Framework to evaluate external costs of shipping

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Contents

1. Introduction

The activities that utilize the marine environment are today many, ranging from oil and natural gas extraction, to fishing and aquaculture to renewable energy installations and finally shipping and leisure boating. Thus, there is a need to understand the pressures and impacts from the different sectors on the marine environment to ensure sustainable use of marine resources. One framework to study this is the ecosystem service approach where the benefit the natural environment supply to human society via economic and social benefits, are mapped and assessed as well as the associated costs of environmental degradation due to different human activities (Beaumont et al. 2007).

Ecosystem conditions refers to the physical, chemical and biological condition of an ecosystem at a particular point in time. In EU, member states are obligated to monitor the condition (or status) of both freshwater and marine ecosystems. This is regulated via two EU Directives; the Water Framework Directive (WFD, 2000/60/EC) which covers freshwater, transitional and coastal waters up to 1 nm from the continental baseline and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) which handles all marine waters up to the Exclusive Economic Zone. The overarching aim of both WFD and MSFD is that all water bodies in the EU shall reach or maintain god status of waters, habitat and resources. This condition is termed "Good Ecological Status" (GEcS) in the WFD and "Good Environmental Status" (GES) in the MSFD. The status and conditions of ecosystems are also strongly linked to human well-being through ecosystem services as ecosystems need to be in good status in order to provide multiple ecosystem services (Pandeya et al. 2016).

Shipping is an activity responsible for a range of different pressures affecting the marine environment via discharge of hazardous compounds from greywater, bilge water, scrubber water and antifouling paints; emission of nutrients from blackwater, greywater, food waste and deposition of nitrogen oxides (NO_X); emissions of acidifying compounds from scrubber wash-water and deposition of sulphur oxides (SO_X); spread of invasive species from hulls or ballast water; and finally, underwater noise.

Shipping also affect air quality, human health, and global warming via air pollutants with transboundary properties such as fine particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO_X), sulfur oxides (SO_X). Emissions to air of black carbon and greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) are also important for the global warming impact. The knowledge about ecosystem and health impacts of air pollution is comparatively well developed, much because land-based emissions of air pollutants have been regulated in international and national regulations since the 80-ies in a tight science-policy regime.

Since the 80-ies, analytical progress has been substantial in areas such as air pollution inventories and monitoring, emission dispersion modelling, as well as integrated assessment modelling of cost effective international air pollution control. Since the 90-ies, these analytical progresses have been complemented with additional interest from environmental economists as well as health researchers. Currently, the effect of large-scale air pollution emission changes on ecosystem-, human health-, and economic impacts can be modelled with reasonable accuracy, and analysis of these impacts are done with established methods and models. Due to the transboundary nature of air pollution emissions, emissions are governed not only by national legislation but also by international legislation and agreements. Some examples of high relevance for shipping emissions are the revised EU Sulphur-in-fuels / Fuel Quality Directive (Directive No 1999/32/EC & 2009/30/EC) and the International Maritime Organisations' (IMO) use of sulphur and nitrogen emission control areas (SECA and NECA respectively) as well as limits on sulphur content in fuel (IMO 2017).

Although shipping emission impacts on air quality are relatively well established, the knowledge base is not the same for impacts on the marine environment and a coherent environmental impact assessment of shipping has not yet been made. This risk policies to be biased towards air pollution whilst trading off impacts on marine environments. Therefore, it is important that we gain a better understanding on how shipping and other sectors affect marine ecosystems, as the pressure on marine resources and the demand for marine ecosystem services in many marine water bodies are too high. The focus of this report is the shipping industry and to assess what damage it may cause on human health, marine ecosystems and the climate. Determining the total impact of shipping is a complex task, primarily with respect to marine ecosystems, as the water emissions is very diverse ranging from hazardous compounds, acidifying substances, underwater noise, eutrophying substances to invasive species.

The aim of this report is to develop a framework to determine how different pressures from shipping affect ecosystem services and human health, with an emphasis on marine environment due to larger knowledge gaps in this area. The framework could in a later stage be used to determine the resulting cost for society due to shipping induced degradation of ecosystem services and impacts on human health and climate.

2. Background

2.1. DPSIR concept

The DPSIR (Drivers, Pressures, State, Impact and Response) framework is a structured theoretical framework aiming to analyze environmental problems and to identify and propose accurate measures to reduce the problem as such (Borja et al. 2006, Atkins et al. 2011, Relvas and Miranda 2018) (Figure 1). DPSIR starts with identifying the driving force that causes specific environmental Pressures. The Pressure on the environment can in turn change the State of the environment. This change in State may cause an Impact on ecosystems and human health as well as the way human can use the ecosystem (i.e. ecosystem services). Society can then act in different ways, e.g. proposing different policies to reduce the Pressure by the specific Driver. The latter is termed Response.

Drivers of change from different sectors can have a positive or negative (pressure) effect on the status of different ecosystems. For example, increasing one or more services may result in the decrease of other services. Increased aqua culture, for example, can result in a higher nutrient load affecting eutrophication and oxygen levels in sediments. Increased transportation demand can on the other hand lead to higher particle concentrations in ambient air, leading to several different types of human health impacts. Knowledge about how different sectors affect human health, ecosystems (and their services) is significant, in particular to support policies which aim to reduce environmental pressures and strive towards a sustainable use of ecosystems. This ecosystem approach is central in the work conducted in e.g. the Baltic Marine Environment Protection Commission (HELCOM) and is used as the basis in most EU member states to ensure good environmental status and sustainable use of marine resources according to the MSFD and WFD (Borja et al. 2010). Similarly, the Impact Pathway Approach (IPA, Bickel and Friedrich (2005)) is central in management of European and EU air quality.

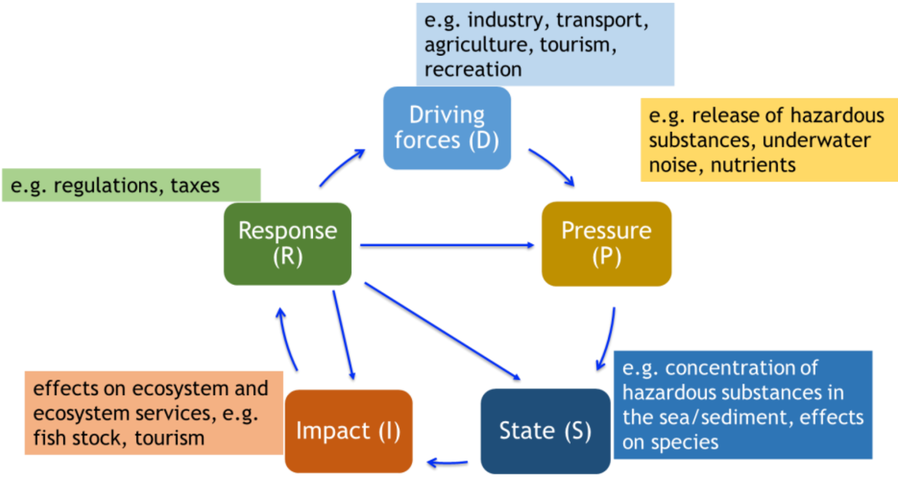

Figure 1. DPSIR Framework for reporting on environmental issues (adopted from EEA, 1995)

2.2. Marine ecosystems, regulations and the ecosystem services approach

Maritime industries such as shipping, marine tourism, fishing, and aquaculture both benefit from and supply ecosystem services as well as have a direct impact on the degradation of ecosystem services. The assessment and valuation are important first steps towards recognizing the degree to which ecosystem services contribute to national economies. Knowing their value also highlights the importance for sustainable management of ecosystems. In Figure 2, the tentative results for the dependency of Swedish human marine activities on Swedish ecosystem services and their impact on ecosystem services are shown (Kraufvelin et al. 2018).

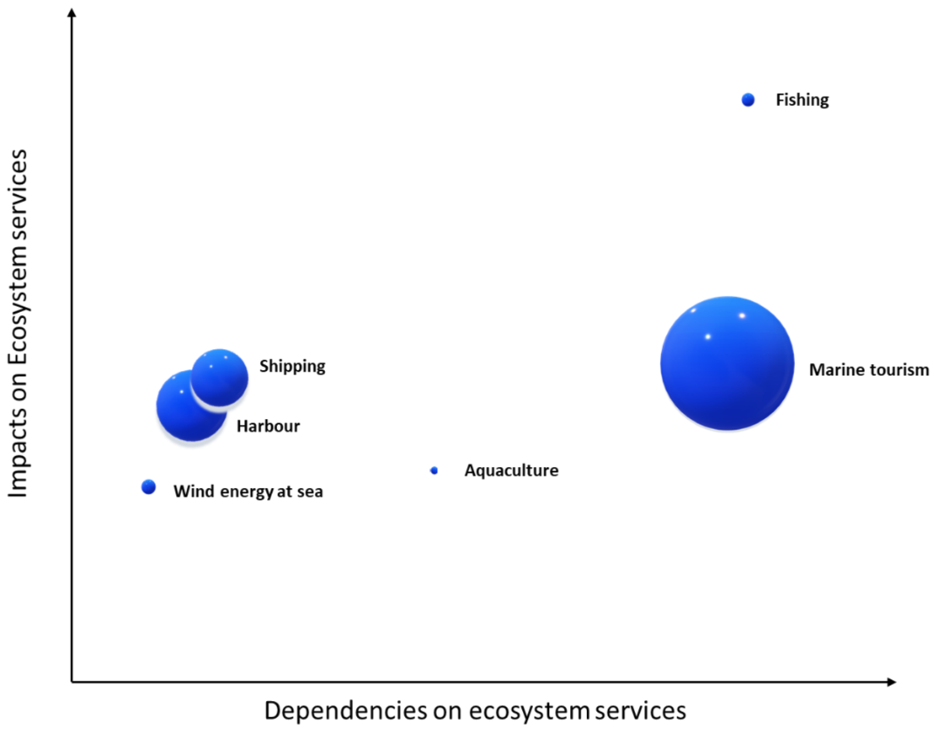

Figure 2. Tentative results for the dependency of human marine activities on ecosystem services (x-axis) and their impact on ecosystem services (y-axis). The size of the bubbles represents their financial value added. The

total financial value of all the sectors represented in the diagram is 1.5 % of the Swedish Gross Domestic Product. Modified From Kraufvelin et al. (2018)

2.2.1. Marine Strategy Framework Directive (MSFD)

The Marine Strategy Framework Directive (MSFD - Directive 2008/56/EC) is the first targeted EU legislation aiming to protect the marine environment and natural resources. The main goal of MSFD is to achieve and maintain Good Environmental Status (GES) of EU marine waters by 2020. The directive defines GES as: *"The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive".* MSFD has adopted an ecosystem-based management as a central part of its objectives to the management of human activities to reach GES (Berg et al. 2015). For example, paragraph 44 of the MSFD states that "*Programmes of measures and subsequent action by Member States should be based on an ecosystem-based approach to the management of human activities"*. The MSFD include 11 qualitative descriptors that helps EU member states to interpret what GES means in practice (Table 1). So-called Indicators shall than be developed describing the status of every descriptor. For example, under Descriptor 5 "Eutrophication is minimised" several indicators describing eutrophication is used to define when GES is reached or not. That includes e.g. concentration of dissolved inorganic nitrogen, dissolved inorganic phosphorus and oxygen dept.

Table 1. Qualitative descriptors in the Marine Strategy Framework Directive (MSFD - Directive 2008/56/EC) describing the status of the marine environment when GES has been achieved

MSFD Descriptors	
Descriptor 1	Biodiversity is maintained
Descriptor 2	Non-indigenous species do not adversely alter the ecosystem
Descriptor 3	The population of commercial fish species is healthy
Descriptor 4	Elements of food webs ensure long-term abundance and reproduction
Descriptor 5	Eutrophication is minimised
Descriptor 6	The sea floor integrity ensures functioning of the ecosystem
Descriptor 7	Permanent alteration of hydrographical conditions does not adversely affect the ecosystem
Descriptor 8	Concentrations of contaminants give no effects
Descriptor 9	Contaminants in seafood are below safe levels
Descriptor 10	Marine litter does not cause harm
Descriptor 11	Introduction of energy (including underwater noise) does not adversely affect the ecosystem

2.2.2. Water Framework Directive

The Water Framework Directive (WFD – Directive 2000/60/EC) is an EU directive focusing on understanding and integrating all aspects of the water environment to be effective and sustainable. The directive includes all freshwater systems but also covers coastal waters up to 12 nautical miles from the territorial baseline of an EU member state. The aim of the WFD is to achieve Good Ecological Status (GEcS) and Good Chemical Status in EU waters. The WFD, which was introduced in year 2000 has been referred to as a once in a generation opportunity to restore Europe's waters and a potential template for future environmental regulations (Voulvoulis et al. 2017).

GEcS is in the WFD defined in terms of the quality of the biological community, the hydrological characteristics and the chemical characteristics. The definition of ecological status handles the abundance of aquatic flora and fish fauna, the availability of nutrients and other aspects like salinity, temperature and pollution by hazardous compounds. Morphological features, such as water flow, water depths and structures of the river beds, are also taken into account.

To define good chemical status, environmental quality standards have been established for 33 chemical pollutants of high concern across the EU via the EU Directive 2008/105/EC, also known as "the EQS directive ".

Despite the high ambitious of the WFD, i.e. that all of the EU member states water bodies shall reach good ecological and chemical status, only 53% and 45% of the water bodies reached good ecological and good chemical status, respectively, in year 2015 (Voulvoulis et al. 2017).

2.2.3. Classification of ecosystem services

Ecosystem services are, according to the European Environmental Agency (EEA, 2015) *"the final outputs or products from ecosystems that are directly consumed, used (actively or passively) or enjoyed by people"*. The ecosystem services approach is increasingly being used to support sustainable management of ecosystems. There are many different classification systems at international, EU and national levels (de Groot et al. 2002). However, the most commonly used classification system of ecosystem services is the approach from the Millennium Ecosystem Assessment Report (Millennium-Ecosystem-Assessment 2005), where the ecosystems are linked to human well-being through the classification of provisioning, regulating, cultural, and supporting services. This classification system is also in use by HELCOM (2010) in their attempt to classify the ecosystem services in the Baltic Sea (Table 2).

Table 2. Classification of ecosystem services according to HELCOM (2010).

Provision ecosystem services	**Regulating ecosystem services**	**Cultural ecosystem services**	**Supporting ecosystem services**
Food	Impact on climate and air quality	Recreation	Biogeochemical cycles
Inedible goods	Sediment retention	Aesthetic value	Primary production
Energy	Reduction of eutrophication	Science and education	Food web dynamics
Space and waterways	Removal of nutrients	Cultural heritage	Biodiversity
Chemicals	Regulation of pollutants	Inspiration	Habitats
Ornamental resources		The legacy of the sea	Resilience
Genetic resources			

2.2.4. Methods for Ecosystem services valuation

A number of different monetary valuation techniques have been developed to estimate the economic values of ecosystem services and the cost of degradation of the services. These are based on either market transaction values of the specific ecosystem services (e.g. fish stock) (Pandeya et al. 2016) or when that estimation is lacking via so called shadow prices. Shadow prices are constructed prices for goods that are not traded in markets (de Bruyn et al. 2010). Water quality (e.g. no eutrophication in the Baltic Sea) is one example. By using shadow prices, the environment (in this case water quality in the Baltic Sea) can be included in various kinds of economic analysis to support decision making. Shadow prices are calculated based on either abatement costs or damage costs. Abatement costs are based on the cost for a specific measure to meet a certain target and is the most frequently used method to value ecosystem services globally (de Bruyn et al. 2010, de Bruyn et al. 2018) as well as in the Baltic Sea (Sagebiel et al. 2016). For damage cost, environmental quality is valued based on estimated damage occurring as a result of different emissions. The damage cost approach is based on information on how much people are prepared to pay for environmental quality, e.g. how much of their income they are willing to sacrifice to improve environmental quality. This is referred to as the willingness-to-pay (WTP). (Costanza et al. 1997, Nieminen et al. 2019).

2.2.5. Characterization and weighting

The number of chemical substances present on the market is estimated to be around 100,000 (KemI 2018). Hence, assessing the cumulative impact on the environment of such a vast number of chemicals is a difficult task. One way to condense the huge mass of data is to generate it into a single indicator, performed in a two-step approach: characterization and weighting of the results. Characterization is a method where so called catherization factors are used to indicate how much a specific quantity (e.g. kg) of a given pollutant contributes to a specific environmental impact (de Bruyn et al. 2010). For example, the organotin compound tributyltin (TBT) are known to be more toxic than copper for most organisms and will therefore have a higher characterization factor than copper on the impact category "marine ecotoxicity". Shipping emits various kinds of pollutants but most of the pollutants can be clustered together into different environmental themes (e.g. acidification, eutrophication and marine ecotoxicity). These themes are also known as midpoint level (Huijbregts et al. 2016). (Figure 3). These changes in the state of the environment that can occur at the midpoint level can subsequently have a direct impact on e.g. human health or on ecosystems. This latter impact is referred to as endpoint level (Huijbregts et al. 2017).

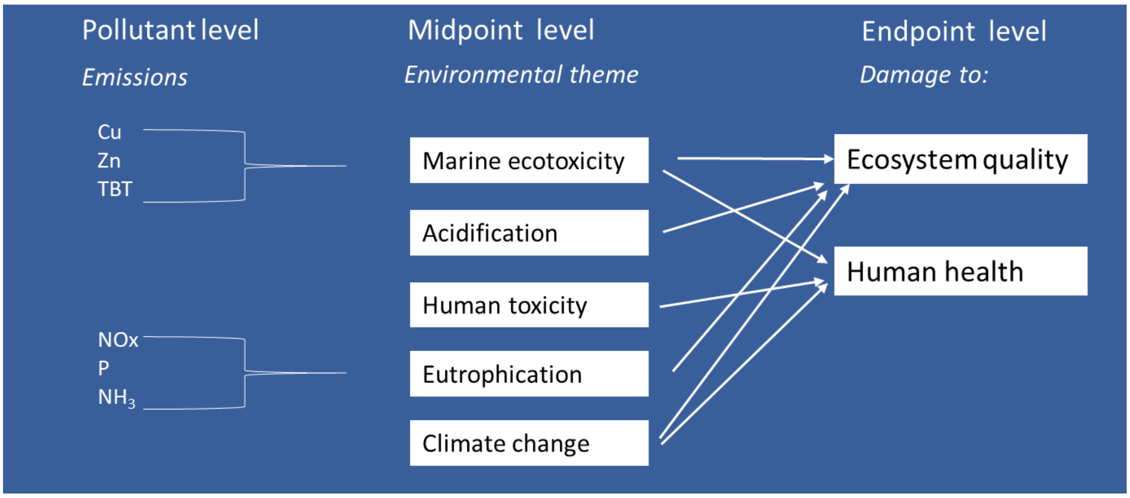

Figure 3. Relationship between pollutant level, midpoint level and endpoint level

Clustering pollutants into different pollutant levels using characterization factors and organize the environmental impacts at midpoint and endpoint levels reduces the number of datapoints. However, it is apparent that characterization will hold a variation of uncertainties depending on the knowledge of different environmental mechanisms involved in e.g. acidification, ecotoxicological responses etc. ReCiPe, which is the most recent and harmonized indicator approach available in life cycle impact assessments, have produced characterization factors for over 3000 organic substances and 20 metals for different environmental compartments (freshwater, marine waters, air etc.) (Huijbregts et al. 2016). The characterization factors in RecCiPe are presented at three different perspectives, representing archetypes of human behavior (Huijbregts et al. 2016):

1. The **individualistic** perspective is based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation.
2. The **hierarchist** perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms.
3. The **egalitarian** perspective is the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available.

Table 4, provides an overview of how the perspectives has been operationalized per impact category. As seen in table 3, no midpoint impact categories have been developed for freshwater acidification or terrestrial eutrophication.

Table 3. Overview of choices for the three perspectives; the individualistic (I), the hierarchist (H) and the egalitarian (E) according to ReCiPe (Goedkoop et al. 2008)

To midpoint impact category:	Perspectives I	H	E
climate change	20-yr time horizon	100 yr	500 yr
ozone depletion	–	–	–
terrestrial acidification	20-yr time horizon	100 yr	500 yr
freshwater eutrophication	–	–	–
marine eutrophication	–	–	–
human toxicity	100-yr time horizon organics: all exposure routes metals: drinking water and air only only carcinogenic chemicals with TD_{50} classified as 1, 2A, 2B by IARC	infinite all exposure routes for all chemicals all carcinogenic chemicals with reported TD_{50}	infinite all exposure routes for all chemicals all carcinogenic chemicals with reported TD_{50}
photochemical oxidant formation	–	–	–
particulate matter formation	–	–	–
terrestrial ecotoxicity	100-yr time horizon	infinite	infinite
freshwater ecotoxicity	100-yr time horizon	infinite	infinite
marine ecotoxicity	100-yr time horizon sea + ocean for organics and non-essential metals. for essential metals the sea compartment is included only, excluding the oceanic compartments	infinite sea + ocean for all chemicals	infinite sea + ocean for all chemicals
ionising radiation	100-yr time horizon	100,000 yr	100,000 yr
agricultural land occupation	–	–	–
urban land occupation	–	–	–
natural land transformation	–	–	–
water depletion	–	–	–
mineral resource depletion	–	–	–
fossil fuel depletion	–	–	–

Characterization will however not lead to final comparable result unless the data is further aggregated. This is called weighing and is used extensively in LCA methods (de Bruyn et al. 2010). Weighing is generally based on two different methods

1. Weighting based on expert panels or questionnaires where experts in the field are asked to describe the relative impact of environmental themes on endpoint levels.

2. Weighting based on monetization where the societal cost due to the degradation of the environment is assessed.

Shadow prices can be used for the latter form of weighting, where it represents the relative socio-economic importance of the impact on different environmental endpoints.

2.2.6. Valuation and the relationship between economic and environmental analysis

The advantage with economic valuation is that valuation of a specific pollutant can be extended to valuation of all pollutants having a similar environmental impact through the use of characterization factors. For example, assume we have a calculated shadow price for copper using damage costs based on its impact on heavy metal concentrations in shellfish for human consumption. The relative contribution of other pollutants representing the same environmental theme (e.g. zinc, lead and cadmium) can be assessed using characterization factors. In the latter, so called Predicted-No-Effect-Concentrations (PNEC), Environmental Quality Standards (EQS) or acute toxicity data (EC50), which represent the relative potential damage on the marine environment can be used for deriving characterization factors. By multiplying the calculated shadow price for copper with the characterization factor of zinc, lead and cadmium an individual shadow prize is obtained for the specific pollutants and when summarized it represent the total prize for the specific environmental impact. The latter can subsequently be compared with other environmental impacts. For example, the damage of biocides from antifouling paints (midpoint level marine ecotoxicity) on ecosystem quality can at a monetary perspective be compared with the damage of emission of nutrients from blackwater (midpoint level eutrophication) on ecosystem quality. In LCA, the toxicity potential (TP) on ecosystems is by convention expressed in kg 1,4-dichlorobenzene-equivalents (1,4-DCB-eq) and is often used as a characterization factor at the midpoint level for marine and aquatic ecotoxicity (Goedkoop et al. 2008, Huijbregts et al. 2016, Huijbregts et al. 2017). Hence, the TP of a specific pollutants is determined by dividing the potential impact of the specific pollutant (i.e. PNEC, EQS or EC50) with the potential impact of 1,4-DCB. In Table 4, various characterization factors (with units) used for different environmental themes (midpoint levels) are shown. Notably, characterization factors have not been developed for marine and freshwater acidification or terrestrial eutrophication.

Table 4. Units used for the different characterization factors according to ReCiPe (Huijbregts et al. 2016).

Environmental theme (midpoint level)	ReCiPe (2013)
Terrestrial acidification	kg SO_2-eq.
Marine eutrophication	kg N-eq.
Human toxicity: cancer	kg 1,4 DCB-eq.
Human toxicity: non-cancer	kg 1,4 DCB-eq.
Marine ecotoxicity	kg 1,4 DCB-eq.

2.2.7. Monetary valuation

There are quite few available studies that have valued the impacts of hazardous compounds on the marine environment (Martin-Ortega et al. 2011). One of the reasons for the knowledge gap is the complexity to determine how different hazardous compounds affect the State of the environment and in particular the resulting Impact on Ecosystem and Ecosystem services. However, some pollutants have been studied quite extensively, e.g. the organotin compound tributyltin (TBT) which was a widely used biocide in antifouling coatings (Bettin et al. 1996). Recent environmental monitoring in the Baltic Sea suggest TBT pollution to be widespread (Figure 4), with 93 % of the sampled coastal Swedish marine water bodies exceeding the threshold value for GES in sediments (Lagerström and Ytreberg 2018). In a recent study by Noring et al. (2016) the valuation of ecotoxicological impacts from TBT was assessed in Sweden. The study, based on peoples' willingness-to-pay (WTP), concluded that households in Sweden are willing to pay 108 USD per year to achieve GES with respect to TBT contamination. The total WTP was divided with the total amount of TBT released to the environment during the period 1965-2001 to generate a shadow price for TBT in USD/kg TBT. In the last stage, the shadow price for TBT was divided with the characterization factor to derive a generic marine ecotoxicity value expressed in 1.4 DCB-eq (Noring 2014). The result for marine ecotoxicity and weighting values for other environmental themes are shown in Table 5 (Noring 2014).

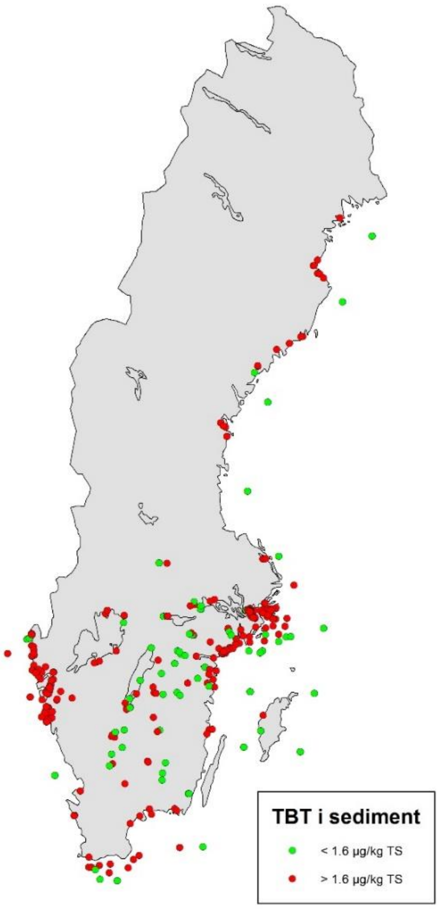

Figure 4. Concentration of tributyltin (TBT) in Swedish water bodies. From Lagerström and Ytreberg (2018)

Table 5**.** Weighting values for damage costs, in € according to Ecovalue14 (Noring 2014)

Environmental theme	**Weighting: mean value (€)**	**Weighting:interval (€)**
Terrestrial acidification	3.33/kg SO_2-eq	3.33/kg SO_2-eq
Marine Eutrophication	10/kg N	10/kg N
Freshwater Eutrophication	74.4/kg P	74.4/kg P
Human toxicity	0.312/kg 1,4 DCB-eq	0.0022–0543/kg 1,4 DCB-eq

Marine ecotoxicity	1 /kg 1,4 DCB-eq	1/kg 1,4 DCB-eq

Calculated shadow prices for over 400 pollutants (based on both damage and abatement costs) released to air, soil and freshwater have also been determined in a large research project conducted at CE Delft in 2010 (de Bruyn et al. 2010). These shadow prices were updated in 2018 and covers the impacts of over 1,000 chemicals discharged to different compartments, including marine waters (de Bruyn et al. 2018). For the damage cost calculation, characterization factors from the ReCiPe project (Goedkoop et al. 2008) were used. In the 2010 study, three endpoint levels were used; human health, ecosystem quality and resource availability. In the 2018 study, the endpoint levels were expanding and covers the following endpoint levels; human health, ecosystem services, damage to buildings and materials, resource availability and (noise and visual) nuisance.

An indicator for biodiversity loss has been developed for terrestrial ecosystems and is referred to as the Potentially Disappeared Fraction of selected species per m^2 (PDF/m^2). For a given ecosystem, a certain number of species is defined. If the state of the ecosystem changes from one with a higher number of species to one with fewer species, the number of species (biodiversity) is reduced. Hence, a 'delta PDF' can be calculated.

This PDF indicator is used in ReCiPe as a conversion factor between midpoint to endpoint levels allowing the environmental themes (e.g. ecotoxicity, eutrophication and human toxicity) to be linked to the final impact (ecosystem quality and human health). For marine ecosystems, conversion factors for ecotoxicity and eutrophication are available (Table 6).

Table 6. Midpoint to endpoint conversion factors used in ReCiPe (Huijbregts et al. 2016).

Marine ecosystems	unit	Conversion factors
Ecotoxicity	Species·year/kg 1,4-DCB emitted to sea water eq.	1.05E-10
Eutrophication	Species.year/kg N to marine water eq.	1.70E-09

In the CE Delft reports (de Bruyn et al. 2010, de Bruyn et al. 2018), terrestrial ecosystems were valued to € 0.55/PDF/m^2/year in 2008 prices (average European value). The valuation is based on a study by Kuik (2008), who performed a meta-study on the willingness-to-pay for biodiversity found in WTP studies. The terrestrial valuation has in the later CE DELFT report (de Bruyn et al. 2018) been translated to a valuation of freshwater and marine ecosystems by using the terrestrial (1.48 E-8 per m2), marine (3.46 E-12 per m^3) and freshwater (7.89 E-10 per m^3) species density from ReCiPe (Goedkoop et al. 2008). The terrestrial species density is derived based on the global land area (except agriculture areas, desserts and ice regions) divided with the known number of terrestrial species. For freshwater the volume of water in rivers, streams and lakes were divided with the known number of freshwater species. For the marine part, only the photic zone was used (upper 200 m layer) to determine the total volume of marine water. In the 2010 CE DELFT report (de Bruyn et al. 2010), the monetary valuation of terrestrial land (€ 0.55/PDF/m^2/year) was converted to m^3 water by correcting for the difference in species density. This attempt implies large uncertainties as it i) assumes an area (m^2) to be equal as a volume (m^3) ii) assumes that the species on land represent as much "welfare value" as an aquatic species.

The PDF indicator is often used in the assessment of acidification, eutrophication or ecotoxicity impact. Table 7 shows environmental prices at midpoint level and Table 8 summarize the damage costs for some priority and eutrophying pollutants emitted to water using three different midpoints (de Bruyn et al. 2018). As seen in Table 7, the calculated external costs due to ecotoxicity is three order of magnitude higher in terrestrial environments as compared to marine environments. However, using a monetary valuation conducted for terrestrial ecosystems and extrapolate it into other compartments (freshwater and marine ecosystems) will result in large uncertainties. Note also the significant difference in external costs for marine ecotoxicity using the extrapolated valuation in de Bruyn et al. (2018) (0.00756 €/kg 1,4 DCB-eq) as compared to the study by Noring (2014) (1.0 €/kg 1,4 DCB-eq). As highlighted previously, the valuation of ecotoxicological impacts by Noring is based on peoples' willingness-to-pay (WTP) to achieve GES in Swedish water bodies and is hence more relevant as compared to the study by de Bruyn et al. (2018).

Table 7. Midpoint level environmental prices (€$_{2015}$/unit), from de Bruyn et al. (2018).

Environmental theme	**Unit**	**External cost**
Climate change	€/kg CO_2-eq	€ 0.057
Ozone depletion	€/kg CFC-eq	€ 30.4
Human toxicity	€/kg 1,4 DCB-eq	€ 0.158
Photochemical oxidant formation	€/kg NMVOC-eq	€ 2.1
Particulate matter formation	€/kg PM_{10}-eq	€ 69
Terrestrial acidification	€/kg SO_2-eq	€ 5.4
Freshwater eutrophication	€/kg P-eq	€ 1.9
Marine eutrophication	€/kg N	€ 3.11
Marine ecotoxicity	€/kg 1,4 DCB-eq	€ 0.00756
Freshwater ecotoxicity	€/kg 1,4 DCB-eq	€ 0.0369
Terrestrial ecotoxicity	€/kg 1,4 DCB-eq	€ 8.89

Table 8. Environmental prices for emissions to water of prioritary and eutrophying pollutants (€$_{2015}$ per kg 2016 emissions (de Bruyn et al. 2018).

Pollutant	Environmental prize (€/kg emission)			Relevant midpoints		
	Average	Lower	Upper	Eutroph-ication	Human toxicity	Eco-toxicity
Altrazine	€ 11	€ 3.3	€ 20.9		x	x
Benzene	€ 0.0794	€ 0.0568	€ 0.124		x	x
DDT	€ 67.4	€ 47.3	€ 106		x	X
Phosphate	€ 0.629	€ 0.156	€ 1.22	X		
Total nitrogen (N)	€ 3.11	€ 3.11	€ 3.11	X		
Total phosphorus (P)	€ 1.9	€ 0.473	€ 3.71	X		
Zinc	€ 1.14	€ 0.168	€ 2.96		x	X

Cost of degradation means the change in citizens' well-being resulting from a declined status of the environment. This degradation could have many adverse impacts on human well-being both directly and indirectly and could comprise:

- severe algal blooms impacting water quality, oxygen levels and tourism
- reduced fish stocks
- elevated concentrations of contaminants in fish and shellfish impacting leisure fishing, aquaculture and fishing industry
- increased litter on beach and in the sea

- impact on biodiversity due to the introduction of invasive species

The aim of the MSFD is that all waters shall reach good environmental status (GES). If a water body fail to reach GES it will in turn also have adverse effects on human well-being. If, for example, a water body does not reach GES based on descriptor 5 (eutrophication is minimized, see Table 1), the degradation analysis could be based on damage on ecosystem services such as marine and coastal recreation, fish stock, biodiversity etc. Hence, the gap between the current status and the targeted GES status can be used to calculate the cost of degradation (Figure 5).

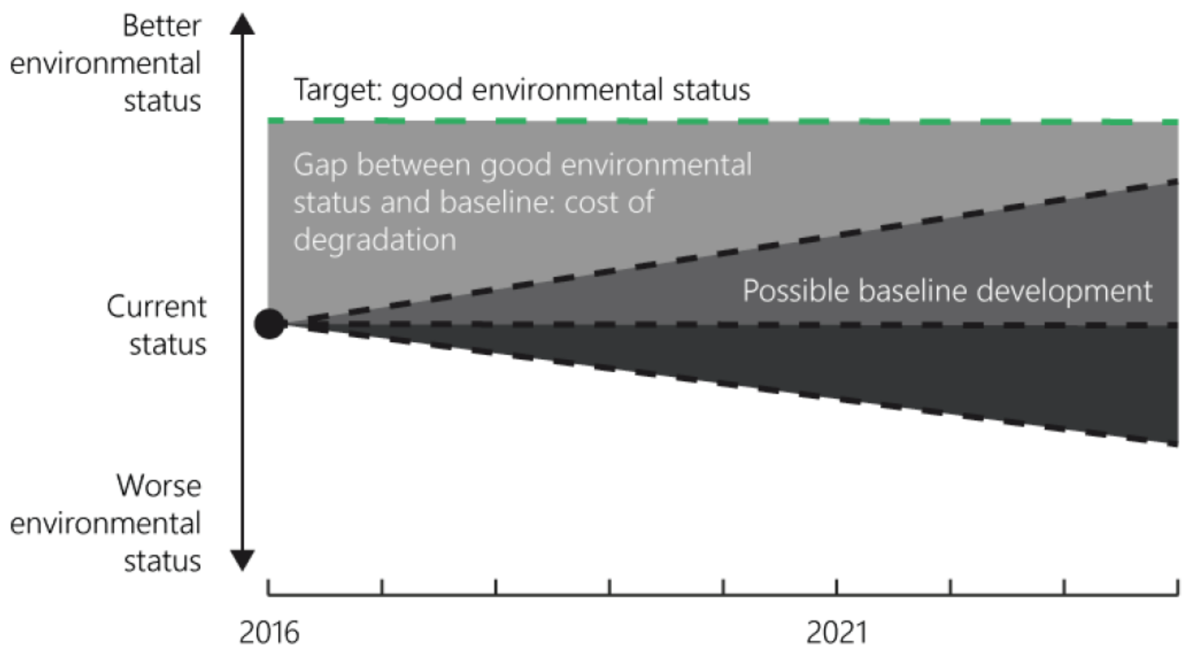

Figure 5. Illustration of the cost of degradation concept. Cost of degradation is the difference in environmental value between the current/baseline environmental status and the good environmental status (From HELCOM (2017a)).

There are several different approaches to assess the cost of degradation, including I) ecosystem service approach, II) thematic approach, and III) cost-based approach (HELCOM 2017a).

In the ecosystem approach, GES and the current baseline is defined as well as the difference in ecosystem services the specific status provide and the corresponding adverse effect on human well-being (see Figure 5).

In the thematic approach, the cost of degradation is determined according to specific degradation themes (e.g. contaminants, marine litter, eutrophication, underwater noise). Hence, the themes are based on environmental problems and the resulting consequence to human well-being.

The cost-based approach does not take into consideration the actual loss of human well-being due to marine degradation. Instead, capitals used for different measures aiming to improve the state of the sea is used as proxies for the cost of degradation.

In the HELCOM report “Economic and social analyses in the Baltic Sea region” (HELCOM 2017a), both the ecosystem approach and thematic approach were used to analyze losses in welfare due to the deterioration of the Baltic Sea environment. In the thematic approach, Descriptor 1 - Biodiversity and food webs (Kosenius and Markku 2015) and Descriptor 5 – Eutrophication (Ahtiainen et al. 2014) were used, while for the ecosystem approach only data regarding recreation was available.

For eutrophication, the gap between current status and the target for GES is estimated to cost 3.8 – 4.4 billion € annually (Ahtiainen et al. 2014).

HELCOM has set environmental targets for nutrient input in order to reach GES with respect to the MSFD descriptor 5. These targets are called maximum allowable input (MAI) and have been developed for both nitrogen and phosphorus for the entire Baltic Sea as well as per Baltic Sea sub basin (Svendsen et al. 2015). Using the annual degradation cost from Ahtiainen et al. (2014) and the remaining reduction load of nitrogen and phosphorus to reach MAI (Table 9) could be used to calculate a sub-basin external cost of nitrogen and phosphorous, respectively.

Table 9. Maximum allowable annual inputs of (a) nitrogen and (b) phosphorus per sub-basin, the average normalized annual inputs during 2010-2012, and the remaining reduction needed to reach MAI. Inputs 2010-2012 in percentages of MAI and classification of achieving MAI with 2010-2012 inputs are also given. Colours in the classification column are as follows: green=MAI fulfilled, yellow=taking into account statistical uncertainty of input data it is not possible to determine whether MAI was fulfilled, and red=MAI not fulfilled and inputs increasing. (Units in columns 2-4: tonnes per year). (modified from Svendsen et al. (2015)).

A)

Baltic Sea Sub-basin	MAI	Average norm. N input 2010-2012	Remaining reduction reaching MAI	Input 2010-12 in % of MAI	Classification based on achieved reduction
Bothnian Bay	57,622	56,962	0	99	
Bothnian Sea	79,372	77,846	0	92	
Baltic Proper	325,000	370,012	45,012	114	
Gulf of Finland	101,800	116,568	14,768	115	
Gulf of Riga	88,417	91,257	2,840	103	
Danish Straits	65,998	53,545	0	81	
Kattegat	74,000	63,685	0	86	
Baltic Sea	792,209	824,875	62,621	104	

B)

Baltic Sea Sub-basin	MAI	Average norm. P input 2010-2012	Remaining reduction reaching MAI	Input 2010-12 in % of MAI	Classification based on achieved reduction
Bothnian Bay	2,675	2,824	149	106	
Bothnian Sea	2,773	2,527	0	91	
Baltic Proper	7,360	14,651	7,291	199	
Gulf of Finland	3,600	6,478	2,878	180	
Gulf of Riga	2,020	2,341	321	116	
Danish Straits	1,601	1,514	0	95	
Kattegat	1,687	1,546	0	92	
Baltic Sea	21,716	31,883	10,640	147	

There are a few other studies that have estimated the economic benefits of reaching GES. Norton and Hynes (2014) have performed a study in Ireland where they calculated the benefit of reaching GES based on 3 different scenarios as compared to marine waters at GES conditions. The results showed the cost of degradation at the current environmental status to be 342 M€/year, and up to 749 M€/year in a high level of degradation scenario, as compared to GES conditions. The results also showed marine pollution to be one of the most important aspects where a change from a decrease in pollution to an increase in pollution would result in a marginal cost per person per year of €74.37. The cost of degradation at current conditions (compared to GES) was 28.26 €/person/year. In another study by Nieminen et al. (2019), it was concluded that Finns are willing to pay 105–123 €/person/year to achieve GES in the Baltic Sea. That would result in €432–509 million annually.

2.3. Air pollution impacts, regulations and the impact pathway approach

Air pollution, being one of the earliest environmental problems to gain international policy importance due to the transboundary nature, has been relatively well analyzed since decades in the western hemisphere. Correspondingly, governance of air quality in Europe is now a joint science-policy venture with heavy reliance on scientific output synthesized primarily by the UNECE:s Air convention.

2.3.1. International agreements and legislations on air quality

The first international agreement to govern air quality in Europe is the 1979 Convention on Long Range Transboundary Air Pollution (CLRTAP or Air Convention for clarity), with the latest progress being the 2012 amendment of the 1999 Gothenburg protocol, which set 2020 targets for air pollution emissions from parties to the Convention (United Nations 2013). The EU, whilst engaging later in the issue, has since the late 1980-ies developed a framework of continuously updated regulations that govern EU air quality. Some of the regulations are source-specific, as the Industrial Emissions Directive (ref No 2010/75/EU), the above mention fuel quality directive, and the euro standard regulations that control emissions from vehicles (Commission Regulation (EC) No:s 715/2007, 692/2008, 595/2009, 582/2011, 2016/646 etc.). On a wider level are the EU NEC Directive (2016/2284/EU), which sets national 2030 emission targets for all EU member states, and the EU Air Quality Directive (2008/50/EC), which sets ambient air quality standards for all parts of EU.

Emissions to air from shipping were relative to land-based emissions relatively unregulated until 2008 when IMO decided to regulate from 2020 the allowed sulphur content (<0.5%) in all fuel used, and to have even lower allowed sulphur content (<0.1%) in extra sensitive sea areas from 2015 (sulphur emission control areas). This was followed by an EU update of the 1999 Sulphur-in-fuels Directive (1999/32/EC) to harmonise EU and IMO regulations (amendment 2012/33/EU). In 2017 IMO designated the Baltic Sea and North Sea as nitrogen oxides emission control areas, regulating maximum allowed NO_x emissions from ships constructed after 31st December 2020 (IMO 2017).

2.3.2. Methods to valuate impacts from emission reductions

To support decision makers, scientists are synthesizing existing knowledge on air pollution within the impact pathway approach, which allows for step-by-step analysis of air pollution emissions, dispersion, exposure, impact, as well as monetized value (Figure 6).

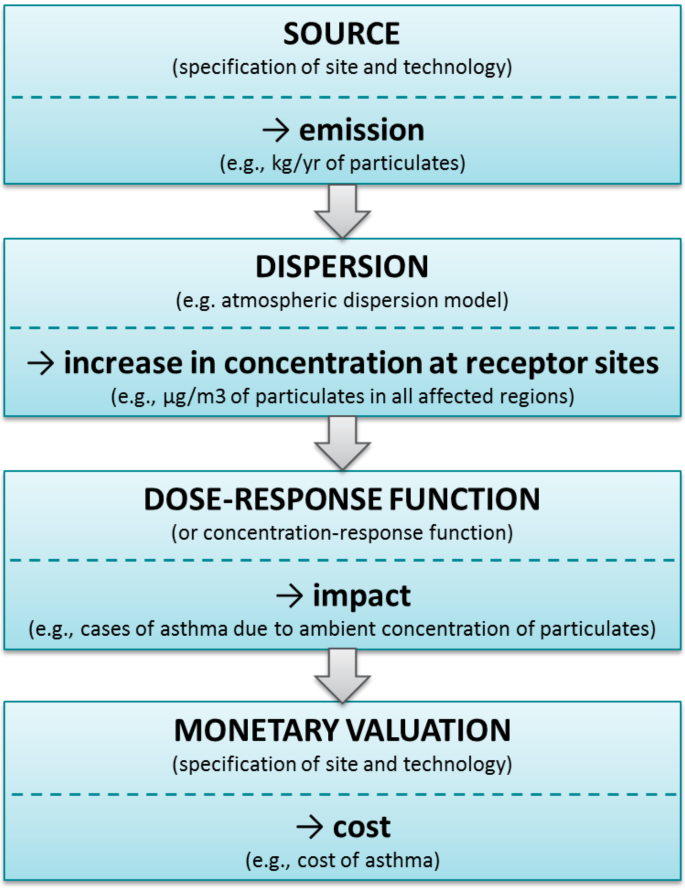

Figure 6: The impact pathway approach, adapted from (Bickel and Friedrich 2005)

In each step in the impact pathway approach there is one or several academic disciplines represented to produce scientifically reliable results to the next party. For example, emission inventory experts deliver emission estimates on high spatial and temporal resolution to emission dispersion modelers, who then can check their model results (calculated concentrations) with results (measured concentrations) of air quality measurement experts. Through this process, the knowledge on air pollution has advanced to a stage where simplified but integrated assessment models (IAM) can calculate scenarios of future air quality and valuation models can monetize the environmental and human health impacts of the different scenarios. There are today two main policy support tools commonly used by the European Commission and the Air Convention for policy analysis, the GAINS model and the ARP model. The GAINS model can, based on exogenous scenarios on Drivers, calculate emissions, ambient air concentration, as well as environmental impacts per country in Europe for any given scenario year (Amann et al. 2011, Amann 2012). The ARP model use GAINS output on population-weighted average ambient air concentration of $PM_{2.5}$, O_3, and NO_2 together with epidemiological results on relations between air pollution and health impacts (European Centre for Environment and health 2013, Heroux et al. 2015) to calculate country and year-specific health impacts of air pollution and corresponding external costs of air pollution (Holland et al. 2013, Holland 2014). Together these models can follow the entire impact pathway and deliver support to policy makers on impacts of policy proposals.

2.3.3. Methods to valuate external costs of air pollution

In contrast to the current state-of-the-art when monetizing negative impacts in the marine environment, the valuation of air pollution is based fewer environmental themes but also on more controlled experiments and long time series of data collection for mainly health effects. These experiments and time series have enabled production of simplified exposure response functions (ERF) that connect levels of concentration of pollutants in ambient air with changes in negative health outcomes. Functionally, the valuation of external costs of air pollution caused by a shift from scenario *n* emissions to scenario *n+1* emissions in the ARP model is as follows:

$$Value = \sum_{i,j,k}(\Delta conc_{i,j} * ERF_{i,k} * baseline\ risk_{i,k} * Valuation_k)$$

Where:

i, j, k : country, pollutant, health impact
Δconc : change in concentration between scenario n and n+1
ERF : Exposure response function per health impact
baseline risk : baseline risk per helth impact
Valuation : Economic value per health impact.

In contrast to the evaluation of emissions to water, the valuation of emissions to air doesn't separate between individualistic, hierarchist, and egalitarian perspectives. Rather the evaluation of air pollutants focus on a social planner perspective with long time horizon and low discount rates and full inclusion of all environmental and human health impacts recognised.

3. Adopting an ecosystem-based approach to determine the impact of shipping

In the EU BONUS project SHEBA (Sustainable Shipping and Environment of the Baltic Sea region) a framework to understand and assess the linkages from the drivers of shipping in the Baltic Sea to its effects on ecosystem services and human wellbeing has been developed (**Figure 7** and Table 10) (Hassellov et al. 2016). The framework was built on the DPSIR concept and used in the SHEBA project to, in a structured way, determine different pressures of shipping on the environment and how that Pressure will change the State of the environment and how that change may affect ecosystem and ecosystem services (Impact). A slightly modified SHEBA DPSIR framework where these links are connected are presented below.

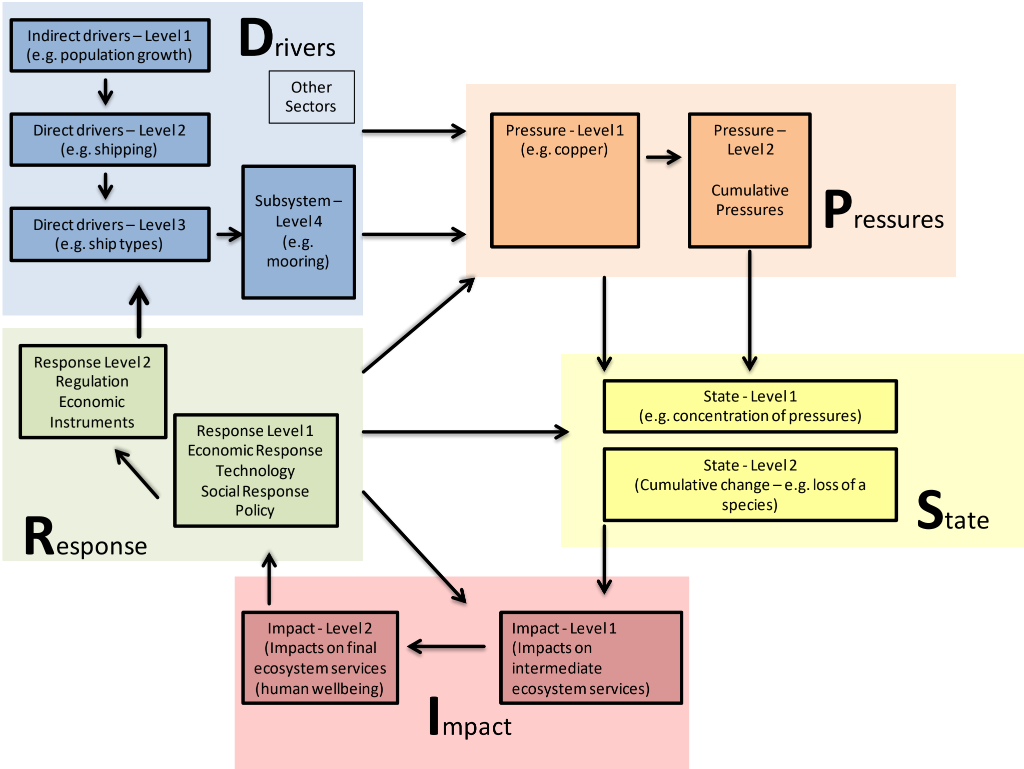

Figure 7. The DPSIR framwork for shipping in the Baltic Sea region developed in the EU BONUS project SHEBA (Hassellov et al. 2016).

Table 10. DPSIR concept for shipping with classes, levels and subcategories. From Hassellov et al. (2016)

Classes	Levels	Description
Indirect Drivers	1	Economic growth, population growth, urbanisation, trade, fuel prices, climate change, etc.
Direct Drivers	2	Shipping and leisure boating
	3	Ship types: Container ship, General cargo ship, Bulk cargo ship, RoRo ship, RoPax ship, Vehicle carrier ship, Refrigerated cargo ship, Cruise ship, Oil tanker, Product tanker, Chemical tanker, LNG tanker, LPG tanker
	4	Emission control technologies (Scrubber, Selective Catalytic Reduction (SCR) etc.)
Subsystem	4	Subsystems: Antifouling, Ballast water, Biofouling on ships, Bilge water, Cooling water, Black water, Grey water, Food waste, Scrubbing water, Stern tube oil, Litter, Engine Exhaust
Pressures	1	Pollutant cathegory: Contaminants, eutrophying substances, invasive species, acidifying substances, litter and underwater noise, primary particulates, ozone precursors, short-lived climate pollutants, greenhouse gases
	2	Cumulations of pollutants
State	1	Concentrations and levels of pollutants in the Baltic Sea and the surrounding atmosphere
	2	The cumulative effect to the environment: E.g. loss of algal species, crustaceans and fish
Impacts	1	Effects on ecosystem services: e.g. maintaining nursery populations and habitats. Direct effects on human health via impacts on the human respiratory and cardiovascular systems.
	2	Effects that changes in ecosystem services have on human wellbeing: e.g. reduced fish stocks, impacts on tourism
Response	1	Changes in techonolgy, society, economy, policy
	2	Specific measures/instruments

3.1. Drivers

DPSIR is a framework to analyze environmental problems and in particular cause-effect relationships in connection with environmental and natural resource management problems (Ness et al. 2010). DPSIR starts with identifying the driving force causing specific environmental pressures. Shipping is a complex industry comprising many different ship categories ranging from tugs, fishing vessels, and passenger ships to oil tankers and container ships (Table 10). The pressure of different pollutants on the environment will vary substantially between each ship category and the impact on ecosystem services will also depend on where and when the emissions take place. For example, impacts on human health due to emissions of PM and PM precursors will be higher in coastal areas compared to open ocean. Therefore, shipping will be split into certain ship types (see Table 10Table 10) allowing that different comparison can be made (e.g. on environmental pressures and impacts). To derive direct links to shipping pressures, the detailed subsystems which directly cause the environmental pressure must be identified. For water emissions, the subsystems comprise antifouling paints, ballast water, biofouling on ship hulls, bilge water, black water, grey water, food waste, scrubbing water and stern tube oil (Table 11 and Figure 8). For air emissions, the subsystems inlude main engines, auxillary engines and boiler engines (Table 11).

Table 11. Subsystems on ships and their potential pressure on the environment.

Subsystems	Description	Pressure category
Anti-fouling paints (water emissions)	Use of anti-fouling systems containing biocides, e.g. Cu	contaminants
Ballast water (water emissions)	Discharge of ballast water mainly in port, transfer of biological pollutants	Invasive species, contaminants,
Biofouling on ship hulls (water emissions)	Ship hull as hard substrata for attachment surface of marine organisms, transfer of biological pollutants.	Invasive species
Bilge water (water emissions)	Bilge water often contains oil, detergents, solvents, etc. which is pumped out in ports. Even though bilge water has to be cleaned with respect to oil it may still contain many other contaminants	Contaminants
Black water (water emissions)	Sewage (nutrients, pharmaceuticals and pathoGES)	eutrophying substances, contaminants
Grey water (water emissions)	Waste water (excluding sewage)	eutrophying substances, contaminants
Food waste (water emissions)	Waste from food supply of ship's crew and passengers	eutrophying substances
Scrubbing water and sludge (water emissions)	Water used in scrubber (cleaning of exhaust gases)	Acidifying substances, contaminants, eutrophying substances
Stern tube oil (water emissions)	Oil used for stern tube (connection between propeller and ship's engine room)	Contaminants
Litter (water emissions)	Ship Waste	Marine litter
Engine exhaust (air emissions)	Operation from ship's engine at the open sea	Greenhouse gases, acidifying substances, eutrophying substances, PM & PM precursors, ozone precursors,
Auxiliary engine operation in ports (air emissions)	Engine operation in ports during loading and unloading	Greenhouse gases, acidifying substances, eutrophying substances, PM & PM precursors, ozone precursors

Subsystems	Description	Pressure category
Boiler operation in ports (air emissions)	Boilers are used for several ship's machinery and services.	Greenhouse gases, acidifying substances, eutrophying substances, PM & PM precursors, ozone precursors
Engine operation (noise)	Loud continuous noise from 10 Hz to 10kHz stemming from engine operations.	Underwater noise

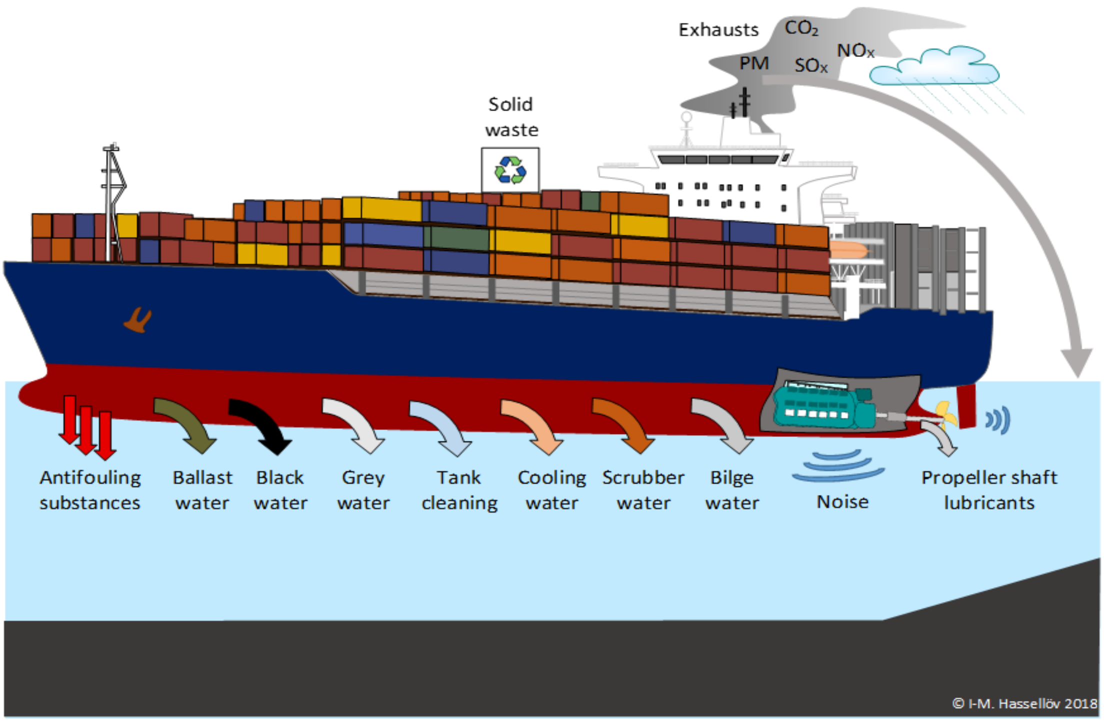

Figure 8. Subsystems from ships which directly cause different environmental pressures (©IM Hassellöv, 2018)

3.2. Pressure

Pressures describe the discharge or loads of different pollutants to the environment, e.g. the load of copper from antifouling paints to the marine environment or the emission of NO_x from engine exhaust gases to the atmosphere. The pressure of shipping on the marine environment can be divided into five pressure categories, i.e. contaminants, eutrophying substances, invasive species, litter, and noise. With this set-up, it is possible to assess to what extent shipping affect shipping relevant MSFD descriptors, i.e. contaminants (Descriptor 8 and 9), eutrophying substances (Descriptor 5), invasive species (Descriptor 2), litter (Descriptor 10) and noise (Descriptor 11) and relevant indicators. In addition, it is also possible to assess how shipping affect coastal water bodies and the WFD indicators for GEcS. In the SHEBA project, emission factors of different pressure categories have been developed for the different subsystems. The emission factors have subsequently been linked to the activity of different vessels in the Baltic (via the STEAM model developed by Jalkanen et al. (2012)). The STEAM model can output gridded pressure data set with a resolution of 1 km *1 km. Hence, the data can be used to assess the pressure at high resolution (e.g. per ship or subsystem) as well as from the entire fleet to the Baltic Sea and its sub-basins.

The following pressure categories will be used for air emissions: Primary particulates (including PM and PM precursors), acidifying compounds, eutrophying compounds, ozone precursors, short-lived climate pollutants and greenhouse gases.

3.2.1. Pressure on the marine environment

3.2.1.1. Contaminants

Contaminants can be discharged or released from many different subsystems (Table 11). In the SHEBA-project, almost 600 contaminants have been identified to be discharged from shipping and emission factors were produced for contaminants from the following sub-systems: antifouling paints, ballast water, bilge water, grey water, black water, scrubber water and stern tube oil. Pressure maps of contaminants in different water bodies have subsequently been calculated by combining the emission factors with shipping activity data in different regions.

3.2.1.2. Eutrophying substances

The total pressure from eutrophying substances, i.e. nitrogen (N) and phosphorous (P), have in the SHEBA project been determined by combining 1) atmospheric deposition of eutrophying substances via atmospheric deposition of NO_X from engine exhaust gases 2) discharge directly to sea, i.e. from grey water, black water, food waste, and bilge water.

3.2.1.3. Invasive species

Invasive species can be transported on the ship hull or via ballast water from one port to another. Ballast water is however regulated via IMO and the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM). Under the convention all ships in international traffic are required to manage their ballast water and sediments to a certain standard. The ballast water management standards will be phased in over a period of time. The convention applies directly to newbuild ships and all other ships must have an installed on-board ballast water treatment system no later than year 2024. As an intermediate solution, ships should exchange ballast water mid-ocean. At present no data are available on emission factors for invasive species from neither ship hulls or ballast water.

3.2.1.4. Acidifying substances

The emissions of SO_X and NO_X from engine exhaust gases will lead to the formation of sulphuric acid (H_2SO_4) and nitric acid (HNO_3) in the atmosphere. The deposition of these substances on the Baltic Sea will have an acidifying effect. Another subsystem that contain and discharge acidifying substances is scrubber water, where the engine exhaust gases are washed with seawater. Scrubbers can operate in two modes; open-loop or closed-loop. When operating in open-loop the wash water is discharged directly back into the sea at a typical rate of 45 m^3/MWh (IMO 2008). When operating in closed-loop mode the wash water is reused after the addition of a buffer, usually sodium hydroxide (NaOH). The discharge rate is therefore much lower, typically 0.3 m^3/MWh (IMO 2008).

3.2.1.5. Litter

Litter can be sorted under three different size classes; 1. Macro-litter from waste handling on sea and in harbours, 2. Micro-litter from e.g. antifouling paint particles 3. Nano-litter, mostly from combustion particles. However, the knowledge gap is huge and no emission factors from shipping are available.

3.2.1.6. Underwater noise

Noise source models have been conducted in the SHEBA project and in other recent research projects such as SONIC, AQUO and BIAS. In the SHEBA project a new model code for noise emission sources has been developed and have been used to generate Baltic Sea wide maps of noise sources from commercial shipping.

3.2.2. Pressures to the atmosphere

3.2.2.1. Pressure via engine exhaust emissions on non-marine environment

As with the marine environment, eutrophication and acidification are resulting also from emissions to air and deposition of eutrophying and acidifying pollutants on soils and freshwater systems. In addition, exhaust emissions are also whilst airborne causing problems with ozone damages, corrosion damages, human health effects, as well as climate impacts.

3.2.2.2. Eutrophying and acidifying substances

Eutrophication in non-marine environments caused by shipping is driven by emissions to air of nitrogen oxides via the engine exhaust subsystem, which are then transported in the atmosphere and deposited on land and freshwater areas. The acidification pressure is driven by the same mechanism but additionally caused by SO_2 emissions from engine exhaust.

3.2.2.3. Ozone and corrosion damages

Engine exhaust emissions of CH_4, NO_x, and NMVOCs can cause formation of tropospheric ozone, which in turn is associated with adverse effects on human health (WHO 2013a), crop yields (Van Dingenen et al. 2009), and forest growth (Subramanian et al. 2015). The exhaust emissions of mainly SO_2 also cause corrosion damages on buildings and materials. Stone material, concrete, and metal constructions are all sensitive to pollution (Tidblad et al. 2014).

3.2.2.4. Health effects

It is not only ozone exposure that cause health effects from ship exhaust emissions. More important is the emission of fine particulate matter and of particle-precursor gases that react in the atmosphere to form secondary particulate matter. These particles, all smaller than 2.5 µm in diameter (hence the abbreviation $PM_{2.5}$), are associated with numerous adverse health effects, including premature fatality (Thurston et al. 2017). Emissions from ships in European seas travel far enough to add substantial amounts to the European air quality with respect to $PM_{2.5}$ concentrations in ambient air and thereby to health effects.

3.2.2.5. Climate impact

It is well known that emissions of CO_2 and CH_4 will cause adverse climate impact. But also exhaust emissions of air pollutants cause climate impact, but with different characteristics. Generally, emissions of SO_x and $PM_{2.5}$ cause climate cooling, but there are sub-fractions of $PM_{2.5}$ that are potent climate forcers: black carbon (BC). But also emissions of NMVOC, NO_x, and other sub-fractions of $PM_{2.5}$ cause climate impacts (Myhre et al. 2013). Further, it is important to recognize the latitude of the Baltic sea and the corresponding relatively large deposition of PM2.5 from exhaust emissions on arctic snow and ice. This albedo effect has been analyzed for the sub-fraction BC, which is considered to have adverse climate impact (Aamaas et al. 2016).

3.3. State

The State represents the condition of the environment and can refer to both environmental concentrations of a specific pollutant or how that increased concentration adversely affect the environmental state in terms of e.g. reduced growth rate, reproduction or loss of species. Here, we will separate the State into two levels where State level 1 refers to the concentration of a specific pollutant in the atmosphere and in the marine environment and State level 2 refers to how a variation in concentration of that pollutant changes the state of the environment in terms of adverse effects on e.g. single species.

3.3.1. State of the marine environment

3.3.1.1. Contaminants

For contaminants the State will be determined both as modelled concentrations in different areas of the Baltic Sea, e.g. harbors, marinas, shipping lanes and reference sites (level 1) but also as effects on the environment, e.g. loss of species of algae, fish etc. (level 2). In the SHEBA project, over 600 unique contaminants have been identified to be discharged from the shipping. As it was not possible to model the fate and spread of all contaminants in the Baltic Sea special attention was given to five key-contaminants representing different subsystems and chemical classes. These contaminants are copper, zinc, dibromochloromethane, naphthalene and pyrene. Copper and zinc were chosen as they are released in high loads from the subsystem antifouling paints and are also present in scrubber discharge water, bilge water, grey and black water. Dibromochloromethane is emitted from ballast water in high concentration and has previously been listed as a compound that may pose a risk to the local aquatic environment (Delacroix et al. 2013). Naphthalene is discharged in high concentrations from bilge water but has also been observed in grey and black water. Pyrene is emitted from primarily from bilge water but is also present in grey water and open loop scrubber discharge water.

For the level 2 assessment impact data from scientific literature and from environmental risk assessment reports where used to identify the most sensitive groups of species. For example, several algal species are known to be sensitive to low copper concentrations and thus, if our modelled data suggest that the concentration in certain areas can be above the predicted no-effect concentration one can conclude that the cumulative discharge of copper may result in adverse effects for algal species and communities.

3.3.1.2. Eutrophying substances

For eutrophying substances State refers to the resulting increase in nitrate and phosphate in the aquatic environment due to the pressure of nitrogen (N) from NOx (air deposition), grey water, black water, food waste, and bilge water and phosphorous (P) from grey water, black water, food waste, bilge water and Lubricant oil (air deposition) (level 1) and the grade of eutrophication/ depletion of oxygen at sea floor/ density-distribution of algal blooms (level 2).

3.3.1.3. Invasive species

Modelling work on the spread of invasive species from shipping has until just recently been lacking. However, in a recent publication by Seebens et al. (2013), the authors developed a conceptual model to calculate the risk of spreading invasive species from shipping. The input data in the model is simple and comprises shipping intensity and habitat matches only. That model can be used to predict presence/absence of invasive species in an ecoregion.

3.3.1.4. Acidifying substances

No modelling exercise was performed in the SHEBA project. However, the effect of shipping on acidification in the Baltic Sea have been assessed by Omstedt et al. (2015) and Turner et al. (2018).

3.3.1.5. Litter

As emission factors of litter from shipping are currently not available, environmental State will not be able to be determined.

3.3.1.6. Underwater noise

Underwater noise maps that have been developed in the SHEBA project will be used for the State Level 1. A literature review will be conducted to estimate if and to what extent adverse effects on marine species is likely to occur (level 2).

3.3.2. State (air quality)

How to assess the state of the pressure categories on non-marine environment is well established via the work of scientific working groups coordinated by the UNECE Air Convention. Within the conceptual framework presented in this report, a policy analysis model (GAINS, (Amann et al. 2011, Kiesewetter et al. 2015)) is used to assess scenario-dependent states for the non-marine environmental pressures except climate change. However, this policy analysis utilizes analysis work done by with other models and other working groups, presented in this text.

3.3.2.1. Eutrophying and acidifying substances, ozone and corrosion damages, health effects

The state of the environmental end points driven by air pollutants emitted to air from the engine exhaust system in ships is commonly estimated by first using chemical transport models such as the EMEP model (Simpson et al. 2012) and combining these results with end-point inventories. Using eutrophication as an example, such models allows for analysis of how much of the total pollutant emissions from all ships in the Baltic sea that are deposited over nitrogen sensitive ecosystem areas. Identification of eutrophication-sensitive and acidification-sensitive areas is done by national experts and co-ordinated via the Air Conventions' Coordination Centre for Effects (Hettelingh et al. 2017). Identificiation and characterization of ozone sensitive ecosystem areas is done via dedicated ecosystem inventories (ICP Vegetation 2013), whilst state of corrosion damages is identified via exposure-response functions (ERF) linking air pollution concentrations with damages on materials and inventories of buildings and materials (Tidblad et al. 2014). The state of human health effects from ozone and $PM_{2.5}$ exposure is identified via meta-analysis of epidemiological studies providing ERFs linking changes in O_3 and $PM_{2.5}$ exposure with human health effects (WHO 2013a, b). The epidemiological evidence on NO_2 exposure on human health is growing, but as of yet there is no consensus on the causality and extent to which NO_2 exposures should be considered having direct health effects (COMEAP 2018). NO_2 health effects are therefore excluded from the estimates proposed in this report, with the corresponding risk of underestimating health effects.

3.3.2.2. Climate impact

Since full analysis of climate impact is unfeasible within the framework considered here, the state assessment of climate impact of exhaust emissions is in this theoretical framework simplified. By using common climate change metrics such global warming potential (GWP) and global temperature potential (GTP) from IPCC (Myhre et al. 2013), a reasonable estimate on the state of climate change can be given. By varying metric choice of time horizon and regional features of emission or impact, the main variances in climate impact can be captured and communicated reasonably well.

3.4. Impact

3.4.1. Impacts on the marine environment

The change in State (level 1 and 2) may have a direct impact on ecosystem services and human well-being. In the SHEBA project, the linkage between State to Impacts on marine ecosystem services was difficult to assess quantitatively. Therefore, a few case studies were performed to quantitatively assess the impact of shipping on human well-being. One example was how nitrogen emitted from shipping affects the concentration of nitrate and algae in the Baltic Sea (State), how this algae blooms affect the oxygen level in deep waters (State) and what impact the increase in anoxic sea areas have on the reproduction of cod and the ecosystem service cod landing (Impact).

3.4.2. Impacts of air emissions on non-marine environment and human health

The assessment of impacts follows the same methods as the assessment of states presented above. Most often, impact assessments are done via the scenario analysis technique which allows for comparison of different logically consistent alternative futures, such as the existence or nonexistence of a nitrogen emission control area. The impact assessment of changes in state is modelled via the impact pathway approach described above (Figure 6). Basically, the potential impacts on the non-marine environment and human health from engine exhaust emissions include forest damages, reduced richness of fish in lakes, reduced ecosystem biodiversity, increased maintenance and repair efforts on infrastructure, premature fatalities, chronic bronchitis, preterm birth, low birth-weight, long-term changes in the global and regional climate systems (including increased occurrence of extreme weather events, sea-level rise, negative human health impacts, as well as reduced biodiversity).

4. Valuation procedure in the VäSt project

In the VäSt project we will use the DPSIR-framework developed in the SHEBA-project to calculate the loads of different pressures to water and air. This approach will allow us to calculate the loads of different pressure categories (hazardous compounds, eutrophying compounds, acidifying compounds and underwater noise) on subsystem, ship and fleet level. However, as no emission factors are available for invasive species and litter from shipping, these pressure categories will not be included in the valuation. For underwater noise no valuation study exists (to our knowledge), and hence underwater noise will neither be included in the valuation.

The conceptual framework for valuation of emissions to water including the links between the different pressure categories, midpoint and endpoint levels are described in Figure 9. Midpoint and endpoint characterization factors produced in ReCiPe will be used. As these characterization factors are developed for average global scenarios, they can be applied to ship emissions at all European marine waters. The drawback with average global characterization factors is that site-specific biotic and abiotic conditions are not taken into consideration. For example, the impact of e.g. hazardous compounds on the marine environment should in general be higher if the discharge occurs in coastal areas (with a high density of marine species) as compared to open ocean (lower density of marine species). As these site-specific environmental conditions is not considered in ReCiPe, it will increase the uncertainty of the results.

At the midpoint level, characterization factors of the different pressures affecting each midpoint (environmental themes) will be used. The characterization factors developed by ReCiPe (Huijbregts et al. 2016) will be used on the different pollutants affecting the midpoint category human toxicity (kg 1,4 DCB eq.), marine ecotoxicity (kg 1,4 DCB eq) and marine eutrophication (kg N-eq). All analyzes will be conducted at an individualistic, hierarchist, and egalitarian perspective, respectively, in order to show the uncertainty.

The valuation will be conducted using three different strategies; i) shadow cost valuation based on damage and abatement costs, ii) case studies developed in the SHEBA project, iii) thematic approach using MSFD descriptors.

For air emissions, a similar external costs valuation framework will be used (Figure 10). The framework includes the following pressure categories; PM and PM precursors, acidifying compounds, eutrophying compounds, ozone precursors, short-lived climate pollutants and greenhouse gases, as was reported in Åström et al. (2018).

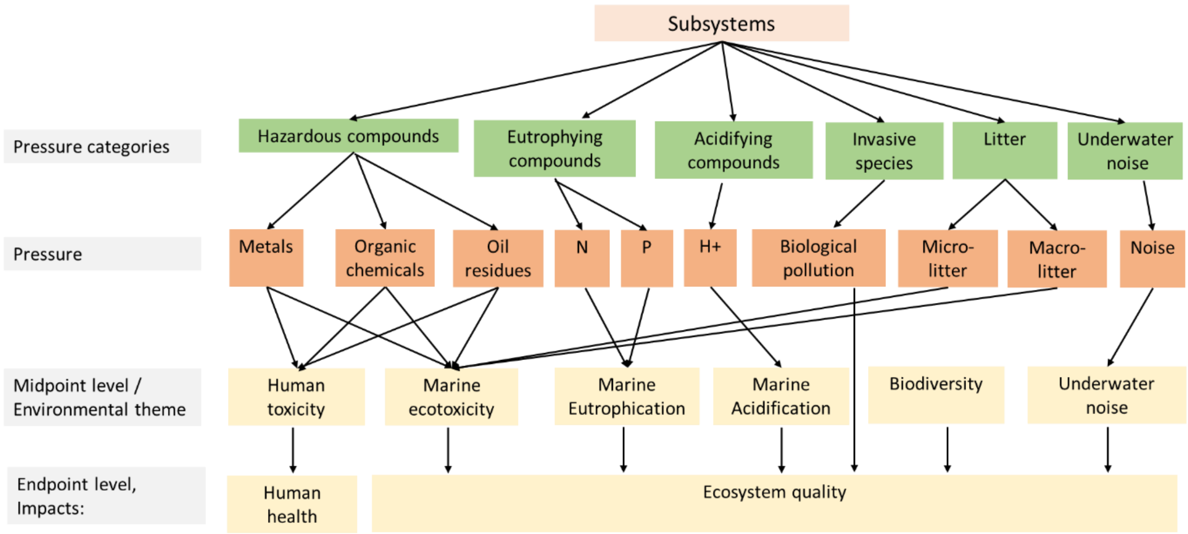

Figure 9. Conceptual framework on how shipping subsystems affects human health and marine ecosystem quality. Subsystems include Antifouling, Ballast water, Biofouling on ships, Bilge water, Cooling water, Black water, Grey water, Food waste, Scrubbing water, Stern tube oil, Litter and marine deposition of engine exhaust gases.

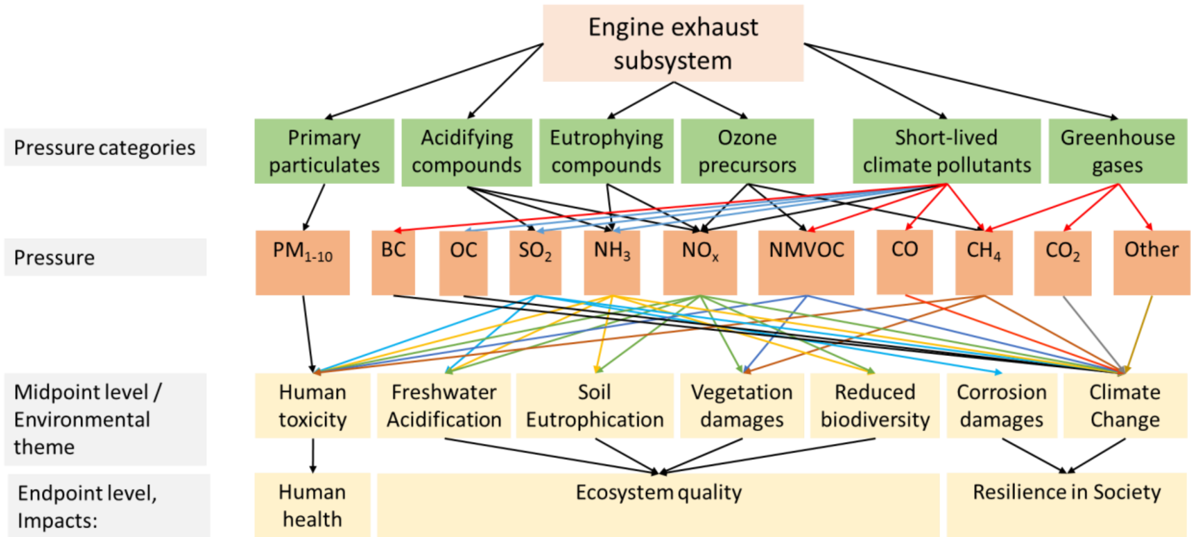

Figure 10. Conceptual link between shipping engine exhaust subsystems and environmental impacts, adapted from Myhre et al. (2013), Maas and Grennfelt (2016), Relvas and Miranda (2018). Current state-of-the-art economic evaluation includes the mid- and endpoint levels: Human health, Vegetation damages, Corrosion damages, and Climate Change. The red and blue arrows from Pressure categories to Pressure indicate warming (red) and cooling (blue). The colours on the arrows from Pressure to Midpoint are included for clarity.

4.1. Shadow cost valuation based on damage and abatement costs

For water emissions, data from de Bruyn et al (2010), de Bruyn et al (2018) and Noring (2014) will be used (see Table 5, Table 7 and Table 8) to calculate damage costs of different hazardous compounds and eutrophying compounds at the midpoint levels human toxicity, marine ecotoxicity and marine eutrophication and the corresponding impact on human health and ecosystem quality.

Characterization factors from ReCiPe will be used to valuate the impact of other hazardous compounds than reported by Bruyn et al (2010), de Bruyn et al (2018) and Noring (2014).

For emissions to air, only damage costs are utilized as basis for the shadow cost valuation (Holland et al. 2013).

4.2. Case studies developed in the SHEBA project

External cost of nitrogen on the ecosystem service cod has been developed in the SHEBA project and will be used to calculate external costs to the environmental theme “eutrophication and its impact on cod landings”.

4.3. Thematic approach using MSFD descriptors

HELCOM has set environmental targets for nutrient input in order to reach GES with respect to the MSFD descriptor 5. These targets are called maximum allowable input (MAI) and have been developed for both nitrogen and phosphorus for the entire Baltic Sea as well as per Baltic Sea sub basin (Svendsen et al. 2015). Using the annual degradation cost from Ahtiainen et al. (2014) and the remaining reduction load of nitrogen and phosphorus to reach MAI (Table 9) will allow us to calculate sub-basin external costs of nitrogen and phosphorous, respectively.

For contaminants, environmental quality standards in water, sediment and biota have been established for 33 chemicals of high concern across the EU via the EU Directive 2008/105/EC, including the polyaromatic hydrocarbons (PAH) Benzo(a)pyrene, anthrazene and fluoranthene which are known to be emitted from shipping. In the latest chemical assessment conducted by HELCOM (2017b), it was concluded that GES is not reached in any of the Baltic Sea sub-basins. In Sweden, also copper and zinc are monitored and included in the status assessment within the WFD. Both metals are relevant for shipping and are discharged from the subsystems antifouling paints, greywater, scrubber water and blackwater. Recent data from VISS (vatteninformationssystem Sverige) show 2/3 of coastal Swedish water bodies (n=39) not to reach GEcS due to elevated copper concentrations. In the VÄST project, we will be able to calculate the relative contribution of these hazardous compounds from shipping in comparison with other natural and anthropogenic sources and to what extent shipping impair the reaching of GES and/or GEcS. However, as no monetary estimation has been conducted in the Baltic Sea with respect to descriptor 8 and 9 (contaminants) a thematic approach using MSFD descriptors will not be possible to achieve at present.

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