Daewel, Akhtar) *references*
* Impact on aquaculture, synergistic use of wind farms… *(ref)*

**p. Waterborne traffic** (Jukka-Pekka Jalkanen)

Shipping has a large impact on the environment, both in the water and in the atmosphere. The impacts are manifold and include the release of toxic bio/antifouling agents from ship hulls, the release of ballast water and waste, black and grey water, scrubbing and bilge water, the generation of underwater noise, and the release of combustion products to the atmosphere.

The Baltic Sea has some of the densest maritime traffic in the world with more than 2,000 ships in the area, on an average day (https://imohq.exposure.co/protecting-vulnerable-seas-from-shipping-and-marine-pollution). Nowadays, 80 % of the world´s trade is operated by sea traffic (UNCTAD, 2019), and 1 % of that global transport is via the Baltic Sea. 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 St. Petersburg and other ports in the eastern Baltic Sea. The main hazards on this route seem to be the shallow and narrow Katet channel. The northern part of the Baltic Sea and the Gulf of Finland can also be affected by severe ice conditions in winter.

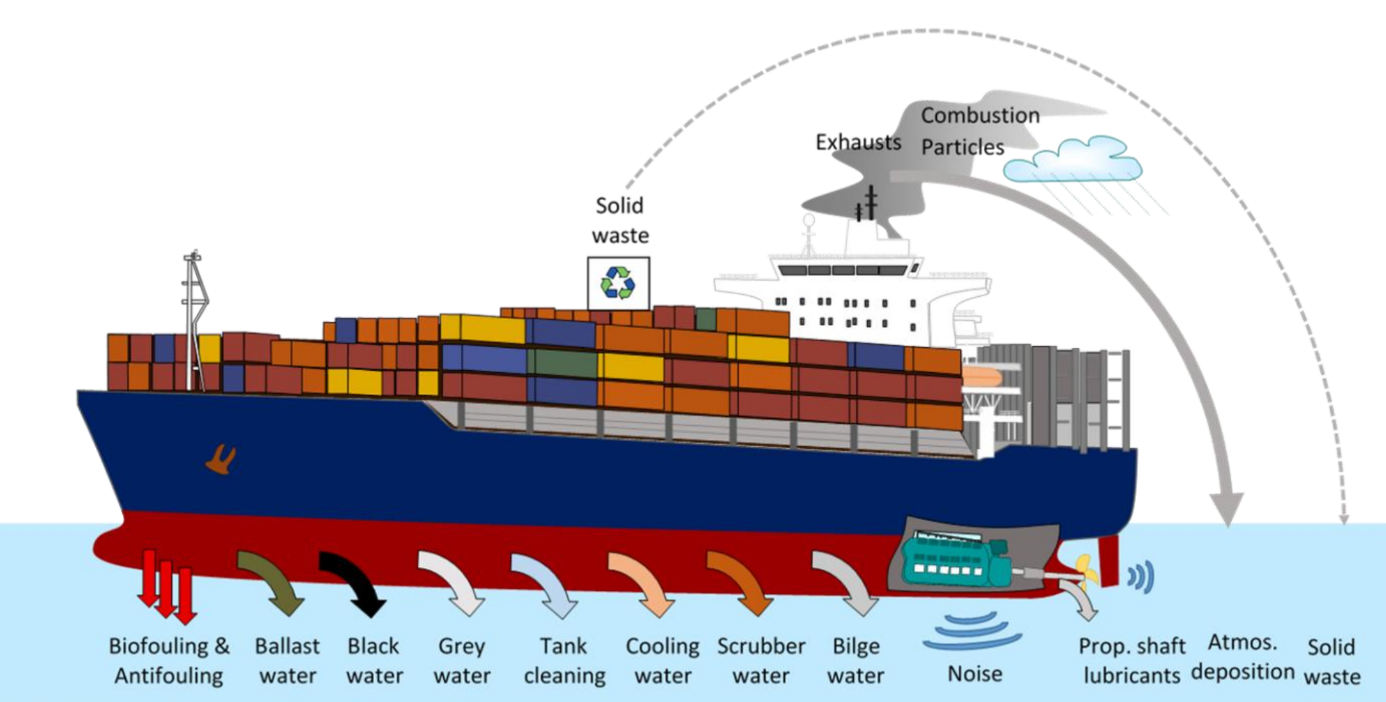


Figure: from Fig. 15 in sheba final report

Air emissions are fairly well known, vessel activity can be tracked using ship specific position reporting systems like AIS (Automatic Identification System) and emissions as well as discharges can be estimated using modeling tools (Jalkanen et al, 2009; 2012; 2018; 2020; Johansson et al, 2013, 2017). Shipping contributes to various environmental pressures, some of which are listed in Fig 15. Various pollutant streams are regulated by IMO MARPOL convention, 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, but underwater noise from ships remains unregulated. The reduction of air emissions have 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, 2011). Ship emitted NOx deposition contributes to eutrophication with a share of less than 10% of various biogeochemical variables, but this share is three to eight times larger than shipping contribution to total nitrogen input to the Baltic Sea (Raudsepp et al, 2013; 2019).

Changes required by the Sulphur reduction in marine fuels have led to quick adoption of SOx scrubbers, which are used to clean the exhaust gases by spraying them with water, which is released back to the sea. The large volumes of seawater needed make scrubber effluent release the second largest discharge stream from ships to the sea. The full impacts of SOx scrubbing is currently unknown, but several countries have prohibited the use of SOx scrubbers in port areas, anticipating potential water quality problems. In 2021, the NOx emissions regulation will be in force for new ships. This requirement is not applied retroactively for old vessels, which means that the full 80% reduction on ship emitted NOx will be visible 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 sulphur and nitrogen regulatory changes by using Liquid Natural Gas (LNG) as a shipping fuel. To this 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.

Sewage releases to the Baltic Sea will become illegal from passenger traffic in 2023, which will reduce nitrogen inflow from ships to the sea by 90% (Jalkanen et al, 2020). Introduction of non-indigineuos species through vessel hulls can be mitigated by using antifouling paints. Organotin compounds have been banned for more than a decade (AFC, 2008), but these and various other organometallic compounds remain in use especially in recreational boats. The traffic patterns of ships and recreational boats are different, ships travel along designated shipping lanes, whereas boats mostly 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 maximum. Estimated annual quantities of copper released to the Baltic Sea are about 282 and 57 tonnes for ships and boats (Jalkanen et al, 2020; Johansson et al, 2020).

Oily bilge water releases are allowed, if their oil content is below 15 ppm and vessel is not in coastal waters. Discharges of grey water (wash water from sinks, washing machines etc), emissions of energy (noise, light, heat) to the sea are currently not regulated, but importance of noise as pollution is recognised.

**Impacts of shipping on other anthropogenic drivers**

* Shipping may have an impact on **climate** (\*\*) through the emission of combustion gases and particles/aerosols (black carbon, methane, CO2) to the atmosphere with potential relevance for regional climate. In the Baltic Sea region, CO2 from shipping is less than two percent from global CO2 emissions from ships (Johansson et al, 2017; HELCOM, 2020). The global shipping emitted about 991 million tonnes of CO2 to atmosphere in 2015 (IMO, 2020), in which the Baltic Sea fleet share of CO2 was about 15 million tonnes (Johansson et al, 2017).
* 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) is evident but not well understood (e.g. Jägerbrand et al. 2019).
* There may be an impact of shipping on **offshore wind farms (\*)** through the danger of collisions in detrimental conditions (storms, loss of maneuverability). Furthermore, the location and approval of wind farms are dependent on shipping routes. Areas for specific purposes are allocated by maritime spatial planning (HELCOM, 2013).
* Shipping effects on **coastal processes (\*\*)** like erosion have been demonstrated but are not well understood; but it has been shown that in places, shipping dominates the coastal process regime through generation of dangerous waves and swell in narrow passages and rivers with potential harm for banks and coastal constructions (swell damage)(Grundmann 1966, Zaggia et al, 2017; Scarpa et al, 2019, Ulm et al. 2020).
* It has been shown that shipping is a considerable source for emission of airborne nitrogen to 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, 2019). Direct discharge from ships to the sea includes **Nutrients** (\*\*) and pharmaceuticals in the form of black, grey and bilge water, but also and food waste (Jalkanen et al, 2020).
* 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 two pH units (IMO, 2009). Even with these requirements, gradual acidification of ocean areas may occur with high adoption rate of open loop scrubbers as a means to comply with sulphur emission restrictions. Ocean acidification because of the climate change and CO2 solubility is estimated as 0.002 pH units/year (Rhein et al, 2013), whereas scrubber adoption will reduce pH with additional 0.0001 pH units/year (Turner et al. 2018). Confined water areas, like estuaries and ports, may experience larger (up to 0.015 pH units) reductions (Teuchies et al, 2020)*.*
* There is a connection between shipping and **fisheries (\*)** through competition between fishing grounds and shipping routes, the generation of underwater noise, and the contamination of fish by heavy metals and antifouling agents .(ref)
* There is a clear connection to the introduction of **non-indigenous species (\*\*\*)** as ballast water or attachment on hulls are a major pathway for the introduction of new species (Bressy & Lejars, 2014; Davidson et al., 2009).
* Shipping is a major source of water pollution in general, also for **organic** and other **contaminants (\*\*).** This is through the release of organic contaminants and heavy metals to seawater through scrubber water, and other contaminated water (black and grey water, antifoulings), but mostly inorganic contaminants like copper, zinc. (Jalkanen, 2020; Magnusson et al, 2018; Ytreberg et al, 2020). Pyrene concentrations are particularly high along shipping lanes due to release of bilge and scrubber water. *(what is pyrene and why is it important to mention, ref)*
* Furthermore, shipping can be a source of **marine litter (\*\*)** and microplastics through the disposal of solid waste to the water. *(ref)*
* 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

**q. Organic contaminants (Undeman)**

Thousands of organic chemicals, both synthetic and naturally occurring, are released intentionally or unintentionally to the Baltic Sea environment due to human activities. Emissions occur from industries, households, agriculture, forestry, urban areas, traffic, boating, power plants etc.

Negative effects arising from organic contaminants can be related to their toxicity to living organisms as well as non-toxic impacts (e.g. degradation of stratospheric ozone). It is well known that organic contaminants can negatively impact the Baltic Sea populations of marine predators (white tailed sea eagle, gray seals, ringed seals etc.), with effects propagating through the entire ecosystem as evident from the catastrophic situation in the 1970’s and 1980’s (Lehtonen et al., 2017). Today, the total effects of organic contaminants in the Baltic Sea is not known (Lehtonen et al., 2017)

Transfer routes and efficiencies, from emission sources to the Baltic Sea, depend on various factors: mode of emission (emissions to air, soil or water), physio-chemical properties (water solubility, vapor pressure, hydrophobicity, degradability in various media and organisms), and environmental characteristics (temperatures, wind speeds, organic carbon content in soil, water, air, food chain structure etc., Wania and Mackay, 1999). Many legacy pollutants are currently reaching the Baltic Sea primarily via atmospheric deposition e.g. (Breivik and Wania, 2002; Armitage et al., 2009; Bartnicki et al., 2016). Sources are located both within and outside the Baltic Sea regions. For other contaminants, riverine transport is the major transport route (e.g. pharmaceuticals, Lindim et al., 2016). For many organic contaminants detected in the Baltic Sea however, transport occurs via several pathways and it is difficult to determine their relative importance due to lack of measurements and complex emission patterns.

It is not known if the total chemical load to the Baltic Sea is increasing or decreasing. In many cases, e.g. for the banned chemicals that are monitored, emissions and environmental/biotic concentrations are declining, or now leveling off. Emissions from reservoirs in the technosphere and eventually environmental concentrations of e.g. PCBs are projected to level beyond 2050 (Breivik et al., 2016; Glüge et al., 2017).

Organic contaminants (e.g. dioxins and dioxin-like PCBs) are currently present in Baltic Sea fish in too high levels, making sales restrictions and recommendations of maximum fish intake necessary to protect human health (Pihlajamäki, Sarkki and Haapasaari, 2018). The lacking control of emitted substances in identity and amount results in the risk of unknown organic substances accumulating in the Baltic Sea and its food webs. The combined effect of the thousands of chemicals present in the Baltic Sea is not known, nor which type of chemicals are the main drivers for the mixture toxicity (van den Brink et al., 2018).

Concentrations and distributions of organic contaminant can be affected by physical forces like degradation and passive transport due to atmospheric and aquatic processes, by biological activity or by human action, which may all be influenced by climate change.

Climate change and other drivers can directly influence (reduce or enhance) concentrations of organic contaminants in different environmental matrices by impacting transport and transformation of chemicals (Macdonald et al., 2003; Noyes et al., 2009; Kallenborn et al., 2012; Balbus et al., 2013). How an organic pollutant is impacted by changing environmental characteristics depends on the emission patterns and physical chemical properties of the pollutant e.g. (Meyer, Wania and Breivik, 2005). 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, Quinn and Wania, 2011).

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, air-vegetation, leading to a different distribution between environmental compartments, like increased volatilization from sea water to air (Macdonald et al., 2003). 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, Macleod and Cousins, 2014). Changing precipitation patterns influence chemical transport via atmospheric deposition (rain dissolution and scavenging of particles, Armitage, Quinn and Wania, 2011) and runoff, transporting terrestrial organic 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).

Few modeling studies have been performed that assess the total effect of climate change on environmental concentrations for a wide range of organic pollutants. However, several case studies were made for selected substances including PCBs, dioxins, HCB and HCHs (Gouin et al., 2013). Due to counteracting effects, the total impact of climate change on environmental concentrations are simulated to be within a factor of ca. 2 for many persistent organic pollutants (Gouin et al., 2013). A modeling study by Kong et al (2014) assessed the impact of climate change on concentrations of different organic pollutants in the Baltic Sea. Concentrations of highly volatile compounds typically increased due to climate change in all compartments and under all emission modes. For more water soluble and hydrophobic compounds, concentrations increased due to climate change mainly in air and the marine compartments, and decreased in soil and freshwater (Kong, Macleod and Cousins, 2014).

Concentration trends of legacy pollutants in Arctic wildlife have been attributed to climate change-induced changes. For example, with earlier ice break-up in the year, polar bears (Ursus maritimus) starve and switch to more contaminated prey which results in higher concentrations of contaminants in the tissue (McKinney, Peacock and Letcher, 2009; Jenssen et al., 2015). Increasing PCB concentrations in burbot (Lota lota) were connected to increased organic matter concentrations (Armitage, Quinn and Wania, 2011). Climate change may affect bioaccumulation in food webs by influencing body size, growth rates and -conditions, temperature dependent ventilation rates, or biotransformation rates (Alava et al., 2017). Indirect impacts may show due to changes in primary production, the number of trophic levels (increases bioaccumulation if biotransformation is slow), diet preferences (e.g. a shift from pelagic to benthic food chain, or to prey at a higher trophic level). Low growth rates were suggested to explain the observed lack of decreasing dioxin levels in herring (Clupea sp.) in the Bothnian Bay during the last decades (Miller et al., 2013).

Baltic Sea organisms are thought to be particularly sensitive to toxic chemicals, as many organisms are marine species that already live in brackish water at non-optimal salinity, i.e. under osmotic stress. 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). Only few studies have been conducted, but there are indications that Baltic Sea organisms are more sensitive to metals and some organic contaminants than non-Baltic organisms of the same species (Magnusson and Norén, 2012; Lehtonen et al., 2017).

Hydrophobic organic contaminants sorb to organic carbon, hence, changes in organic carbon cycling influence distribution of organic contaminants (Nizzetto et al., 2010). Increased primary production in the sea influences the air-water exchange of some organic contaminants (Dachs et al., 2002). The downwards 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 sorb to the particles (Borgå, Saloranta and Ruus, 2010).

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. Moreover, eutrophication can lead to changes in food web structure, which indirectly influences bioaccumulation. Increased primary production changes the light regime in the water column, which in turn affects photolysis of organic contaminants, e.g. PBDEs (Kuivikko et al., 2007; Leal, Esteves and Santos, 2013).

Indirect effects can be induced by changed human activities due to climate change. Increasing temperatures can enhance the volatilization of chemical components in materials and stockpiles, affect land use, yields and types of crops, leading to a different use of pesticides. Similarly, a wider distribution of pests in changing ecosystems may be attempted to be controlled by an increased or changed use of pesticides. Potentially increasing forest fires may result in elevated emissions of combustion by-products such as PAHs (Gouin et al., 2013).

**Impacts of organic contaminants on other anthropogenic drivers**

* Organic contaminants may enter the coastal sea by **submarine groundwater discharge (?)**. Investigations in the southern Baltic Sea suggest that SGD may be an important source of methane, DOC, DIC (Szymczycha et al., 2012; Kotwicki et al., 2014; Donis et al., 2017), nutrients (Szymczycha et al., 2012; under review) and trace metals (Szymczycha et al., 2016). Therefore, a loading of organic contaminants to the coastal sea seems plausible, but there is as of now no direct evidence.
* Organic contaminants have a strong impact on **fisheries (\*\*).** Contaminants in fish above accepted thresholds have implications for marketing possibilities of the fish. High concentration of contaminates e.g. dioxins, have an impact on 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, 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).

**r. Unexploded ordnance (UXO) and dumped military material (DMM)** (Jazek Beldowski)

As a result of military conflicts in the 20th century, large quantities of warfare material ended up in global river, lakes, seas and oceans. Thousands of tons of various poisonous chemicals were purposely and accidentally submerged in both coastal or deep-sea areas, and the Baltic Sea is no exception. Many navy units and munition transports lost cargo or were destroyed during battles and later sunk, while aerial raids dropped significant amounts of bombs and aerial mines to coastal areas. Mine warfare, intense in both World Wars, introduced ca. 160 000 mines to the Baltic Sea, of which barely 20% has so far been removed or destroyed in clearance operations. This “Unexploded Ordnance” (UXO) is dispersed in many areas of the Baltic Sea. On top of that, the Baltic Sea was used as a dumpsite for at least 40.000 tons of chemical munitions (Discarded Military Material, DMM). Sea dumping operations took place soon after World War II, leaving official and unofficial underwater dumpsites unmonitored for several decades (Knobloch et al. 2013).

Nowadays, sea dumped chemical munitions pose a recognized environmental hazard for marine ecosystems. Recent studies performed in the dumpsites revealed that 50% of all UXO and DMM have already corroded, and their constituents have leaked to the surrounding sediments. Many substances among explosives and chemical warfare agents used as munition fillings have a demonstrated toxicity on terrestrial organisms, therefore, the dumped warfare material poses a potential threat also to aquatic organisms. On the other hand, the aquatic conditions are dramatically different from the terrestrial ones in a way that could possibly alter their effects on biota. Solubility, oxidation and hydrolyzation are among various factors that shape the fate and bioavailability of a chemical compound in aquatic ecosystems. The environmental pathways of degradation, transport and transformation of explosives and chemical warfare agents is complex and generally depends on multiple factors. However, it can be concluded, that those substances are persistent, and their degradation products may be as toxic as their parent compounds. Hydrodynamic models indicate that they may spread into neighboring areas, increasing chances of biological uptake. Indeed, first indications of bioaccumulation of explosives and chemical warfare agents in the Baltic Sea in organisms are already being reported (Niemikoski, Straumer et al. 2020). Recently, complex risk assessment methods using neural networks have been developed, taking into account environmental parameters, state of munitions, and the potential impact on biota, to assess present and future risks of dumped munitions.

The corrosion of munitions at the Baltic Sea bottom progresses, which will probably increase their impact on the environment in the near future. According to corrosion models, many containers have already released toxic substances to the environment, while others could do so in next 30-40 years. At the same time, intensifying anthropogenic activities could disturb munitions and accelerate this process. This is mostly connected with the offshore industry and increased use of the sea bottom. Hence, several scenarios should be considered:

1. Slow release of toxicants and local contamination maintained

2. Gradual increase of release and spread of contaminated areas

3. Rapid release of contamination and massive pollution

4. 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 into an overall assessment. In the third scenario, severe consequences for the entire Baltic Sea or specific areas adjacent to dumpsites 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 like white phosphorus, happen every year. The process may intensify in case of progressing corrosion of containers or anthropogenic disturbance of munitions due to offshore activities.

With increasing marine traffic and expansion of offshore activities, the presence of scattered explosives and dangerous chemicals pose a threat for workers and overall safety in the seas. The first two scenarios may have an impact on fishery, by affecting fish health and diminishing recruitment and, a limited impact on fish consumers, as they assume low contamination. There are also no existing quality regulations for food contaminated by chemical warfare agents, thus, safe rates of fish consumption by humans are not known yet, which puts the whole Baltic Sea area fisheries industry at potential risk. For example, the Bornholm Deep is a prominent dumpsite of warfare agents and it is at the same time the only spawning area for the migrating Eastern stock of Baltic Sea cod, a heavily harvested fish population. 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 high investments of coastal communities on maintaining safety on the beaches.

The first scientific examinations of dumpsites started in the late 1990’s and gained momentum in the last decade, so considerable knowledge gaps exist. Most of the research performed in the Baltic Sea area focused on chemical munitions. Degradation processes of chemical warfare agents and explosives are almost fully recognized, as well as transport mechanisms, although the list of breakdown products is still incomplete. However, not much is known about the metabolic pathways of munition related compounds in biota. This may lead to an 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. Further surveys and identification of the scattered munitions is needed to quantify their amount and state of corrosion.

The deep basins of the Baltic Sea with their partly hypoxic and anoxic “benthic deserts” overlap largely with the deep-sea warfare agent dumpsites. Local biodiversity of is low but irregular “Major Baltic Inflows” can replenish the oxygen supply, resulting in a temporal return of benthic organisms to close vicinity to the leaking objects (Czub et al. 2018). Simultaneously, the 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. Therefore, the frequency of anoxic events may amplify the pollutants release, while oxygen-rich conditions can increase their bioavailability.

Elongated warm period caused by climate change can significantly affect munitions in shallow waters, which were mostly used as conventional warfare material dumpsites. Not only the presence of hard metal objects as substrates for colonialization 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. This is caused by the release of nitrates during biodegradation of TNT and similar substances (Jessim 2018). Higher-level organisms, as ie. 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 take place for a larger part of the year. Apart of that, 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 toxic effects of munition related contaminants. The analysis of biomarkers for environmental stress in fish and mussel from the dumpsites show that chemical warfare agents and explosives act in a similar way on marine organisms, therefore the existence of other stressors can amplify the adverse effect.

**Impacts of dumped military material on other anthropogenic drivers**

* The management and treatment of dumped military material and unexploded ammunition may be an issue for **coastal management (?) and maritime spatial planning,** asallocating space for the construction of pipelines and other infrastructure need to consider about dumping sites, and actions may be necessary to cope with consequences of leaking ammunition, which are generally offshore in deep basins, but sometimes closer to the coast. *References*
* Dumped munitions may affect the development of **offshore wind farms (\*)** as these installations need to be installed in safe distance from dumping sites. This also holds for all offshore activities affecting the sea bottom. *references*
* Dumped ammunition sites can be dangerous for **fishing (\*\*)** vessels, 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 dumpsite of warfare agents and it is at the same time the only spawning area for the migrating Eastern stock of Baltic Sea cod, a heavily harvested fish population. *references*
* **Organic contaminants (\*\*\*)** concentrations can be heavily affected by leaking substances from dumped ammunitions, the poisons in question are largely organic substances Apart of that, 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 toxic effects of munition related contaminants. *reference*
* On tourism *references*
* Biodiversity, ecosystem structure, bentic communities, artificial reefs, leaking substances *references*

**s. Marine litter and microplastics (Oberbeckmann)**

Plastic litter has been known to occur in the oceans since the 1970s, but the public, scientific, and political awareness tremendously has increased over the last decade. Data on concentrations of plastic particles in the Baltic Sea are rare, and we are just beginning to understand the sources, distribution and fate of this pollution.

Plastic litter is generally categorized as macro- (>25mm), meso- (5-25mm), and micro-(<5mm) litter, with the smallest size classes being the most abundant ones in the environment, but at the same time the most difficult to detect. Larger particles (>2mm) can be easily sampled by nets and implemented in cost-effective monitoring, meeting the requirements of the Marine Strategy Framework Directive (Haseler et al. 2019). Sampling of smaller microplastics requires a more elaborate procedure (Enders et al. 2020).

Plastic contributes the largest share of human-generated litter and enters 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, fishery, and marine aquaculture (Andrady 2011, Derraik 2002, Hinojosa and Thiel 2009).

In the Baltic Sea, litter dropped at beaches is a major source for larger micro- to macroplastics, including cigarette butts (Haseler et al., in review). Regarding the smaller size fractions, municipal waste water was identified as substantial source for microplastics into the Baltic Sea (Baresel and Olshammar 2019, Schernewski et al., in review), especially stormwater runoffs including sewer overflow events, wastewater treatment plants (despite relatively good removal efficiencies), and untreated wastewater. Other sources for plastics into the Baltic Sea are marinas, agriculture, and industrial spills.

Concentrations of plastic particles in the Baltic Sea are scarce and highly variable, due to challenging and not yet harmonized methodologies. Generally, the polymers detected most frequently are the ones produced in highest quantities, such as polyethylene and polypropylene. The beaches of the Baltic Sea are significantly polluted with plastic particles, with reported numbers ranging between less than 10 to over 1000 plastic particles/kg dry weight (Urban-Malinga et al. 2020). An extensive survey of 190 sandy beaches across the whole Baltic Sea area yielded 9345 plastic particles >2mm, mostly industrial pellets (19.8 %), non-identifiable plastic pieces 2–25 mm (17.3 %), and cigarette butts (15.3 %) (Haseler et al., in review). The Warnow estuary in the southern Baltic Sea, as an example for non-beach sediment, showed microplastic abundances (>0.5mm) ranging between 46 and 379 particles/kg dry weight, with concentrations decreasing towards the opening to the Baltic Sea (2 /kg). With regard to plastic floating on the water surface, the numbers appear comparable or lower than those of other world regions (Gewert et al. 2017, Tamminga et al. 2018, Rothausler et al. 2019). Generally, distinct differences can be detected between areas with high versus low anthropogenic activity, with an increase pf plastic particles and fibers 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 days for polymers (0.02–0.5mm) in the water body, assuming beaches as 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). A long-term exposure of microplastics on early life stages of sea trout showed no effects on hatching rate, larvae survival, or growth, but 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, in particular for experimental studies targeting small microplastic fractions, and as 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 weak interactions between microplastics and microorganisms. Environmental parameters, such as nutrient concentrations or salinity, appear to be stronger factors in shaping plastic communities than polymer properties of plastic (Kesy et al. 2019, Oberbeckmann et al. 2018). A specific enrichment of microplastics with potential pathogenic bacteria, e.g. *Vibrio*, 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 is unlikely to occur in the Baltic environment at time scales relevant for human society (Oberbeckmann and Labrenz 2020). Rather, microorganisms are solely degrading residual monomers (Klaeger et al. 2019). Likewise, plastic additives or pollutants accumulating on plastic particles, such as polycyclic aromatic hydrocarbons (PAH), are more susceptible to bacterial degradation. In any case, published data on PAH accumulation on plastic and subsequent degradation are still missing for the Baltic Sea. Hence, microorganisms obviously cannot help to mitigate plastic pollution in the Baltic Sea, so it the emissions of plastic particles needs to be reduced.

In order to mitigate plastic pollution in the Baltic, several measures are possible. For example, a reduction of cigarette butts at beaches may be prevented via environmental education, fines, or a smoking ban (Kataržytė et al. 2020). With regard to microplastics from municipal wastewater, a reduction of sewer overflows from currently 1.5% to 0.3% of the annual wastewater loads would notably lead to 50% less total emissions from urban sources into the Baltic Sea (Schernewski et al., in review). So both socio-economic and technological approaches need to be taken into account.

**Impacts of marine litter and microplastics on other anthropogenic drivers**

* 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 public concern is mainly focused on fish consumption. At the same time, the fishing industry is contributing to the 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 the largest source of plastic in the Pacific (Lebreton et al. 2018).
* Ingestion of microplastics has been demonstrated for diverse **marine species** ranging from zooplankton to bivalves and fish. Ecotoxicological effects are a matter of constant research, with methodological challenges especially in the small microplastic range. Some studies on Baltic biota point from indifferent / minor effects to genotoxic effects, but no final conclusion has been reached so far. **REFERENCE**
* Plastic litter can accumulate **organic contaminants** that ad- or absorb from the particle surface. PAHs were found to accumulate on plastic particles in contrast to natural control particles (unpublished data, BONUS MICROPOLL). It has been discussed whether such contaminants can enter the food web via uptake of microplastics, but so far there is no sufficient evidence. **REFERENCE**
* 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 major pollution source on Baltic beaches (e.g. pieces from firework and cigarette butts) **REFERENCE**

**t. Underwater noise (Dähne)**

*Text and impacts pending, expected*

**u. Tourism (Saarinen)**

*Text and impacts pending, expected*

**6. Synthesis and conclusions**

*This section should discuss the matrix and the interrelations between the different drivers and climate change on the one hand, and among the different drivers on the other.*

*From each section in Ch 5 discuss 1-2 major points, the most evident and important ones; also highlight and discuss the lack of knowledge related to the effects of multiple drivers….*

*Discuss approached to tackle the problem of multiple drivers and their cumulative or synergistic effects, explain different modeling approaches…*

*Demonstrate that this paper should be an easily accessible state-of-the-art assessment of this topic. Should be also digestable by non-experts.*

*This is an early brainstorming version below…*

Climate change is a global driver of the marine systems that influence directly marine properties such as temperature, sea ice, sea level, salinity changes, and oceanic acidification. At the regional or local level, climate change interacts with several other regional and local drivers. The observed variations in the Baltic Sea region vary significantly in many parameters. The main reason for this is the Baltic Sea location between the North Atlantic and Eurasian air masses, an area that leads to considerable seasonal and inter-annual variation in low- and high-pressure systems. However, the anthropogenic climate signal is beginning to emerge from the background variability as can be observed in e.g., sea ice extent, temperature, and sea-level change.

Climate change causes many environmental problems and, together with other drivers, reduces the marine ecosystems' resilience. Within the scientific community, there is a growing understanding of the importance of developing tools to address multiple stressors' combined effects. If scientists cannot isolate and detect changes or cannot attribute the reasons for changes, the management of a healthy environment will be problematic.

This article aims to make an inventory of different drivers and, when possible, discuss how they are connected. Here we elaborate on the relationships of the various factors with climate change on the one hand and between the different elements, on the other hand. The following drivers are investigated: Socio-economic drivers, regional climate change, sea level, coastal processes, nutrient loads and eutrophication, hypoxia, acidification, submarine groundwater discharge, non-indigenous species, land use and land cover, agriculture, aquaculture, fisheries, river regulations, and restorations, coastal management, offshore wind farms, shipping, organic contaminants, unexploded and dumped warfare agents, marine litter, underwater noise, and tourism.

It is clear that socio-economic factors, such as population growth, urbanization, technological development, and values, play a significant role in healthy environmental development and are closely related to life style and climate change. The way of including socio-economic impacts are today to add several prescribed emissions storylines to the climate models, which allow studies of alternative future states. The large spread in the different scenarios reflects the uncertainty in future development, and for the Baltic Sea region, wintertime temperatures are expected to increase 2-6°C.

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