DOCTORAL THESIS

Nutrient Discharges from Maritime Activities in the Baltic Sea: Sources, Significance and Regulatory Implications

Suvi-Tuuli Juulia Lappalainen

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Suvi-Tuuli Juulia Lappalainen

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Merendustegevusest tulenev toitainekoormus Läänemeres: allikad, olulisus ja regulatiivsed mõjud

SUVI-TUULI JUULIA LAPPALAINEN

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List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I **Lappalainen, S.-T.**, Kotta J., Tombak M.-L., Tapaninen U. (2024). Using Machine Learning Methodology to Model Nutrient Discharges from Ports: A Case Study of a Fertilizer Terminal. Journal of Marine Science and Engineering; 12(1), 143. https://doi.org/10.3390/jmse12010143

II **Lappalainen, S.-T.**, Tapaninen U., Kotta J. (2024). Nitrogen and Phosphorus Discharges from Cargo Ships' Black and Grey Waters—A Case Study of a Baltic Sea Port. Oceans; 5(3):560-570. https://doi.org/10.3390/oceans5030032

III **Lappalainen, S.-T**., Kotta, J., Aiken, D., Tapaninen, U. (2026). Maritime and Port Contributions to Coastal Nutrient Loading in the Baltic Sea: Apportionment and Regulatory Implications. Sustainability, 18(8), 3983. https://doi.org/10.3390/su18083983

Copies of the publications constituting the thesis are included in the appendices and marked in the text in Roman numbers as presented above.

Author's Contribution to the Publications

The author is the first author of the three publications included in this dissertation. Contribution to the papers in this thesis are:

I Main author. The author was responsible for the research design, performed the data collection, drafted the manuscript, with co-authors contributing to literature review, model related aspects, supervision and review.

II Main author. The author was responsible for the research design and conceptualization of the study, performed the data collection, conducted the calculations, drafted the manuscript, with co-authors contributing to ship type specific nutrient discharge modelling, supervision and review.

III Main author. The author led the research design, performed the data collection and analysis, developed the qualitative regulatory assessment scale, drafted the manuscript, with co-authors contributing to regulatory assessment, supervision and review.

1 Introduction

1.1 Background and Motivation

Eutrophication caused by excessive nitrogen and phosphorus inputs remains the most severe environmental pressure affecting the Baltic Sea (Andersen et al., 2017; Conley, 2012; Kuliński et al., 2022; Murray et al., 2019). Due to its semi-enclosed nature, limited water exchange, and long residence time, the Baltic Sea is particularly sensitive to nutrient enrichment, and recovery from accumulated nutrient loads is slow. Despite decades of international cooperation, including the Baltic Sea Action Plan (BSAP) and the EU Marine Strategy Framework Directive, nutrient reduction targets have not been achieved in several sub-basins, including the Gulf of Finland (Finnish Environment Institute [SYKE], 2024; Helsinki Commission [HELCOM], 2026; Malone, 2020; Räike, 2020).

While nutrient discharges from both land-based and maritime activities have been the subject of extensive research and regulation, they are typically assessed within separate scientific and regulatory frameworks. Regional nutrient assessments, such as the HELCOM Pollution Load Compilation, focus primarily on annual and periodic inputs of nutrients and selected hazardous substances entering the Baltic Sea through established waterborne and catchment-related pathways, whereas port-based nutrient-rich fertilizer cargo handling is not identified as a distinct nutrient-source category in the general assessment framework (HELCOM, 2022). At the same time, nutrient losses from dry bulk fertilizer storage and handling in Baltic Sea ports have been recognized by HELCOM as a substantial but insufficiently addressed source of nutrient pollution, requiring dedicated BAT/BEP guidance for ports, terminals, manufacturers and shipping companies (Kleijn et al., 2024). Earlier regional reports have also emphasized that fertilizer ports represent a potential nutrient-input source for which available information remains incomplete and further assessment is needed (Coalition Clean Baltic, 2017; Utriainen et al., 2020). More broadly, dry bulk cargo residues have been described in the peer-reviewed literature as an overlooked marine pollution pathway, with environmental assessment limited by insufficient information on cargo composition, bioavailability and toxicity (Grote et al., 2016).

At the same time, maritime nutrient discharges are governed primarily through international shipping regulations under International Maritime Organization [IMO], whereas land-based nutrient inputs are managed through a combination of HELCOM nutrient reduction targets, European Union environmental legislation and national permitting systems. These sector-specific governance arrangements have been associated with challenges related to policy integration and coherence in Baltic Sea eutrophication management (Albrecht et al., 2025; Rosemarin et al., 2025; Tynkkynen et al., 2014).

The selection of this research topic is motivated by three interrelated considerations. First, empirical evidence indicates that certain maritime-related activities—particularly fertilizer cargo handling in ports—can constitute locally significant point sources of nitrogen and phosphorus, despite being weakly studied and regulated in comparison to other point sources (Coalition Clean Baltic, 2017; Utriainen et al., 2020). Second, previous studies suggest that maritime nutrient pathways, such as black and grey water discharges from ships, contribute only marginally to total nutrient loads (Raudsepp et al., 2019), yet are subject to stringent regulatory controls (IMO; Government of Finland, 2009). Third,

existing nutrient assessments rarely integrate maritime and port-related sources into a unified source-to-sea framework alongside riverine and land-based inputs (SYKE, 2024; SYKE, 2025).

1.2 Research Gap and Research Questions

Despite considerable progress in understanding the causes of Baltic Sea eutrophication, important knowledge gaps remain regarding nutrient discharges from maritime and port activities. Nutrient inputs from shipping have been examined in studies addressing ship wastewater, grey water, food waste, and other sources (Hänninen & Sassi, 2009; Raudsepp et al., 2019; Vaneeckhaute & Fazli, 2020; Ytreberg et al., 2020; Jalkanen et al., 2021). However, these sources are rarely compared directly with port-related nutrient discharges and dominant land-based nutrient sources within a unified analytical framework. As a result, the relative significance of maritime and port-related nutrient inputs to Baltic Sea nutrient loading remains insufficiently understood.

This limitation is particularly relevant because certain port-related activities, such as nutrient-rich cargo handling, are often absent from official nutrient load inventories despite their potential local importance. Quantitative assessment of this nutrient pathway remains constrained by limited monitoring data and methodological challenges (Anttila-Huhtinen, 2021). Consequently, existing knowledge does not provide a comprehensive basis for comparing the magnitude and environmental significance of different nutrient sources across the land–sea interface. This represents the first research gap addressed in this thesis: the lack of a unified analytical framework for identifying, quantifying, and comparing nutrient sources across maritime, port, and land-based sectors.

The governance of Baltic Sea eutrophication has evolved into a complex multi-level system involving HELCOM, European Union legislation, national governments, regional authorities, and sector-specific regulatory frameworks. Previous studies have shown that governance fragmentation and differences in sectoral regulation continue to challenge the efficient implementation of nutrient reduction measures (Kern, 2011; Tynkkynen et al., 2014; Karlsson, 2016; Bohman, 2018). Furthermore, implementation challenges rather than lack of scientific understanding are increasingly recognized as major barriers to achieving good ecological status in the Baltic Sea (Brady et al., 2022; Andersen et al., 2023).

The second research gap concerns the consistency of regulatory responses to nutrient pressures. Some maritime nutrient sources are subject to strict discharge restrictions despite relatively small nutrient contributions, while other sources with demonstrated nutrient impacts are regulated more loosely. Similar discrepancies between environmental pressures and regulatory efforts have been identified in studies of agricultural nutrient management and implementation of the Baltic Sea Action Plan (Andersson et al., 2022; Thorsøe et al., 2022; Brady et al., 2022). Nevertheless, there has been limited systematic assessment of whether the level of regulation applied to different nutrient sources is aligned with their relative environmental significance. This creates an incomplete understanding of how evenly nutrient sources are treated within the existing governance framework.

This thesis addresses these gaps by combining quantitative source apportionment with regulatory analysis. By linking empirical load estimates with a structured assessment of regulatory frameworks, the study enables a systematic evaluation of the

environmental significance of maritime nutrient sources and the extent to which existing governance arrangements reflect observed nutrient pressures.

The overall purpose of this doctoral thesis is to assess the role of maritime activities in nutrient loading of the Baltic Sea by identifying and quantifying relevant sources, evaluating their environmental significance, and analysing the regulatory frameworks governing these discharges.

To achieve this purpose, the thesis addresses the following tasks:

1. To identify the principal maritime- and port-related sources of nitrogen and phosphorus discharges to the Baltic Sea by literature review.
2. To develop and apply suitable quantitative methods for estimating nutrient loads from maritime activities that are insufficiently covered by routine monitoring.
3. To assess the magnitude of maritime and port nutrient discharges in comparison with dominant land-based sources at the coastal scale.
4. To analyse and compare the regulatory instruments governing different nutrient sources and evaluate their alignment with observed nutrient pressures.
5. To identify governance gaps and potential opportunities for improving nutrient management at the land–sea interface.

The thesis addresses the following research questions (Table 1):

Table 1: Research questions.

Research question	Linked articles
RQ 1. **Sources**: What are the principal maritime- and port-related sources of nitrogen and phosphorus discharges to the Baltic Sea, and how can these sources be systematically identified and quantified?	Articles I, II
RQ 2. **Significance**: How significant are nutrient discharges from maritime and port activities in relation to total nitrogen and phosphorus inputs to Baltic Sea coastal waters, particularly in comparison with dominant land-based sources?	Articles I, II, III
RQ 3. **Regulatory Implications**: To what extent do existing international, European Union, and national regulatory frameworks governing maritime and port activities correspond to the magnitude and environmental relevance of nutrient discharges in the Baltic Sea?	Article III

1.3 Overview of Methodology and Case Studies

The thesis employs mixed method research design combining empirical measurements, modelling, calculation-based load estimation, and regulatory analysis. In the first case study, the nutrient discharges from fertilizer cargo handling are quantified using field measurements of stormwater quality and data-driven modelling approaches, including machine-learning-based Boosted Regression Trees, to capture spatial and temporal variability. In the second case study, nutrient generation from cargo ships black and grey waters is estimated using vessel traffic data, crew characteristics, and established emission factors. Total nitrogen and phosphorus loads are calculated by multiplying

nutrient generation rates per person by the number of crew members and the estimated voyage duration from the previous Baltic Sea port to the case port. In the article III, these source-specific estimates are integrated into a comparative load-based nutrient apportionment framework consistent with HELCOM Pollution Load Compilation principles. In parallel, the regulatory context governing each nutrient source is analysed using a qualitative classification scale that reflects the type and stringency of regulatory instruments, ranging from the absence of controls to explicit discharge prohibitions.

The thesis is based on a combination of primary and secondary data sources. Primary data include stormwater nutrient measurements collected at fertilizer loading terminals and port-specific operational data. Secondary data comprise official nutrient load statistics produced by environmental authorities, ship traffic and port call databases, environmental permits, and international, EU, and national regulatory documents. Peer-reviewed scientific literature provides methodological baselines and contextual information for both nutrient quantification and regulatory analysis.

1.4 Structure of the Thesis

This doctoral thesis follows a publication-based structure, in which three peer-reviewed scientific articles form the empirical core of the research.

The first two articles present source-specific case studies examining nutrient discharges from (i) fertilizer cargo handling at a port terminal and (ii) cargo ship wastewater discharges, with particular emphasis on sewage (black water) and grey water. The third article integrates the identified nutrient sources within a coastal-scale comparative assessment, combining load-based nutrient apportionment with an evaluation of the applicable regulatory framework.

The thesis consists of an introductory part, the three appended publications, a synthesis of findings, and concluding remarks outlining the scientific contributions, policy relevance, and directions for future research.

Chapter 1 (Introduction) presents the background and motivation for studying nutrient discharges from maritime activities, identifies key knowledge gaps in existing research, formulates the research questions, and describes the overall structure of the dissertation. It also outlines the theoretical and practical novelty of examining maritime and port-related nutrient discharges within an integrated source-to-sea and regulatory framework.

Chapter 2 (Literature review) examines the current state of knowledge on nutrient inputs to coastal waters, focusing on shipping-related activities. It reviews existing approaches for nutrient load estimation, discusses the representation of shipping sources within broader nutrient assessments, and analyses the regulatory and governance frameworks governing nutrient discharges in the Baltic Sea region. This chapter establishes the theoretical, methodological, and regulatory foundation for addressing Research Questions RQ1–RQ3.

Chapter 3 (Methodology) describes the overall methodological approach adopted in the thesis. It explains the case study design, the combination of empirical measurements, modelling and calculation-based load estimation, and the integration of heterogeneous data sources within a harmonized load-based apportionment framework. The chapter also details the qualitative approach used to analyze and classify regulatory instruments across different governance levels and acknowledges methodological limitations of the study.

Chapter 4 (Results) presents and synthesizes the findings of the three articles in relation to the three research questions. The results proceed from the identification of maritime and port-related nutrient sources (RQ1) to the assessment of their relative significance compared to other nutrient sources (RQ2), and finally to the evaluation of the regulatory frameworks governing these sources (RQ3).

Chapter 5 (Discussion) interprets the findings in relation to previous research and the broader context of Baltic Sea eutrophication governance. The chapter discusses the implications of the source-apportionment results for understanding the relative significance of maritime, port-related, and land-based nutrient sources and evaluates the extent to which existing regulatory frameworks correspond to the observed nutrient pressures. It further considers the implications of the findings for regulatory consistency, policy development, and nutrient management, and reflects on the limitations and transferability of the study.

Chapter 6 (Conclusions) summarizes the main findings, clarifying the scientific and practical contributions of the research, and proposes directions for future research on shipping-related nutrient discharges.

1.5 Theoretical and Practical Novelty

The theoretical contribution of the thesis lies in applying a source-to-sea perspective to compare selected maritime and port-related nutrient pathways with dominant land-based inputs within one coastal case-study area, and in linking quantified nutrient pressures with a structured assessment of regulatory attention. The work contributes to environmental governance research by demonstrating how fragmented regulatory regimes can lead to misalignment between environmental impacts- and policy focus.

The practical novelty lies in providing empirically grounded evidence that can support the development of more targeted and effective nutrient management measures. In particular, the thesis highlights fertilizer cargo handling at ports as a manageable but under-regulated nutrient source and demonstrates that from a nutrient-load reduction perspective, further tightening of ship wastewater regulation is likely to deliver only limited additional reductions compared with measures targeting larger nutrient sources. However, wastewater regulation may still be justified for reasons beyond nutrient reduction, including hygiene, local water quality, public acceptability and broader marine pollution prevention.

The need for integrated assessments that combine nutrient source quantification with governance analysis has been repeatedly identified in Baltic Sea literature (Gilek & Karlsson, 2016; Tynkkynen, 2015; Reckermann et al., 2022). Nevertheless, empirical studies linking measured nutrient pressures from shipping and ports directly to regulatory stringency remain limited.

2 Literature Review

2.1 State of the Baltic Sea

The Baltic Sea is one of the most eutrophication-sensitive marine regions in the world due to its semi-enclosed nature related to limited water exchange with the North Atlantic, shallow water depth, brackish water, and long residence time of approximately three decades (Conley, 2012; Madjidian, 2013; Nellesen et al., 2019). In addition, the catchment area of the Baltic Sea, as shown in Figure 1, is four times bigger than the sea itself with dense population of 85 million people and intense human activities (Meier et al., 2023). The Baltic Sea is also one of the busiest maritime regions globally, with up to 15% of the world's cargo traffic being handled within its waters. At any given time, approximately 2000 ships are present in the Baltic marine area, with a monthly passage of roughly 3500–5500 vessels through its waters (HELCOM, 2009).



Figure 1: The Baltic Sea Drainage Basin reaches to 14 countries (Ahlenius, 2016).

At the moment, the Baltic Sea is one of the most polluted sea areas globally: approximately 97% of its surface suffers from eutrophication (HELCOM, 2023). Nutrient enrichment has accumulated over more than a century. Since the 1850's, approximately 100 million tons of nitrogen and 4.5 million tons of phosphorus have entered the sea, with more than half of these inputs occurring during the recent fifty years (Savchuk, Eilola et al., 2012). This sustained loading has resulted in long-term ecological degradation that is slow to reverse (Savchuk, 2018). Excessive inputs of nitrogen (N) and phosphorus (P) have fuelled widespread algal blooms, reduced water transparency, and caused

recurring hypoxia and anoxia in bottom waters (Nellesen et al., 2019). These impacts have cascading effects on biodiversity, fisheries, and overall ecosystem functioning (Savchuk, Gustafsson et al., 2012; Murray et al., 2019). In recent years the total input has decreased, with nitrogen falling 12% and phosphorus 30% between reference period 1997–2003 compared to 2022. However, the input is still over the maximum allowable input especially in the Gulf of Finland (HELCOM, 2024). In addition, the due to the effect of climate change, even reaching the HELCOM maximum allowable input levels would not be sufficient to reach the good environmental status of the Baltic Sea during the next decades (Savchuk, 2018).

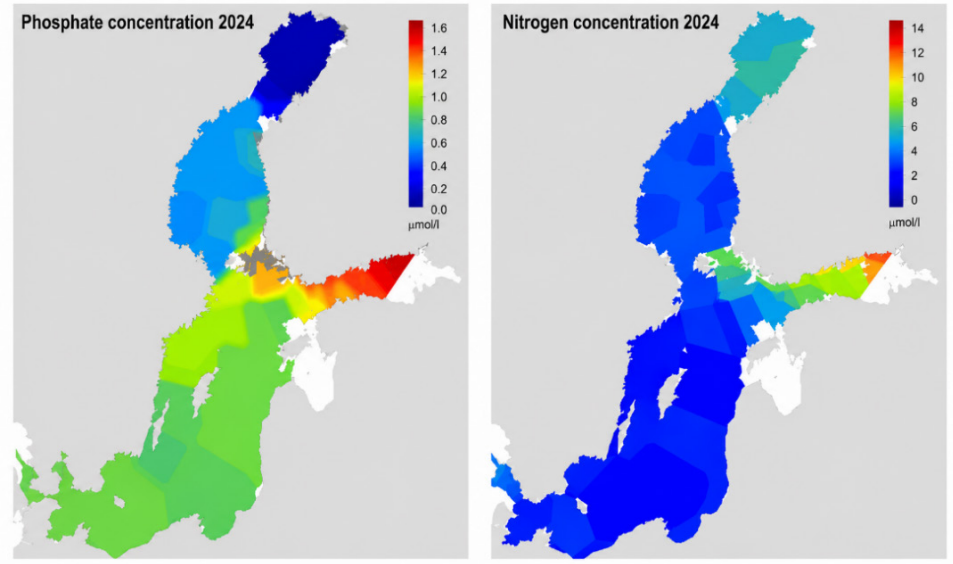


Figure 2: Surface-layer phosphate and nitrogen concentrations (µmol L^{-1}) in the Baltic Sea during the winter period of 2024. The highest concentrations occur in the eastern Gulf of Finland (SYKE, 2024).

Figure 2 shows the concentration of phosphate and nitrogen in the surface waters and reveals that the eutrophication of the Baltic Sea has biggest impact in the southern, southeastern and southwestern coasts of Finland. The signs of eutrophication are cyanobacterial blooms, water turbidity, and oxygen depletion in the seabed. The situation is worst in the eastern parts of the Gulf of Finland and the Archipelago Sea. During the recent years, the situation in the Gulf of Finland coast has slightly improved but in the Archipelago Sea the amount of cyanobacteria has further increased (SYKE, 2025).

In this thesis the focus is on one of the most eutrophicated areas as the case studies are located in the Finnish coast of the eastern Gulf of Finland.

2.2 Nutrient sources

According to studies, the average waterborne nitrogen input to the Baltic Sea has been 580 000 tons and phosphorus 22 700 tons during the years 2013-2022 (HELCOM, 2025). Approximately 74% of the nitrogen load and 97% of the phosphorus load reach the Baltic Sea via rivers or as direct waterborne discharges. Agriculture is the main contributor to the nutrient load. Other waterborne contributions originate from managed forestry,

upstream point sources, municipal wastewater treatment plants, industrial facilities, and transport (HELCOM, 2021a). The rest, 26% of the nitrogen load and 3% of the phosphorus load, is supplied via atmospheric deposition (Kiedrzyńska, et al 2014). Figure 3 describes the relative contributions of the nitrogen and phosphorus sources to the Baltic Sea.

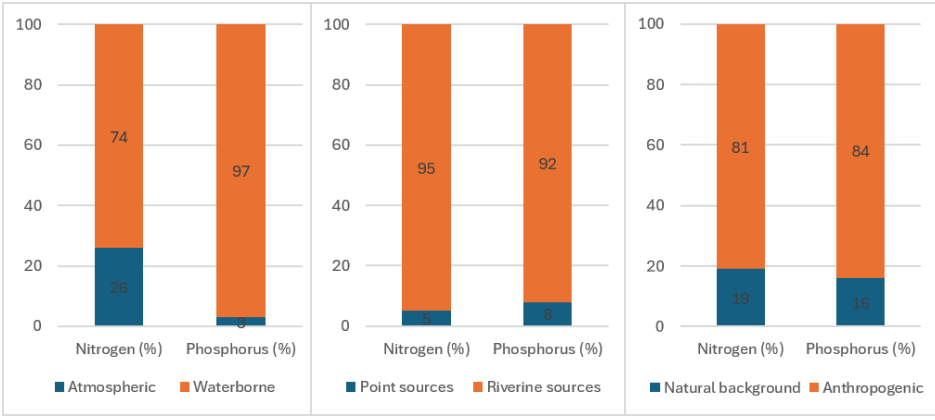


Figure 3: Relative contributions of different nutrient sources to the Baltic Sea for nitrogen and phosphorus. The figure compares (left) atmospheric deposition with waterborne inputs, (middle) point-sources with riverine inputs within waterborne loading, and (right) natural background with anthropogenic sources (adapted from Kiedrzyńska et al., 2014).

Waterborne nutrient inputs to the Baltic Sea show contrasting trends in recent years. In 2023, total nitrogen (TN) inputs reached approximately 689,000 tonnes, representing a 19% increase compared to the 2013–2022 average and a 22% rise from 2022 levels. In contrast, total phosphorus (TP) inputs were about 21,400 tonnes, which is 5.7% lower than the 2013-2022 average but still 22% higher than in 2022 (HELCOM, 2025).

Inputs from direct point sources have declined markedly since 1995—by around 57% for nitrogen and 83% for phosphorus—and accounted for only a small share of total waterborne inputs in 2023 (3.8% for TN and 5.0% for TP) (HELCOM, 2025). Input from diffuse sources has not decreased accordingly.

In Finland, approximately 90% of the human-induced phosphorus load and 80% of the nitrogen load come from diffuse sources, including cultivated fields, commercial forests, scattered settlements, and atmospheric deposition. Wastewater from industries and urban centers has a relatively minor national impact but can have a major local impact (SYKE, 2025). Shares of different nitrogen and phosphorus sources in Finland in 2024 are illustrated in Figures 4 and 5.

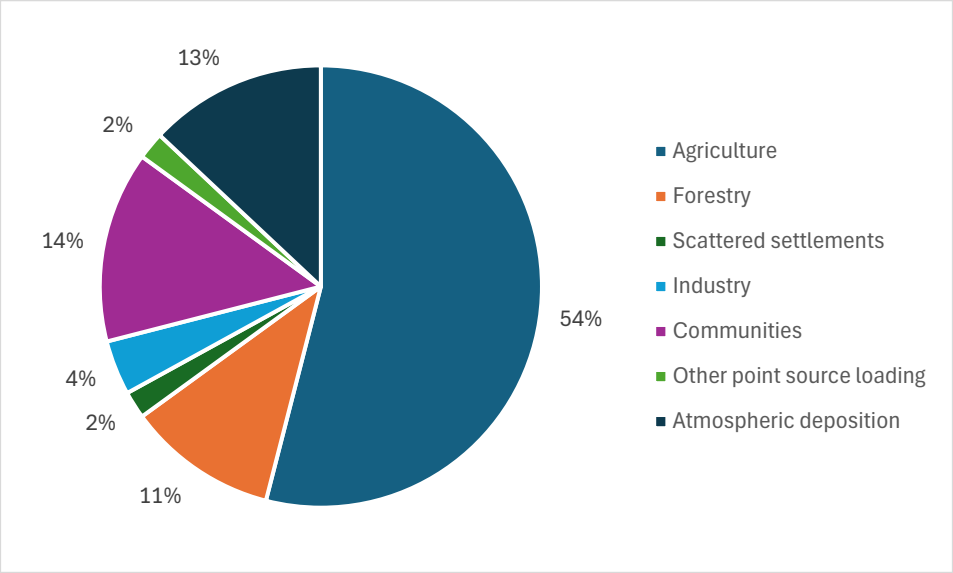


Figure 4: Biggest human sources of nitrogen to Finnish waters are agriculture, communities and forestry (adapted from Syke, 2025).

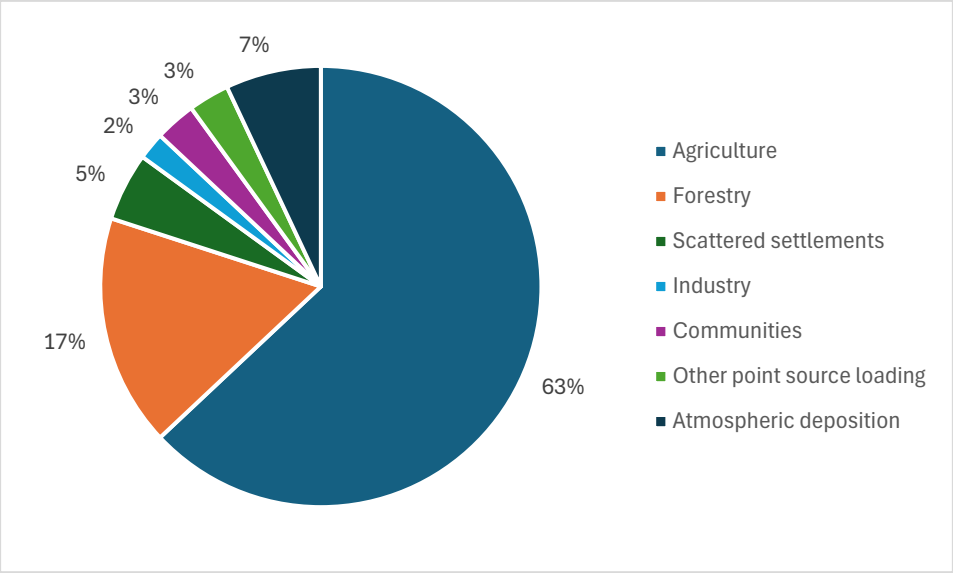


Figure 5: Biggest human sources of phosphorus to Finnish waters are agriculture and forestry (Syke, 2025).

Developing integrated nutrient source assessments is challenging because nutrient pathways are often analyzed separately and with different methodological approaches (Baresel & Destouni, 2005; Vermaat et al., 2012; Grizzetti et al., 2012).

Existing synthesis studies largely exclude maritime nutrient sources or treat them separately, making direct comparison challenging and leaving several ship and port related pathways unquantified. By combining riverine land-based inputs with available maritime discharge data and explicitly including fertilizer cargo loading addressed

elsewhere in this thesis, the study responds to RQ1 and RQ2 by improving the systematic identification and comparison of nutrient sources.

2.3 Regulatory framework

Nutrient inputs to the Baltic Sea are governed through a multi-layered regulatory framework that integrates international maritime conventions, regional environmental cooperation, European Union legislation, and national regulatory systems. This governance structure reflects both the transboundary nature of eutrophication and the diversity of nutrient sources, ranging from diffuse agricultural runoff to point-source discharges from wastewater treatment plants, industry, ports, and ships. Coordination across regulatory levels is essential, as no single instrument is sufficient to address nutrient pressures in a semi-enclosed sea with a large multinational catchment area (HELCOM, 2021a; Murray et al., 2019).

2.3.1 EU regulations

For EU Member States, nutrient regulation is implemented through EU environmental legislation, most notably the Water Framework Directive (WFD) (Directive 2000/60/EC, 2000), the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC, 2008), the Nitrates Directive (Council Directive 91/676/EEC, 1991), and the Urban Wastewater Treatment Directive (UWWTD) (Council Directive 91/271/EEC, 1991). These instruments collectively provide a complementary regulatory framework for controlling nutrient inputs from both point and diffuse sources. They establish environmental quality objectives, regulate specific sources of nutrient emissions, and require monitoring and assessment of water quality and environmental status (Joint Research Centre, 2022).

The WFD governs inland and coastal waters up to one nautical mile, directly linking river basin management to coastal nutrient inputs. The MSFD extends this approach to marine waters, explicitly identifying eutrophication as a descriptor of good environmental status. The UWWTD has been particularly effective in reducing phosphorus and nitrogen loads from municipal wastewater treatment plants, contributing substantially to progress toward BSAP targets (Preisner et al., 2021).

2.3.2 International maritime regulations

At the global level, nutrient inputs from shipping are regulated through the International Convention for the Prevention of Pollution from Ships (MARPOL), which addresses different pollution pathways via separate annexes. Nutrient-relevant discharges are primarily governed by MARPOL Annex IV (sewage) and MARPOL Annex V (garbage), both of which apply to ships operating in the Baltic Sea.

Annex IV regulates sewage discharges from ships and, following the designation of the Baltic Sea as a Special Area, imposes stringent requirements on onboard treatment systems and the delivery of sewage to port reception facilities (IMO, 2023a; HELCOM, 2020). However, there are no requirements for grey water discharge in the MARPOL Annex IV.

Annex V regulates discharge of cargo residues, which are defined as remnants of cargo remaining on deck or in cargo holds after loading or unloading, including residues entrained in wash water. Cargo residues are classified as garbage under Annex V, and their discharge into the sea is generally prohibited, particularly when the cargo is deemed harmful to the marine environment (HME). Since the 2013 amendments, solid bulk cargoes must be declared by the shipper as HME or non-HME, and the discharge of

residues containing HME substances is prohibited, including within Special Areas such as the Baltic Sea (IMO, 2023b). For non-HME cargo residues, Annex V allows limited discharge under specific conditions outside Special Areas; however, within the Baltic Sea Special Area, discharge restrictions are considerably stricter, effectively requiring the use of port reception facilities for cargo residues and associated wash waters.

2.3.3 National regulations in the Baltic countries

At the national level, Baltic Sea countries implement nutrient regulation through environmental protection acts, water laws, and permitting systems. In Finland and Sweden, nutrient discharges from municipalities, industry, and ports are regulated through integrated environmental permits aligned with EU directives and HELCOM recommendations. Denmark has implemented particularly stringent agricultural nutrient controls, contributing to its relatively strong progress toward NIC compliance (HELCOM, 2021a).

In Poland, Germany, Latvia, Lithuania, and Estonia, national legislation similarly transposes EU requirements, though differences in enforcement capacity, agricultural structure, and infrastructure development result in variable outcomes. Russia, as a non-EU HELCOM Contracting Party, applies national water and environmental legislation aligned with BSAP commitments, but regulatory instruments and enforcement mechanisms differ from those of EU Member States (HELCOM, 2018).

Across all countries, national legislation represents the primary enforcement layer, translating international and regional objectives into binding requirements. Nevertheless, differences in legal scope and administrative practice contribute to uneven nutrient reduction performance across the region (Andersen, 2023).

2.3.4 Regional coordination

Regional coordination plays an important role in Baltic Sea nutrient management because nutrient pollution frequently crosses national boundaries as well as activities in different sectors. The Helsinki Commission (HELCOM) provides the main framework for coordinating nutrient reduction efforts among Baltic Sea countries through the Baltic Sea Action Plan (BSAP). The BSAP establishes science-based nutrient reduction targets by defining Maximum Allowable Inputs (MAI) and allocating Nutrient Input Ceilings (NICs) for nitrogen and phosphorus to individual countries and sea basins (HELCOM, 2021a).

HELCOM does not replace national legislation but supports implementation through common objectives, monitoring methodologies, and periodic Pollution Load Compilations (PLC). These assessments provide a harmonized basis for evaluating nutrient inputs from different countries and sectors and support a source-to-sea approach linking catchment activities with marine environmental objectives (HELCOM, 2018; Larsen & Svendsen, 2021).

Despite substantial reductions in point-source discharges from municipal and industrial sources since the 1970s, most Baltic Sea sub-basins still exceed their nutrient reduction targets, particularly for nitrogen (HELCOM, 2021a; HELCOM, 2025). Consequently, future progress depends increasingly on addressing diffuse nutrient losses from agriculture and other non-point sources, which are more difficult to regulate and control (Bohman, 2018; Murray et al., 2019).

In addition to nutrient reduction targets, HELCOM develops recommendations, Best Available Technologies (BAT), and Best Environmental Practices (BEP) to support environmental management in sectors relevant to Baltic Sea protection. Recent guidance

has addressed nutrient losses from fertilizer handling in ports, emphasizing preventive measures, monitoring, stakeholder cooperation, and harmonized environmental practices across the region (Kleijn et al., 2024). Although HELCOM recommendations are not legally binding, they have considerable influence on national policies and sectoral environmental management throughout the Baltic Sea region.

Study answers to RQ3 by enabling assessment of whether the current distribution of regulatory attention corresponds to the magnitude and environmental relevance of different nutrient inputs to the Baltic Sea.

2.4 Land-based sources

Land-based activities constitute the dominant source of nitrogen and phosphorus inputs to the Baltic Sea and are therefore central to the implementation of regional eutrophication mitigation strategies. These inputs originate primarily from agriculture, with additional contributions from managed forestry, municipal wastewater treatment, and industrial point sources. Together, these sources form the basis for the nutrient reduction obligations allocated to Baltic Sea states under the HELCOM Baltic Sea Action Plan (BSAP) and its associated Nutrient Input Ceilings (NICs).

Agriculture is the dominant source of anthropogenic nutrient inputs to the Baltic Sea, accounting for the majority of diffuse nitrogen and phosphorus loads entering the marine environment through riverine pathways (Murray et al., 2019). Intensive fertilizer application, livestock production, and manure management have significantly increased nutrient surpluses in soils, enhancing leaching and runoff especially during high-flow events (Wulff et al., 2014). Despite substantial reductions in point-source discharges since the 1990s, agricultural nutrient loads have declined only modestly, and in several sub-basins remain the primary obstacle to achieving good ecological status (HELCOM, 2021a). Long-term accumulation of phosphorus in agricultural soils can sustain elevated nutrient losses even after fertilizer applications are reduced (Heckrath et al., 1995; Schoumans & Groenendijk, 2000; Li et al., 2019). In the coming years, climate change is expected to increase annual and especially winter runoff, shorten the snow cover period and therefore increase both nutrient leaching from agricultural areas and natural background leaching in the Baltic Sea catchment. (Huttunen et al., 2015). Additionally, nutrient inputs from agriculture are often directed toward marine regions that are specifically vulnerable to eutrophication, notably shallow coastal zones and archipelagos where water circulation is limited (Nakari, 2026).

Forestry also contributes to nutrient loading, particularly through drainage, clear-cutting, and soil disturbance, which can increase the export of nitrogen, phosphorus, and organic matter to surface waters (Moldanová et al., 2022). Although forestry-related loads are generally smaller than those from agriculture, they can be locally significant in boreal catchments and interact with agricultural pressures (HELCOM, 2018). Long-term modeling indicates that historical agricultural nutrient accumulation has created substantial legacy loads in soils and sediments, delaying ecosystem recovery even when current inputs are reduced (Tanzer et al., 2021). Forestry is a major source of nutrient loading to the Bothnian Bay, contributing over one-third of phosphorus and one-quarter of nitrogen from human activities, largely due to peatland drainage, soil treatment, and historical fertilization. While phosphorus loads have declined since the 1990s mainly due to reduced fertilization, nitrogen loads have not decreased—and in some areas have increased—due to long-term drainage impacts and climate-driven runoff, even as new fertilization practices aim to limit discharges (Nakari, 2026).

Overall, studies consistently show that effective mitigation of Baltic Sea eutrophication depends primarily on reducing nutrient losses from agriculture and, to a lesser extent, managed forestry, through targeted, catchment-specific measures and long-term policy commitment (Murray et al., 2019; HELCOM, 2021a).

Water protection in agriculture in Finland is governed by the so-called Nitrates Decree, the Phosphorus Decree issued under the Fertilizer Act, legislation on structural support for agriculture, the Water Act, and the Environmental Protection Act, as well as several other laws and regulations, such as those concerning plant protection products and fertilizers. The operation and environmental impacts of livestock farming are also guided through environmental permitting procedures and a general notification procedure.

The Finnish Phosphorus Decree, introduced in 2023, tightened restrictions on the use of mineral phosphorus fertilizers aiming to reduce nutrient losses from agriculture. However, manure application remains subject to partly different regulatory provisions, allowing higher phosphorus inputs under certain conditions. While this approach supports the utilization of livestock manure, concerns have been raised regarding its effectiveness in preventing long-term phosphorus accumulation in agricultural soils and subsequent nutrient losses to water bodies (Laakso & Luostarinen, 2019; Iho et al., 2023).

Environmental aspects are also included in the European Union's Common Agricultural Policy (CAP). In practice, environmental protection measures are guided by the support conditions included in the CAP, the eco-schemes, and a voluntary agri-environmental payment scheme for farmers with its associated measures. Slightly less than 90 percent of Finland's farmland and farms are covered by this scheme. It has had a positive environmental impact although not entirely as expected, due in part to shortcomings in the targeting of measures. Previous studies have demonstrated the effectiveness of mitigation measures such as buffer zones, constructed wetlands and gypsum amendment in reducing phosphorus losses from agricultural catchments (Uusi-Kämppä et al., 2000; Tanner & Sukias, 2011; Ekholm et al., 2012; Uusitalo et al., 2012). The latest CAP programming period covers the years 2023–2027 (SYKE, 2022).

Municipal wastewater treatment plants and industrial facilities constitute the principal point sources of nitrogen and phosphorus inputs to the Baltic Sea. Historically, untreated or insufficiently treated municipal and industrial effluents represented one of the dominant anthropogenic drivers of eutrophication in the region. Since the late twentieth century, extensive investments in wastewater infrastructure and the implementation of the EU Urban Wastewater Treatment Directive have resulted in substantial reductions in nutrient discharges from these sources (Preisner et al., 2021; HELCOM, 2021a).

Despite these improvements, municipal wastewater remains the second-largest anthropogenic nutrient source to the Baltic Sea after agriculture, particularly with respect to phosphorus. According to recent assessments, domestic wastewater accounts for a significant share of anthropogenic phosphorus inputs, while its relative contribution to nitrogen loading is smaller but still environmentally relevant in densely populated coastal catchments (HELCOM, 2021a). Remaining discharges originate primarily from wastewater treatment plants lacking advanced nutrient removal, combined sewer overflows during high-flow events, and households in scattered settlements not connected to centralized treatment systems (Preisner et al., 2021).

Industrial nutrient inputs have declined markedly over recent decades due to stricter permitting, technological improvements, and process optimization. Industrial facilities now contribute only a minor fraction of total nutrient loads at the Baltic Sea scale;

however, they may exert locally significant impacts in coastal areas receiving direct discharges (HELCOM, 2018). Industrial effluents often contain nutrients in forms that are readily bioavailable, which may enhance their eutrophication potential relative to diffuse sources.

Overall, the scientific literature indicates that while point-source nutrient loads from municipal and industrial sources have been successfully reduced, further progress is constrained by diminishing returns from conventional treatment upgrades and by residual discharges associated with stormwater, legacy infrastructure, and small-scale settlements. Consequently, continued nutrient management in the Baltic Sea requires maintaining high treatment standards, addressing urban runoff and overflow events, and integrating wastewater controls with broader catchment-scale nutrient reduction strategies (Murray et al., 2019; HELCOM, 2021a).

In this study, land-based nutrient sources are assessed through riverine nitrogen and phosphorus discharges to the Baltic Sea, which inherently integrate all upstream diffuse and point sources within each catchment. This approach enables inclusion of land-based inputs irrespective of their individual size or sectoral origin, but it does not allow for disaggregation of riverine loads into specific contributing activities such as agriculture, forestry, or scattered settlements. Consequently, the analysis focuses on the aggregate impact of land-based sources rather than their internal composition. In addition to riverine inputs, coastal land-based point sources are included only where activities operate under environmental permits, namely municipal wastewater treatment plants and industrial facilities, as these have been formally identified by environmental authorities as the dominant regulated point contributors to coastal nutrient loading. This methodological choice ensures consistency with reporting under HELCOM and national regulatory frameworks while enabling a meaningful comparison between land-based and maritime nutrient sources in relation to the study's research questions on source identification, relative significance, and regulatory relevance.

2.5 Maritime sources

Shipping contributes to about 0.3% of the total phosphorus and 1.25 – 3.3% of the total nitrogen input to the Baltic Sea (Raudsepp et al., 2019). Based on previous studies (European Environment Agency. & European Maritime Safety Agency., 2021; Jägerbrand et al., 2019; Jalkanen et al., 2021; Nellesen, 2019, Moldanová et al., 2022), the identified nitrogen and phosphorus discharge from shipping activities originate from food waste, grey and black water (sewage), bilge water, scrubber water, tank cleaning and treated ballast water. The overall discharge pathways from shipping are shown in Table 2.

Table 2: Overview of the main shipboard discharge streams, the substances they may contain, and the corresponding international regulations governing their discharge (adapted from Jalkanen et al., 2021).

Substance group	Biofoul. Antifoul	Ballast water	Black water	Grey water	Tank/ hold wash	Cooling water	Scrubber water	Bilge water	Noise, vibration	Stern tube oil	Atmos. Depos.	Food waste
Acidifying substance							x				x	
BOD/COD		x	x	x								x
Halocarbons, POP		x										
Hydrocarbons, PAH		x		x	x		x	x		x	x	
Litter, PM					x						x	x
Metals	x			x		x	x	x		x		
NIS	x	x	x	x								
Nutrients, N, P		x	x	x	x		x	x			x	x
Energy, noise									x			
Shipping regulation	AFS	BWMC	MARPOL Annex IV	MARPOL Annex IV	MARPOL Annex I, V		MARPOL Annex VI	MARPOL Annex I		MARPOL Annex I	MARPOL Annex VI	MARPOL Annex VI

Literature indicates that black water (sewage) and grey water discharges represent the primary pathways of nitrogen and phosphorus release from shipping activities (Huhta et al., 2007; Hänninen & Sassi, 2009; Raudsepp et al., 2019; Jalkanen et al., 2021).

Before the latest change in IMO regulations, 75% of grey water discharges in European waters came from passenger ships. Additionally, over 90 % of the nitrogen in food waste came from passenger ships, mainly in summertime during most intensive passenger traffic season (Jalkanen et al., 2021).

Shu et al. (2022) further demonstrated that passenger vessels are the dominant source of ship-generated wastewater. In their case study, passenger ships accounted for approximately 83% of the total wastewater generated, whereas cargo ships contributed around 12% Shenzhen port and part of Hong Kong Port. The authors concluded that wastewater generation is driven primarily by the number of persons onboard rather than vessel numbers alone, emphasizing the importance of considering passenger traffic separately when assessing nutrient and wastewater inputs from shipping.

Since the entry into force of the MARPOL Annex IV Special Area requirements in the Baltic Sea between 2019 and 2023, passenger ships carrying more than 12 passengers have been required either to discharge sewage to port reception facilities or to use approved onboard treatment systems capable of reducing most nitrogen and phosphorus before discharge at sea (IMO, 2023a).

Marpol Annex IV contains regulations regarding ships' black waters (sewage) but there are no regulations concerning grey waters. According to Annex IV cargo ships are allowed to discharge untreated sewage to the Baltic Sea if the distance to nearest land is more than 12 nautical miles. If the sewage is comminuted and disinfected, it can be discharged more than 3 nautical miles to the nearest land and ship is en route and proceeds at least 4 knots speed. The regulations have tightened during the making of this study. Since 2023, sewage discharge to the Baltic Sea from passenger vessels is only permitted if the ship has an approved and certified wastewater treatment plant according to IMO resolution MEPC.227(64), which stipulates a reduction of 70% in nitrogen levels and of 80% in phosphorus levels. Passenger ships not equipped with an on-board sewage treatment facility according to the specifications must discharge the sewage (black water) to a port reception facility (IMO, 2012).

There are also Finnish national regulations covering the country's territorial waters. According to the Act on Environmental Protection in Maritime Transport (2009), since 2025 it is prohibited to discharge untreated and treated sewage into Finnish territorial water from any ships above 400 GT. In addition, the same prohibition will enter into force for grey waters in 2030.

Food waste contributes nutrients in smaller quantities compared to sewage and grey waters, and below the level at which it would influence coastal nutrient balances (Vaneeckhaute & Fazli, 2020; Ytreberg et al., 2020). Therefore, within maritime nutrient sources, food waste is of secondary importance, overshadowed by wastewater discharges (Grote et al., 2016; CE Delft, 2024).

In summary, food waste from ships is excluded because its contribution to nutrient loading is relatively small at both the basin scale and within the maritime sector itself, and its inclusion would not materially improve the understanding of nutrient pressures or management options examined in this thesis.

Within shipping-related inputs, nutrient discharges from bilge water, ballast water, and exhaust gas cleaning system (scrubber) wash water have been examined only to a limited extent and are generally considered minor contributors in comparison to other pathways. Existing Baltic Sea assessments do not identify these three streams as significant contributors to basin-scale nutrient loading. Comprehensive reviews of maritime pressures consistently conclude that their contribution to total nitrogen and phosphorus loads is negligible relative to land-based sources and below the level of detectability in sea-basin nutrient budgets (HELCOM, 2018; Jägerbrand et al., 2019; Reckermann et al., 2022). Consequently, none of these discharge streams materially affect eutrophication dynamics at the Baltic Sea scale and they are excluded from this study.

Existing assessments of human pressures on the Baltic Sea identify cargo-related nutrient inputs as marginal at the sea-basin scale, with no indication that they contribute measurably to overall nitrogen or phosphorus loads when compared to dominant land-based fluxes (HELCOM, 2018; Reckermann et al., 2022). Consequently, nutrient inputs from cargo residues are negligible in relation to the total nutrient load driving eutrophication in the Baltic Sea.

Cargo residues are generally treated in the literature as an incidental rather than systematic source of nutrient loading. Reviews of dry bulk shipping highlight potential environmental risks associated with cargo loss, but also emphasize that such losses are highly variable, episodic, and strongly dependent on cargo type, handling practices, and port infrastructure (Grote et al., 2016). With the exception of fertilizers, most bulk cargoes transported in the Baltic Sea (e.g. ores, coal, aggregates, industrial raw materials) do not represent significant sources of bioavailable nitrogen or phosphorus.

As a result, even within shipping-related nutrient inputs, cargo residues are of clearly lower importance than wastewater discharges and, in many cases, lower than port-related nutrient pathways such as stormwater runoff or industrial effluents (HELCOM, 2018). Their contribution to nutrient loading is therefore minor relative to other maritime sources. It should be noticed that there is limited existing research and sample data on cargo residues and hold wash water monitoring, as well as discharges from non-HME cargo loading and unloading. However, port-focused studies demonstrate that fertilizer terminals can represent non-negligible local nutrient sources, particularly in enclosed or weakly flushed coastal waters (Grote et al., 2016). For this

reason, fertilizer cargo handling is included in this study, while other cargo residue pathways are excluded.

This study addresses the research questions by identifying and assessing the principal ship-borne nutrient discharge pathways relevant to the study area and by examining their significance and regulatory treatment in the Baltic Sea context. In response to RQ1, the analysis focuses on direct maritime discharges of nitrogen and phosphorus, with sewage (black water) and grey water consistently identified in the literature as the dominant nutrient pathways from shipping, while other streams such as bilge water, ballast water and scrubber wash water are excluded due to their negligible contribution and limited empirical evidence. With respect to RQ2, maritime nutrient inputs are evaluated relative to total coastal nutrient loading, recognizing that although shipping contributes only a small fraction at the sea-basin scale, wastewater discharges may represent locally relevant pressures in intensively trafficked areas. Passenger ship wastewater and food waste are excluded from the empirical analyses as their contribution is currently minor in the study area and because sufficient site-specific data are lacking. Finally, in relation to RQ3, the study examines how recent regulatory changes—particularly the tightening of sewage discharge requirements for passenger vessels—have reshaped the maritime nutrient balance, while cargo vessels remain subject to more permissive MARPOL provisions. By restricting the analysis to environmentally relevant and data-supported discharge pathways, the study enables a focused assessment of maritime nutrient sources and their alignment with existing regulatory frameworks).

2.6 Sources from port activities

A port is located at the interface between maritime transport and land-based activities, and its discharges can be attributed to either domain depending on the type, origin and recipient of the discharge. In this study, the focus is in ship loading operations carried out at ports, specifically on nutrient-contributing fertilizers. Other potential discharges originating from land-based activities at port, such as dredging and water construction works, storage and material handling, are outside the scope of this study.

Fertilizer cargo handling in ports is an important exception to the general insignificance of cargo residues. Fertilizers contain high concentrations of readily bioavailable nitrogen and phosphorus, and losses during storage, loading, and unloading can result in localized nutrient discharges to adjacent waters if not properly managed. This risk has been explicitly recognized in Baltic Sea policy and technical guidance documents (Stern, 2019; Kleijn et al., 2024).

As shown in Figure 6, over 45 million tons of fertilizers are loaded or unloaded to ships in the Baltic ports with a steady annual growth in quantity (John Nurminen, 2021, Utriainen et al., 2020). Fertilizers are managed in more than 70 ports in the Baltic Sea region, with the largest quantities in 2019 being handled at Klaipeda (13 million tons), Saint Petersburg (9), Vyborg (4), Gdynia (2), Gdansk (2), HaminaKotka (2), Szczecin (1.7), Tallinn (1.6), Rostock (1.6), Police (1.3), and Liepaja (1.1) (John Nurminen Foundation, 2021). Smaller ports, such as Uusikaupunki, Kokkola and Lübeck, handle more limited volumes, often linked to specific industrial or transit functions.

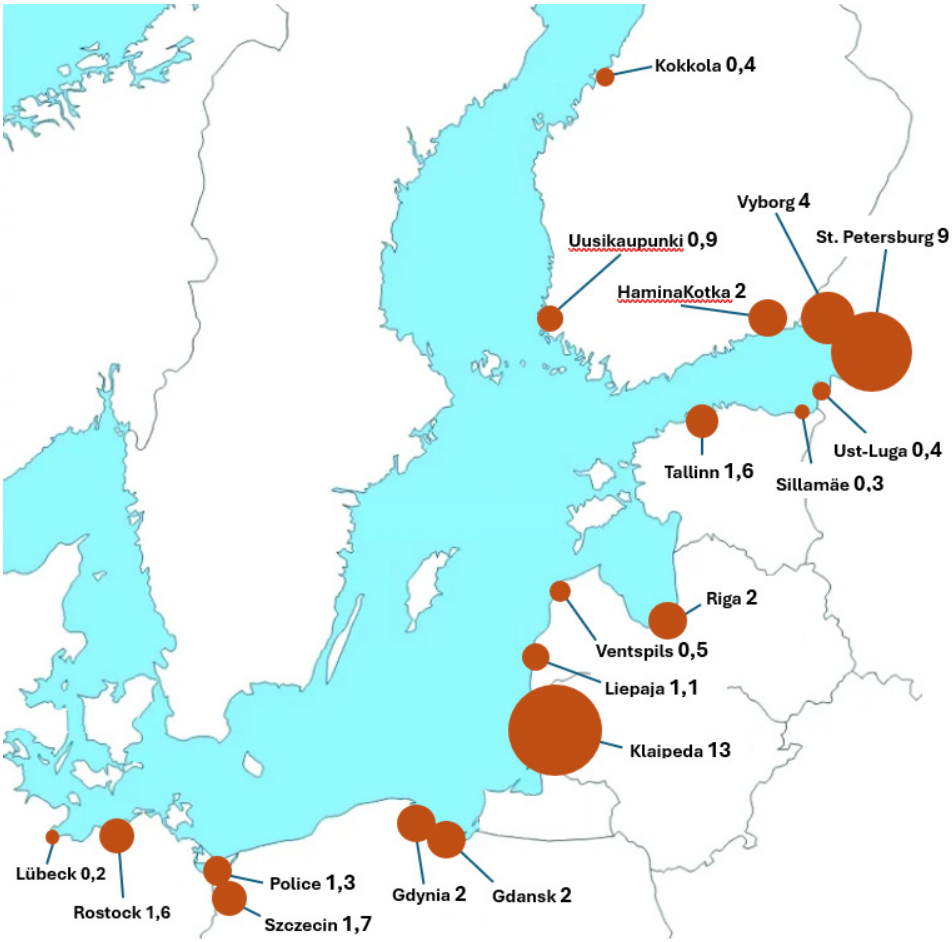


Figure 6: Dry bulk fertilizer loading at Baltic Ports (million tons) in 2019 (adapted from John Nurminen Foundation, 2021).

Applying an indicative cargo-loss factor of 0.05% to Baltic Sea fertilizer handling volumes (Grote et al., 2016) suggests that approximately 22,000 tons of fertilizer may be lost somewhere in the transport and handling chain each year. However, only an unknown fraction of this material is likely to reach the marine environment directly, depending on port infrastructure, cleaning practices, stormwater management and recovery measures. Fertilizer losses are primarily associated with ship loading and unloading processes—particularly when outdated handling techniques are used—as well as temporary open storage and insufficient stormwater management at port facilities. Overall, fertilizer flows are dominated by dry bulk cargo, with liquid fertilizers and containerized shipments forming smaller but environmentally significant sub-streams. (Utriainen et al., 2020)

Regulatory control of fertilizer discharges remains limited and fragmented. Under MARPOL Annex V, fertilizers are classified as non-harmful cargo, and even in the Baltic Sea Special Area, residues and cargo hold wash waters may be discharged at sea when port reception facilities are unavailable (IMO). Most Baltic ports do not provide dedicated reception facilities for fertilizer wash waters, and responsibility for their management

typically rests with shipowners. According to Finnish Act on Environmental Protection in Maritime Transport, an environmental permit is needed for activities with pollution risks. Environmental permits generally cover port activities at an aggregate level rather than fertilizer handling specifically, and no binding, quantitative limits for nutrient discharges are commonly applied. As a result, reductions in fertilizer-related nutrient inputs currently depend largely on technology choices and voluntary practices rather than harmonized regulatory requirements. (Utriainen et al., 2020)

Environmental aspects of fertilizer handling in ports are not specifically addressed by EU-level legislation. Instead, requirements related to fertilizer handling are mainly derived from national regulations, port-specific rules, or voluntary codes of conduct. The updated Baltic Sea Action Plan (HELCOM, 2021a) establishes nitrogen and phosphorus reduction targets, with actions related to shipping and ports to decrease the nutrient loads from dry bulk fertilizer handling. Thus, although fertilizer terminals are recognized as significant sources of nutrient load, no systematic and reliable monitoring of discharges have been conducted. Neither have the total nutrient loads to the sea from the discharges from fertilizer loading in port areas been systematically assessed.

Ports apply markedly different measures to minimize fertilizer discharges to sea. The most effective mitigation is achieved at terminals using closed and mechanised handling systems, including covered conveyors, enclosed railcar unloaders, sealed transfer points and enclosed storage facilities. Containerized transport and big-bag handling, used at several Baltic ports, effectively reduce spillage, dust emissions and the need for cargo hold washing. In contrast, ports relying partly on crane-and-grab operations and open handling systems are more vulnerable to fertilizer losses through dust, quay contamination and subsequent wash-off via stormwater. Across all port categories, operational practices, personnel training and dry mechanical cleaning of quay areas play a critical role in reducing nutrient releases. (Utriainen et al., 2020)

Where port infrastructure and operational practices are appropriately designed and managed, nutrient losses arising from fertilizer cargo handling could, in principle, be captured and recycled rather than released to the marine environment (Kleijn et al., 2024).

Although fertilizers are widely recognized as nutrient-rich cargoes and substantial quantities are estimated to be lost during maritime transport and port handling, empirical studies that directly quantify fertilizer-related nutrient discharges to the marine environment remain scarce. In addition, fertilizer handling and transport are largely absent from studies that integrate maritime and land-based nutrient sources to produce a comprehensive assessment of overall nutrient inputs to coastal waters. As a result, fertilizer-derived nutrient loads remain poorly represented in comparative source apportionment frameworks, despite their potential local significance.

This knowledge gap is further reinforced by regulatory shortcomings. Fertilizers are not classified as harmful to the marine environment (HME) under MARPOL, and consequently their handling, residues and wash waters are subject to relatively weak international regulation. At the regional, national and port levels, legislative requirements vary considerably, and specific, binding limits for nutrient discharges from fertilizer handling are typically lacking. This regulatory asymmetry contrasts with the high nutrient content and bioavailability of fertilizers and contributes to their limited visibility in maritime nutrient governance.

At the same time, a wide range of technical and operational measures to reduce fertilizer losses at ports and during ship loading and unloading has already been identified. Many of these measures—such as enclosed handling systems, improved cleaning practices, stormwater management, and staff training—are both effective and cost-efficient. However, their implementation is largely voluntary, as they are primarily formulated as best available techniques (BAT) or best environmental practices (BEP) rather than mandatory requirements. Consequently, uptake depends on individual port operators, terminals and shipowners, leading to uneven application across the Baltic Sea region.

This research directly addresses these challenges by quantifying fertilizer-related nutrient discharges (RQ1), positioning fertilizer handling within the broader framework of maritime and land-based nutrient sources (RQ2), and critically examining the mismatch between environmental pressure, mitigation potential and regulatory control (RQ3). By doing so, the study contributes evidence needed to better integrate fertilizer handling into nutrient source assessments and to inform future policy and regulatory development.

Beyond nutrient-contributing cargo loading, port construction and routine operational activities constitute additional, though typically localized, nutrient pathways to coastal waters. Construction, dredging, and land reclamation can mobilize nutrient rich sediments accumulated in port areas, temporarily increasing concentrations of sediment bound phosphorus and nitrogen and altering coastal biogeochemical conditions, particularly in enclosed or weakly flushed areas (Golubkov & Golubkov, 2022; HELCOM, 2018). Ports also generate wastewater from cleaning, maintenance, and service activities, which may contain elevated nutrient concentrations (HELCOM, 2019). These port related nutrient inputs are small relative to catchment scale agricultural loads, and they are not systematically reflected in Nutrient Input Ceiling accounting (HELCOM, 2025). Due to their assessed insignificance, these pathways are excluded from this study.

2.7 Other sources

In addition to land-based diffuse and point sources by human activities, maritime and port activities and other human related activities, nutrient inputs originate from internal load and airborne load.

Atmospheric deposition constitutes a significant source of nitrogen to the Baltic Sea, contributing on the order of 20–30% of total nitrogen inputs (Bartnicki et al., 2011), whereas atmospheric phosphorus inputs are smaller and generally considered a minor source (Rolff et al., 2008).

Sediments in the sea bottom store large amounts of phosphorus that can be released back into the water, making internal loading a major source of nutrients. Internal phosphorus loading is strongly affected by oxygen conditions in bottom sediments. Under hypoxic and anoxic conditions, previously accumulated phosphorus may be released back into the water column, sustaining eutrophication even when external nutrient inputs are reduced (Lukkari et al., 2008; Mort et al., 2010; Van Helmond et al., 2020). This internal recycling explains why reducing external nutrient inputs does not immediately improve water quality or reduce algal blooms (Helminen, 2025). Although significant technological progress has been made in developing measures to manage these internal nutrient reserves, there is still limited scientific evidence on their long-term effectiveness and potential environmental risks (HELCOM, 2021b).

The "vicious circle" in the Baltic Sea refers to a self-reinforcing cycle where excess nutrient inputs lead to eutrophication and increased organic matter production, which sinks and consumes oxygen during decomposition, causing hypoxia or anoxia in deep waters. Under anoxic conditions, phosphorus is released from sediments, creating a surplus that promotes nitrogen-fixing cyanobacteria growth, further fueling eutrophication. This process perpetuates itself, worsening oxygen depletion and expanding hypoxic and anoxic zones despite reductions in nutrient inputs (Kuliński et al., 2022).

Atmospheric deposition and internal nutrient loading are excluded from this study because this research focuses exclusively on direct nutrient discharges to water resulting from human operations, particularly from a maritime and shipping perspective.

3 Methodology and Research Design

3.1 Theoretical Framework

This dissertation is based on the observation that nutrient inputs to the Baltic Sea are typically studied, monitored, and regulated through separate sectoral frameworks.

Research on Baltic Sea nutrient loading has traditionally focused on agriculture, riverine inputs, municipal wastewater treatment plants, and industrial discharges, which are systematically monitored and included in nutrient inventories and management programmes (HELCOM, 2021a). In contrast, maritime and port-related nutrient sources have often been assessed separately from land-based sources. Some sources, such as ship-generated wastewater, have received considerable scientific and regulatory attention, whereas port-related sources, such as fertilizer cargo handling, remain poorly quantified and are often absent from integrated nutrient assessments.

Environmental governance literature suggests that regulatory priorities are influenced not only by environmental impacts but also by data availability, monitoring practices, and institutional responsibilities (Gilek & Karlsson, 2016; Tynkkynen et al., 2014). Consequently, nutrient sources that are well documented and regularly monitored tend to receive greater regulatory attention than sources for which limited information exists. This may result in a mismatch between actual nutrient pressures and the level of regulatory control applied to different sources.

The theoretical premise of this dissertation is that fragmented research and governance can lead to an incomplete understanding of nutrient sources and their relative significance. To address this issue, the study combines nutrient source quantification with regulatory analysis within a common source-to-sea framework with a specific focus on maritime and port related discharges. The framework links two dimensions: environmental significance, measured through nutrient loads, and regulatory attention, assessed through the applicable regulatory instruments. Comparing these dimensions provides a basis for evaluating whether current governance structures correspond to the actual contribution of different nutrient sources to Baltic Sea eutrophication.

3.2 Research Design

This dissertation adopts a mixed-methods research design that combines quantitative nutrient load assessment with qualitative regulatory analysis. The purpose of the design is to evaluate nutrient discharges from maritime and port-related activities and to assess whether the level of regulatory control applied to different nutrient sources corresponds to their environmental significance. By integrating source quantification, comparative load assessment, and governance analysis, the study provides a comprehensive framework for examining nutrient management in the Baltic Sea.

The dissertation is based on three interrelated peer-reviewed articles, each addressing a distinct component of the overall research problem. Together, the articles form a sequential research process progressing from source identification and quantification to comparative assessment and regulatory evaluation.

The research follows a comparative case-study approach. Case studies are particularly suitable for examining complex environmental issues in which ecological processes, human activities, and governance systems interact within a real-world context (Stake, 1995; Yin, 2016). The selected case study area, the Hamina–Kotka–Pyhtää coastal region

in the eastern Gulf of Finland, contains major maritime, port-related, industrial, municipal, and riverine nutrient sources within the same geographical system. This enables direct comparison of different nutrient pathways and their corresponding regulatory frameworks under comparable environmental conditions.

The overall research design is explanatory and comparative. First, nutrient inputs from selected maritime and port-related activities are identified and quantified using empirical measurements, modelling techniques, and calculation-based methods. Second, these nutrient inputs are compared with major land-based nutrient sources within a common source-apportionment framework. Finally, the regulatory instruments governing each source category are analyzed and compared to evaluate whether regulatory attention is proportional to observed nutrient pressures.

Article I examines nutrient discharges associated with fertilizer cargo handling operations in a port environment. The study applies stormwater monitoring and machine-learning-based modelling to quantify nutrient losses from fertilizer handling activities and to identify the factors influencing discharge levels.

Article II focuses on cargo ships' black and grey water. Nutrient generation is estimated using vessel traffic data, voyage characteristics, ship-specific operational data, and established emission factors. The analysis provides an estimate of the potential magnitude of nutrient inputs associated with cargo ship wastewater.

Article III integrates the findings of Articles I and II with data on riverine inputs, municipal wastewater treatment plants, and industrial discharges. Using a common source-apportionment framework, the study compares the relative significance of different nutrient sources in the case-study area. In parallel, a systematic regulatory analysis is conducted to compare the regulatory instruments governing the identified nutrient pathways.

The research design follows sequential logic aligned with the dissertation's research questions. Research Question 1 is primarily addressed through Articles I and II by identifying and quantifying nutrient sources originating from maritime and port activities. Research Question 2 is addressed through the comparative source-apportionment analysis conducted across all three articles. Research Question 3 is examined through the integrated regulatory assessment undertaken in Article III, which evaluates the relationship between environmental pressure and regulatory control. The relationship between the research questions, data sources, methods and the three constituent articles is illustrated in Table 3.

Table 3: Research questions, datasources, methods and linked articles.

Research question	Data sources	Methods	Linked articles
RQ 1 **Sources**	Stormwater data, vessel data	Measuring, modelling, load estimation by calculation	Articles I, II
RQ 2 **Significance**	All nutrient datasets	Source apportionment, comparative analysis	Articles I, II, III
RQ 3 **Regulatory Implications**	Legislation, permits, HELCOM, MARPOL	Regulatory mapping and classification	Article III

3.3 Study Area and Case Selection

3.3.1 Selection of study area

The dissertation applies a case-study approach focusing on the Hamina–Kotka–Pyhtää coastal area in the eastern Gulf of Finland (Figure 7).

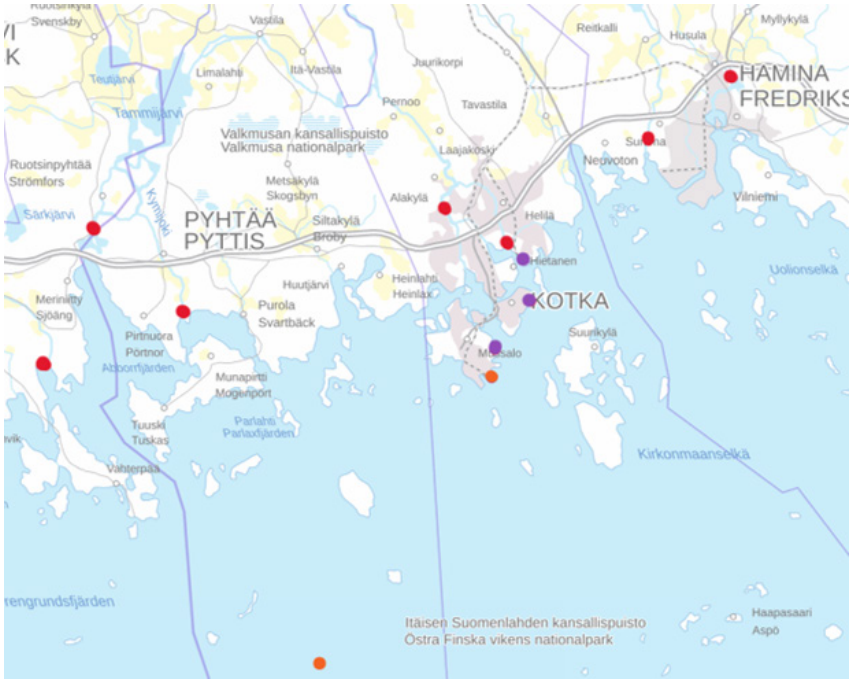


Figure 7: The research area in the Gulf of Finland and studied nutrient sources: Rivers (red dots) from west to east are Taasia, Kymi/Ahvenkoski, Kymi/Pyhtää, Kymi/Koivukoski, Kymi/Korkeakoski, Summa, Vehka. The point sources (purple and orange dots) from north to south are Stora Enso: Sunila Mill pulp factory, Kotkamills Oy cardboard factory, Mussalo Wastewater treatment plant, fertilizer cargo loading berth at the Port of HaminaKotka Oy and maritime traffic. Figure compiled by the author.

The area was selected for four reasons. First, the eastern Gulf of Finland is among the most eutrophicated parts of the Baltic Sea and receives high inputs of nitrogen and phosphorus, making it highly relevant for studying nutrient sources and mitigation measures.

Second, the area contains all major nutrient source categories typically identified in Baltic Sea assessments. Nutrient inputs originate from the Kymi River and smaller local rivers, municipal wastewater treatment plants, industrial facilities, agriculture, forestry, and maritime activities associated with a major general sea port in Finland. This enables direct comparison between maritime, port-related, and land-based nutrient sources within a single coastal area.

Third, exceptionally detailed data on cargo handling at port is available for the area. Fertilizer cargo-related nutrient discharges are typically not intensively studied and accessible elsewhere. For this port, we have been able to study nutrient discharges associated with fertilizer cargo handling, making it possible to integrate these results with other nutrient sources to produce a comprehensive assessment of total nutrient inputs.

Finally, the area is governed by a combination of international maritime conventions, European Union legislation, HELCOM recommendations, Finnish national regulations, and point source-specific environmental permits. This provides a suitable framework for evaluating how different nutrient sources are regulated and whether the level of regulatory control corresponds to their environmental significance.

3.3.2 Selection of Nutrient Sources

The study focuses on fertilizer cargo handling and cargo ships' black and grey waters as the primary maritime and port-related sources.

Fertilizer cargo handling was selected because fertilizers contain high concentrations of readily bioavailable nitrogen and phosphorus and because previous studies have identified fertilizer handling as a potentially significant but poorly quantified nutrient pathway. Although fertilizer losses during handling, storage, and loading have been acknowledged in technical reports and policy documents, empirical measurements of nutrient discharges to coastal waters remain scarce. Furthermore, fertilizer-related nutrient inputs are generally excluded from both maritime nutrient assessments and broader source-apportionment studies, despite the large quantities of fertilizers handled annually in Baltic Sea ports. The availability of detailed monitoring data from the Port of HaminaKotka provided a unique opportunity to address this knowledge gap.

Ships' black and grey waters were selected because they represent the nutrient discharge pathway most frequently addressed in studies and maritime environmental regulation. International, regional, and increasingly national regulations focus strongly on wastewater generated on board ships, particularly sewage discharges. This source therefore provides a useful benchmark for evaluating whether regulatory attention corresponds to actual nutrient pressures. In addition, sufficient vessel traffic data, ship characteristics, and wastewater-generation factors were available to enable quantitative assessment of nutrient inputs associated with cargo ship operations.

The wastewater assessment focuses exclusively on cargo ships. This decision was driven by both the characteristics of the study area and recent regulatory developments. The Port of HaminaKotka does not operate regular passenger traffic, and cruise vessel visits are infrequent. According to port statistics, only occasional cruise vessels call at the port, and passenger volumes remain low compared with major Baltic passenger ports. In 2021, only one cruise vessel visited the port and discharged its wastewater directly to port reception facilities. Consequently, passenger ship wastewater cannot be considered a significant local nutrient source within the study area.

From a regulatory perspective, passenger ship sewage has also become increasingly controlled through the MARPOL Annex IV Special Area requirements that entered into force for the Baltic Sea during 2019–2023. These regulations require most passenger vessels either to deliver sewage to port reception facilities or to treat it according to advanced nutrient-removal standards before discharge. As a result, the environmental significance of passenger ship sewage in the Baltic Sea has decreased considerably. In contrast, cargo ships continue to operate under more permissive wastewater discharge rules and therefore remain the most relevant vessel category for examining the relationship between nutrient loading and regulatory control.

Several other potential nutrient pathways were excluded from the empirical analyses. These include food waste, bilge water, ballast water, scrubber wash water, non-fertilizer cargo residues, dredging activities, and port construction projects. Existing literature indicates that these sources contribute only minor quantities of nitrogen and phosphorus

relative to the major nutrient sources considered in this study. In addition, reliable site-specific data were unavailable for many of these activities, making robust quantification difficult. Their exclusion therefore improves analytical consistency while allowing the study to focus on nutrient pathways with greater environmental relevance and stronger empirical support.

The study also excludes atmospheric nutrient deposition and internal nutrient loading from marine sediments. While both processes are important components of the Baltic Sea nutrient cycle, they do not represent direct nutrient discharges arising from maritime or port-related operations and therefore fall outside the scope of this research. The dissertation focuses exclusively on human-generated nutrient inputs to water and their management through existing governance frameworks.

3.4 Data Sources and Materials

This dissertation utilizes both primary and secondary datasets to quantify the selected nutrient inputs and to evaluate the regulatory frameworks governing these activities.

Primary data were collected specifically for this research and include stormwater monitoring data from fertilizer cargo handling operations and operational data used to estimate nutrient generation from cargo ships' black and grey waters. Secondary data were obtained from environmental monitoring programmes, environmental reports, official statistics, legislation, environmental permits, and policy documents. These sources provide information on riverine nutrient loads, municipal wastewater discharges, industrial discharges, and the regulatory instruments applicable to different nutrient sources.

Table 4: Nutrient data origin and collecting methods used in the thesis.

Nutrient source	Source category	Data type and origin	Method for collecting/ analysing data and sampling frequency
Kymi River branches Ahvenkoski, Koivukoski and Korkeakoski	Riverine / diffuse	**Secondary** data from environmental reports (Holmberg, Raunio, 2022; Nakari, Anttila-Huhtinen 2022).	**Measured.** Water flow is measured monthly from the measuring points. Total nitrogen and total phosphorus samples are taken by certified environmental samplers and analysed in an accredited laboratory.
Taasia River, Summa River, Vehka River	Riverine / diffuse	**Secondary** data from environmental reports (Holmberg, Raunio, 2022; Nakari, Anttila-Huhtinen 2022).	**Simulated.** Due to the infrequent measurement of the flow of this river, simulated flow data from the Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS), specifically the VEMALA load calculation module, is used in load estimations.
Fertilizer loading at port	Port activity / point	**Primary** data (Article I of this thesis).	**Measured.** samples from storm water wells. The total N and total P analyzed in an acredited laboratory. Boosted Regression Trees (BRT) model was used to assess the daily nutrient discharges at the site over the course of a year.

Nutrient source	Source category	Data type and origin	Method for collecting/ analysing data and sampling frequency
Kymi River Pyhtää	Riverine / diffuse	**Secondary** data from an environmental report (Holmberg, Raunio, 2022).	**Calculated.** Due to its low flow, no samples are taken; instead, its contribution to the total substance load is assumed to be 2%, based on the value from 1992.
Municipalities: Mussalo wastewater treatment plant	Land-based / point	**Secondary** data from quarterly reports to the authority (Mäkitalo, Ukko, 2021).	**Measured.** Samples taken from incoming and outgoing water twice a month. Total nitrogen and total phosphorus analysed in an accredited laboratory. The treatment results include any bypasses and overflow events.
Industry: cardboard mill Kotkamills Oy	Land-based / point	**Secondary** data from an environmental report (Nakari, Anttila-Huhtinen 2022).	**Measured.** Total nitrogen and total phosphorus analysed from monthly samples taken at the mill.
Industry: pulp mill Sunila Oy	Land-based / point	**Secondary** data from monthly environmental reports (Stora Enso, 2021).	**Measured.** Total nitrogen and total phosphorus analysed from monthly samples taken at the mill.
Ships' Black and Grey waters	Maritime activity / point	**Primary** data (Article II of this thesis).	**Calculated** using the following equation: Nutrient [g] = Individual contribution [g/d] * crew members [persons] * distance to port [nautical miles] / speed [nautical miles/d].

Table 5: Regulatory sources. Table compiled by the author.

Topic	Applicatory area	Data origin
Environmental permits	Site-specific	Environmental permit decisions of all identified point sources in the area.
National legislation	Finland	Environmental Protection Act (527/2014); Water Act (587/2011); Act on Environmental Protection in Maritime Transport (1672/2009); Waste Act (646/2011); Government Decree on Limiting Certain Emissions from Agriculture and Horticulture (1250/2014) ("Nitrates Decree"); Fertiliser Act (711/2022); Government Decree on the Use of Phosphorus-Containing Fertilising Products and Manure (64/2023) "Phosphorus Decree"; and related decrees;
EU Legislation	EU	Water Framework Directive (2000/60/EC); Marine Strategy Framework Directive (2008/56/EC); Nitrates Directive (91/676/EEC); Urban Wastewater Treatment Directive (91/271/EEC); Common Agricultural Policy (CAP) environmental conditionality

Topic	Applicatory area	Data origin
International maritime regulations	Global, maritime sector	IMO MARPOL Convention especially Annex IV and Annex V; IMO resolutions and MEPC guidelines concerning sewage, garbage and wastewater management.
Regional governance instruments	Baltic Sea region	Helsinki Convention (1992); Baltic Sea Action Plan (BSAP, 2021 update); HELCOM Nutrient Reduction Scheme (MAI, CART and NIC targets); HELCOM Recommendations; Pollution Load Compilations (PLC); HELCOM Guidelines for Sea-Based Measures to Manage Internal Nutrient Reserves (2021); HELCOM BAT/BEP guidance documents, including nutrient loss prevention from fertilizer handling in ports.

Together, these datasets (Tables 4 and 5) provide the empirical and regulatory foundation for the dissertation. The environmental datasets enable estimation and comparison of nutrient inputs from different sources, whereas the regulatory materials support evaluation of how those sources are governed. The integration of these data sources allows the dissertation to address both the environmental significance of nutrient discharges and the adequacy of the regulatory frameworks intended to control them.

3.5 Methods

This dissertation combines quantitative nutrient load assessment with qualitative regulatory analysis. Different methods were applied according to the characteristics of each nutrient source and the availability of data. Fertilizer-related discharges were assessed using field measurements and machine-learning modelling, whereas cargo ship wastewater loads were estimated using calculation-based methods. The results were subsequently integrated with existing monitoring data from riverine, municipal, and industrial sources in a comparative source-apportionment framework. Finally, the regulatory frameworks governing each source category were analysed using a qualitative classification method.

Together, these methods provide the basis for identifying nutrient sources (RQ1), assessing their relative significance (RQ2), and evaluating whether the level of regulatory control corresponds to their environmental relevance (RQ3).

3.5.1 Quantification of fertilizer-related nutrient inputs using machine-learning modelling (Article I)

Nutrient discharges from fertilizer cargo handling were quantified using stormwater monitoring and machine-learning modelling. Stormwater samples were collected from fertilizer handling areas during rainfall events and analyzed for total nitrogen and total phosphorus by an accredited laboratory.

Because nutrient losses are strongly affected by rainfall conditions and operational activities, annual loads could not be estimated reliably from sampled concentrations alone. Therefore, a Boosted Regression Trees (BRT) model was developed to relate nutrient discharges to explanatory variables, including rainfall intensity, fertilizer handling volumes, loading timing, and catchment characteristics. Boosted Regression Trees combine regression trees and boosting algorithms to model complex nonlinear relationships and interactions among explanatory variables and have been widely applied in environmental modelling (Elith et al., 2008; Hastie et al., 2009; McCluskey et al., 2014). The developed model was used to estimate daily nutrient discharges and

annual nitrogen and phosphorus loads from fertilizer handling operations. The approach enabled quantification of a nutrient source for which routine monitoring data were not available and allowed identification of the key factors influencing discharge levels.

The method was used to answer RQ1 by quantifying fertilizer-related nutrient inputs from port operations. It also contributed to RQ2 by enabling comparison of fertilizer loading with other nutrient sources in the area. In addition, the results supported RQ3 by showing whether a quantified and locally significant nutrient source was subject to a corresponding level of regulatory control.

3.5.2 Calculation of ship-generated nutrient inputs (Article II)

Nutrient generation from cargo ships' black and grey waters was estimated using a calculation-based approach aligned with previous Baltic Sea shipping studies (Jalkanen et al., 2021). The objective was to estimate the quantity of nitrogen (N) and phosphorus (P) generated on board cargo vessels during their voyages within the Baltic Sea before arrival at the case port.

The calculation required five types of input data:

- Number of vessel calls and vessel type;
- Distance travelled within the Baltic Sea prior to arrival at the case port;
- Average vessel speed;
- Estimated number of crew members on board;
- Per-person daily nutrient generation rates for black water and grey water.

For each vessel, the sailing distance from the previous Baltic Sea port to the case port was determined using MarineTraffic route calculations. If the previous port was located outside the Baltic Sea, the distance was calculated from Skagen, which was used as the entrance point to the Baltic Sea. Average vessel speeds were estimated based on vessel-type-specific values reported in the literature, and average crew sizes were obtained from the Finnish Transport and Communications Agency and supplementary port records.

Duration of each voyage within the Baltic Sea was calculated as distance divided by average speed. The nutrient generation potential was then estimated by multiplying voyage duration by the number of crew members and the daily nutrient generation rate per person. The nutrient contribution per person in black water and grey water was estimated using fixed emission factors which have been earlier reported by Jalkanen et al. (2021), Huhta et al. (2007) and Jönsson et al (2005).

For each vessel, nutrient generation was calculated as:

Nutrient generation [g] = Emission factor [g/d] × crew members [persons] × voyage duration [d]

The calculations represent the theoretical maximum quantity of nitrogen and phosphorus generated on board during voyages. Actual discharges may be lower due to onboard treatment, wastewater storage, or discharge to port reception facilities. The method therefore provides a conservative upper-bound estimate of potential ship-generated nutrient inputs.

3.5.3 Integrated source apportionment using comparative analysis (Article III)

The source-specific results from Articles I and II were integrated with data on riverine inputs, municipal wastewater treatment plants, and industrial discharges. All nutrient loads were converted into annual nitrogen and phosphorus loads and compared within a common source-apportionment framework. This enabled direct comparison of maritime, port-related, and land-based nutrient sources and their relative contribution to total coastal nutrient loading.

3.5.4 Regulatory assessment framework using qualitative regulatory classification (Article III)

To compare the relative stringency of regulatory control applied to different nutrient sources, a qualitative regulatory classification scale ranging from 0 to 4 was developed for this study. The scale was designed to evaluate the strength of legally binding regulatory instruments governing nutrient discharges and inputs across different source categories. The classification reflects the degree to which nutrient releases are directly regulated, monitored, and restricted, ranging from the absence of specific controls to complete discharge prohibition. The classification represents an ordinal scale, in which categories are rank ordered according to regulatory stringency, but the distances between levels are not assumed to be equal (Sekaran & Bougie, 2016).

The assessment was based on a review of regulatory instruments operating at four governance levels: international conventions, European Union legislation, national legislation, and site-specific environmental permits. For each nutrient source, the highest applicable level of regulatory control was identified and used as the final classification. Where multiple regulatory instruments applied simultaneously, priority was given to the most stringent legally binding requirement. Ambiguous cases were assessed conservatively and assigned the lower classification level unless explicit numerical discharge limits or discharge prohibitions could be identified. Table 6 presents the regulatory classification scale used in the analysis.

Table 6. Qualitative regulatory classification scale.

Regulatory level	Criteria
0	No direct regulatory controls on nutrient discharges or inputs
1	Monitoring, mitigation, or operational requirements without numerical nutrient limits
2	Numerical nutrient discharge or input limits established through generally applicable legislation or regulatory programmes
3	Source-specific numerical nutrient discharge limits established through environmental permits, combined with monitoring and reporting obligations
4	Explicit prohibition of nutrient discharges or other equivalent regulatory restrictions

Level 0 indicates that no regulatory instruments directly address nutrient releases from the source category.

Level 1 applies where regulation focuses primarily on operational practices, monitoring requirements, or mitigation measures, but does not establish quantitative limits for nitrogen or phosphorus discharges. Examples include requirements related to cargo handling procedures, environmental management practices, or stormwater management.

Level 2 represents sources regulated through generally applicable legislative or policy instruments that establish numerical limits or restrictions on nutrient inputs or discharges. Such controls are typically applied at sectoral or catchment scale rather than through source-specific permits. Examples include agricultural nutrient management regulations that limit the application of nitrogen or phosphorus to land.

Level 3 applies where nutrient discharges are regulated through environmental permits containing source-specific numerical limits for nitrogen and/or phosphorus. In addition to quantitative discharge limits, these permits typically include monitoring, reporting, and compliance obligations, providing a higher level of regulatory oversight than generally applicable legislation.

Level 4 represents the highest degree of regulatory control and applies where nutrient discharges are explicitly prohibited or where regulations impose functionally equivalent restrictions that prevent discharge under normal operating conditions.

The purpose of the classification is not to assess regulatory effectiveness or enforcement, but rather to compare the relative strength of the formal regulatory controls governing different nutrient sources within the study area. The resulting classification was used to compare the formal level of regulatory control with the magnitude of nutrient loads identified in the empirical analyses. This provided the basis for evaluating whether regulatory attention corresponds to environmental pressure.

3.6 Validity and Reliability

The dissertation combines primary measurements, modelled estimates and officially reported environmental monitoring data. The reliability of the results depends on the quality of each data source and on the consistency between them.

3.6.1 Data quality and reliability

For Article I, nutrient concentrations from fertilizer loading operations were determined from 58 stormwater samples collected at three fertilizer loading areas during eight rainfall events in 2021. All nutrient analyses were carried out by an accredited laboratory using standard analytical methods. Due to the exceptionally high nutrient concentrations, sample dilution was required before analysis, resulting in an estimated analytical uncertainty of approximately 15%.

The reliability of the results is strengthened by an independent assessment conducted within the John Nurminen Foundation Fertilizer Shipping Project (John Nurminen, 2022). The same stormwater monitoring dataset collected in the Port of HaminaKotka was analysed separately using a different calculation methodology to estimate the annual nutrient load from fertilizer handling operations. Despite methodological differences, the resulting annual nitrogen and phosphorus load estimates (261 tons of N and 0.2 tons of P) from the Nurminen methodology were of the same order of magnitude as those obtained in this study (273 tons of N and 0.2 tons of P), providing independent support for the robustness of the overall load assessment.

For Article II, the ship wastewater calculations were based on vessel traffic records, ship characteristics and nutrient generation factors reported in earlier peer-reviewed studies. In addition, actual wastewater samples were collected from some of the cargo vessels visiting the Port of HaminaKotka during 2021–2023. However, nutrient concentrations in the samples varied considerably between vessels, making it difficult to derive reliable conclusions from the measured wastewater data. The calculation-based approach was therefore chosen because it covers all cargo ship calls during the study

year. This makes it a census rather than a sample, which eliminates sampling error (Sekaran & Bougie, 2016). The magnitude of the calculated nitrogen and phosphorus loads corresponds closely with the modelling approaches and estimates presented by Jalkanen et al. (2021), Raudsepp et al. (2019), and HELCOM assessments of nutrient discharges from Baltic Sea shipping.

For Article III, most riverine, industrial and municipal nutrient load data originated from official monitoring programmes and environmental reporting systems. These datasets are routinely used by environmental authorities and HELCOM reporting processes and can therefore be considered highly reliable for comparative source apportionment purposes.

The regulatory analysis was based on publicly available sources, including international conventions, European Union legislation, national legislation, environmental permits, and official policy documents. The classification criteria were applied systematically to all source categories using the same predefined framework. This allows direct comparison between nutrient sources governed by different regulatory systems.

3.6.2 Validity of the methods

The methodological approaches applied in the dissertation were selected according to the nature of each nutrient source.

In Article I, fertilizer-related nutrient losses were estimated using a combination of direct field measurements and Boosted Regression Tree (BRT) modelling. The model explained more than 80% of the observed variation in nutrient discharges, indicating strong predictive performance. Because both monitoring data and environmental variables were included, the model provided a realistic estimate of annual nutrient loads while accounting for temporal and spatial variability.

In Article II, direct measurement of wastewater discharges from all visiting ships was not feasible. Therefore, nutrient loads were estimated using voyage duration, crew size and established per-person nutrient generation factors. The purpose of this approach was not to estimate actual discharges but to determine the theoretical maximum amount of nutrients generated during voyages. Consequently, the results provide a worst-case estimate of potential ship-generated nutrient loads.

In Article III, nutrient loads from different source categories were harmonised to annual nitrogen and phosphorus loads and compared using a source-apportionment approach consistent with HELCOM nutrient assessments. This approach allows comparison between heterogeneous nutrient sources using a common metric and provides a suitable basis for evaluating their relative significance.

For the regulatory analysis, the objective was not to assess legal effectiveness or compliance in practice, but to compare the formal level of regulatory control applied to different nutrient sources. For this purpose, a qualitative regulatory classification scale was developed because no existing framework was identified that would allow direct comparison of nutrient loads and regulatory stringency across maritime, port-related, and land-based sources. The classification criteria were defined before performing the assessment and applied consistently throughout the study. This methodological transparency supports the validity of the comparison, even though the assessment necessarily contains an element of expert judgement.

4 Results

4.1 Overview of Results

The results of the three articles show that riverine inputs were the dominant source of nitrogen and phosphorus loading, while maritime sources contributed a comparatively small share. Fertilizer cargo handling represented the largest identified maritime-related nitrogen source, whereas ship-generated wastewater contributed less than 0.1% of total nitrogen and phosphorus loads in the study area. The regulatory assessment classified nutrient sources according to the level of formal regulatory control, ranging from 1 to 4.

4.2 Nutrient Sources from Maritime and Port Activities (RQ1)

The nutrient sources from Maritime and Port Activities were identified and assessed in articles I and II.

Article I focused on fertilizer cargo handling operations at port. Stormwater monitoring and machine-learning modelling demonstrated that fertilizer handling generates nutrient losses through rainfall-induced runoff from loading and storage areas. The results showed that nutrient discharges varied considerably between rainfall events and were strongly influenced by both precipitation and operational conditions. The model predicted that at the studied port, fertilizer loading generated annual discharges of 272.9 tons of nitrogen and 0.2 tons of phosphorus to the marine environment. These findings identified fertilizer cargo handling as a previously poorly quantified nutrient source capable of generating substantial nitrogen discharges.

Article II examined nutrient generation from cargo ships' black and grey waters. Nutrient loads were estimated using vessel traffic information, voyage characteristics, crew-size estimates, and established wastewater generation factors. Based on vessel traffic records from 2021, a total of 2,545 cargo ships visiting the port were estimated to generate a theoretical maximum of 0.8 tons of nitrogen and 0.1 tons of phosphorus in black and grey water during voyages to the port. Actual discharges to the sea are likely lower, depending on onboard storage, treatment, and delivery to port reception facilities. Although cargo ship wastewater was shown to generate measurable nutrient inputs, the estimated quantities remained relatively small.

4.3 Significance of the nutrient sources (RQ2)

The relative significance of different nutrient sources was assessed in Article III. The analysis integrated the results of Articles I and II with nutrient load data from riverine inputs, municipal wastewater treatment plants, and industrial discharges to enable direct comparison within a common source-apportionment framework.

The total annual nutrient input to the Hamina–Kotka–Pyhtää coastal waters in 2021 was estimated at 7,035 tons of nitrogen and 225 tons of phosphorus. Riverine inputs dominated nutrient loading, accounting for 93.7% of total nitrogen and 91.7% of total phosphorus. Local land-based point sources, including municipal wastewater treatment plants and industrial facilities, contributed 2.4% of nitrogen and 8.1% of phosphorus. Maritime-related sources accounted for the remaining share: port activities contributed 3.9% of total nitrogen and 0.1% of total phosphorus, while ship-generated wastewaters contributed less than 0.1% of both nutrients. Magnitudes of the nutrient discharges are shown in Table 7 and visualized in Figure 8.

Table 7: Estimated annual nitrogen and phosphorus loads from the major nutrient sources to the Hamina–Kotka–Pyhtää coastal area in 2021.

Source	Nitrogen (tons)	Phosphorus (tons)
Rivers	6592.23	206.85
Fertilizer cargo handling at port	272.90	0.20
Industrial and municipal point sources	169.33	18.27
Cargo ships' black and grey waters	0.78	0.13
Total	7035.24	225.45

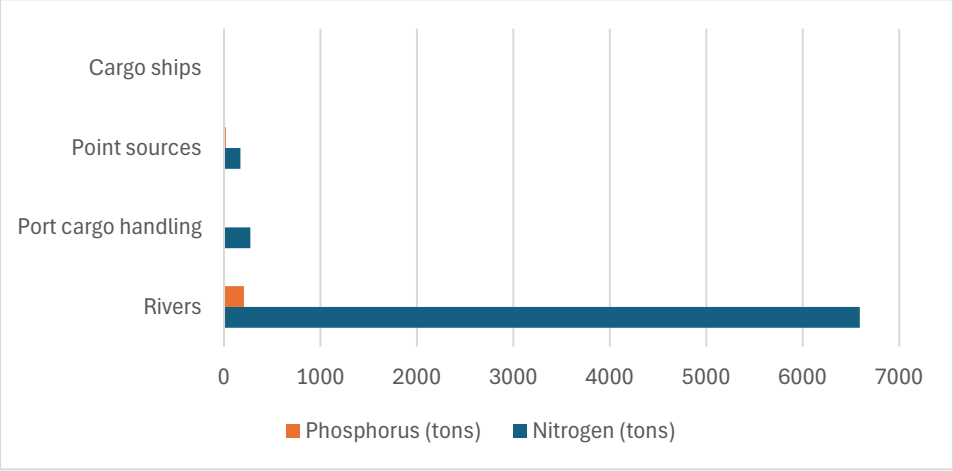


Figure 8: Rivers are dominant sources of both phosphorus and nitrogen discharges in the Hamina–Kotka–Pyhtää coastal area in 2021. Cargo handling at port represents the biggest point source of nitrogen.

4.4 Regulatory implications (RQ3)

Article III evaluated the regulatory frameworks governing the different nutrient source categories and compared the level of regulatory control applied to each source category. To enable evaluation of regulatory stringency across sectors, a qualitative regulatory classification scale ranging from 0 (no direct nutrient regulation) to 4 (discharge prohibited) was applied.

Riverine nutrient loads, which represented the largest source of both nitrogen and phosphorus in the study area, were assigned a regulatory score of 2. Nutrient inputs delivered by rivers originate from a combination of diffuse and point sources within the catchment area. Upstream municipal wastewater treatment plants and industrial facilities operate under environmental permits containing source-specific nutrient discharge limits, whereas agricultural nutrient losses are regulated primarily through nutrient management requirements and restrictions on fertilizer application. Because riverine nutrient loads are governed through a combination of permit-based controls and broader catchment-level management measures rather than direct limits on total riverine nutrient inputs, the riverine source category received a score of 2.

Municipal wastewater treatment plants and industrial facilities discharging directly into coastal waters were assigned a regulatory score of 3. These facilities operate under

environmental permits that include explicit nitrogen and phosphorus discharge limits, monitoring obligations, reporting requirements, and, where necessary, advanced nutrient removal technologies. Their nutrient discharges are therefore directly regulated and continuously monitored.

Fertilizer cargo handling at ports was assigned a regulatory score of 1. Environmental permits and operational requirements generally require preventive measures and environmental monitoring; however, explicit numerical limits for nitrogen and phosphorus discharges were not identified. Consequently, nutrient releases from fertilizer handling are managed primarily through operational and mitigation measures rather than direct nutrient discharge limits.

Ship-generated wastewater received the highest regulatory score of 4 only under the Finnish national regulatory context, particularly when adopted future restrictions on greywater are considered. For a Baltic Sea-wide comparison, black water and grey water should be assessed separately, and current in-force requirements should be distinguished from forthcoming national requirements.

4.5 Limitations and delimitations

Several limitations should be considered when interpreting the results.

The fertilizer loading analysis was based on a limited number of sampling events. Although these events were selected to capture operational loading conditions and rainfall periods, they do not necessarily represent the full range of annual variability. The BRT models explained more than 80% of the variation in nutrient discharge, so they capture the main patterns and magnitudes reasonably well. The remaining unexplained variation of about 20% is probably due partly to variables that were not measured. For example, fertilizer types differ in solubility, so their nutrients may not reach drainage water to the same extent. Solubility can also depend on temperature, which was not included in the models.

Some nutrient load estimates for smaller rivers relied partly on modelled flow data produced by the Finnish Environment Institute's watershed modelling system. While modelled values may differ slightly from measured flows, they remain widely accepted for environmental load assessments and provide reasonable estimates of river water volumes.

The ship wastewater calculations represent theoretical maximum nutrient generation and do not account for all possible onboard treatment processes, wastewater retention, or discharges at other ports. Actual nutrient discharges to the Baltic Sea are therefore likely lower than the calculated figures.

Table 8 summarizes the main uncertainties associated with the different nutrient sources and analytical approaches applied in this dissertation. The table also indicates the likely direction of potential bias and its implications for the study conclusions.

Table 8: Summary of uncertainties.

Nutrient source	Data type	Main uncertainty	Likely bias direction	Effect on interpretation
Fertilizer cargo handling	Measured stormwater samples and modelled annual extrapolation	Limited number of sampling events and variability in operational and rainfall conditions	Overestimation or underestimation of actual annual loads possible	May affect annual nutrient load magnitude but does not alter the conclusion that fertilizer handling is a locally important nutrient source

Nutrient source	Data type	Main uncertainty	Likely bias direction	Effect on interpretation
Riverine inputs	Monitoring data and modelled river flows	Use of modelled flow data for some smaller rivers	Likely small uncertainty in total load calculations	May influence exact load estimates but does not affect the identification of rivers as the dominant nutrient source
Point sources	Reported discharges in monitoring data	Variability in operations and monitoring frequency	Likely small	Limited effect on interpretation because nutrient discharges are measured and reported under environmental permit requirements
Cargo ship waste-water	Calculation-based theoretical generation estimates	Actual discharge behaviour, wastewater treatment, and storage unknown	Likely over-estimation	Results should be interpreted as an upper-bound estimate of potential ship-generated nutrient inputs

The dissertation focuses exclusively on nutrient discharges to water. Atmospheric nutrient deposition, greenhouse gas emissions, and other environmental impacts of maritime activities were excluded from the scope of the research.

Similarly, the study concentrates on nutrient sources that could be quantified with sufficient reliability. Fertilizer cargo handling and cargo ship wastewater were selected because data were available and their nutrient content is well established. Other potential sources, such as food waste, non-fertilizer cargo residues, dredging projects and port construction activities, were excluded due to limited data availability and their comparatively minor contribution to nutrient loading.

Passenger ship wastewater was also excluded from the empirical analyses. The Port of HaminaKotka has no regular passenger traffic, and cruise ship visits are infrequent. In 2021 only one cruise vessel called at the port and discharged its wastewater to port reception facilities. As a result, passenger ship wastewater was not considered a relevant local nutrient source in the study area.

The regulatory assessment has additional limitations. The classification scale evaluates the existence and formal stringency of regulatory instruments but does not measure their practical effectiveness, enforcement intensity, compliance rates, or environmental outcomes. Consequently, a regulation classified as highly stringent may not necessarily result in greater environmental protection if implementation or enforcement is weak.

Furthermore, complex regulatory systems were simplified into a five-level classification scale. Although this simplification was necessary to enable comparison between different nutrient sources, some legal and administrative nuances were inevitably lost. Regulatory classifications should therefore be interpreted as comparative indicators rather than exact representations of regulatory complexity.

Finally, the regulatory analysis reflects the legislative situation at the time of the study. As environmental legislation continues to evolve, particularly in relation to maritime wastewater discharges and nutrient management policies, future regulatory changes may alter the comparative relationships identified in this dissertation.

5 Discussion

5.1 Nutrient discharges from port activities

The results of Article I demonstrated that fertilizer cargo handling can generate substantial nutrient discharges through contaminated stormwater runoff. The machine-learning model estimated annual discharges of approximately 273 tonnes of nitrogen and 0.2 tons of phosphorus from the studied port contributing 3.9% of N and 0.1% of P discharges in the studied area. Although this represented only approximately 0.03% of the nitrogen fertilizer throughput handled during the assessment year, the absolute load was environmentally significant because the amount of handled cargo is large (2-3 million tons) and the discharges occurred directly into coastal waters in a form that can directly be consumed by algae.

The estimated discharge amount is broadly consistent with previous findings concerning fertilizer losses during the transport chain. Grote et al. (2016) estimated average cargo losses of approximately 0.05% during fertilizer transport and handling operations, suggesting that even relatively small proportional losses can result in substantial nutrient discharges when large cargo volumes are involved. The present results therefore support earlier concerns regarding fertilizer losses while providing one of the first quantitative assessments of their contribution to coastal nutrient loading.

The findings are also supported by earlier observations made in the Port of HaminaKotka. Monitoring data collected from stormwater wells in the bulk terminal showed exceptionally high nutrient concentrations, with both nitrogen and phosphorus levels exceeding the threshold values for highly polluted stormwater by one to two orders of magnitude (Anttila-Huhtinen, 2021). Although these monitoring data were not designed to estimate annual nutrient loads, they provide additional evidence that fertilizer handling operations can substantially influence stormwater quality.

Further support for the findings is provided by the John Nurminen Foundation Fertilizer Shipping Project (John Nurminen, 2022), which applied an independent methodology to the same monitoring dataset. Despite using a different calculation approach, the estimated annual load (261 tonnes N and 0.2 tons P) was very similar to the results obtained in this study (273 tonnes N and 0.2 P).

The identification and quantification of fertilizer cargo handling as a nutrient source in the Baltic Sea region is one of the main scientific contributions of this dissertation. Previous Baltic Sea eutrophication studies have primarily focused on agriculture, riverine inputs, municipal wastewater treatment plants, industrial discharges, and, within the maritime sector, ship-generated wastewaters (HELCOM, 2018; HELCOM, 2023). In contrast, nutrient losses associated with port cargo handling have received relatively little scientific attention and are generally absent from source-apportionment assessments. The results of this study indicate that current knowledge of maritime nutrient inputs remains incomplete without consideration of port-related activities. It should be kept in mind that more than 40 million tons of fertilizers are handled in the Baltic ports annually.

5.2 Nutrient discharges from maritime activities

The Article II reported that cargo ships visiting the Port of HaminaKotka generated approximately 0.8 tons of nitrogen and 0.1 tons of phosphorus in black and grey waters

during their voyage in the Baltic Sea in 2021. Ships' wastewaters are minor contributors in magnitude (<0.1% of N and <0.1% of P) and distributed outside coastal waters.

These findings are broadly consistent with other Baltic Sea-wide assessments, which have generally concluded that shipping contributes only a small fraction (<0.1–3% for both nitrogen and phosphorus) of the total nutrient load entering the sea (Huhta et al., 2007; Mujingni,et al., 2024; Wilewska-Bien et al., 2019). Recent HELCOM modelling estimated that shipping activities discharged approximately 490 tonnes of nitrogen and 135 tons of phosphorus to the Baltic Sea in 2024, primarily originating from sewage and grey water discharges, corresponding to less than one percent of overall nutrient inputs to the marine environment (Jalkanen, 2025). Similar conclusions have been reported in earlier material-flow analyses and nutrient budget assessments, which identified shipping as a comparatively minor contributor relative to riverine inputs, agriculture, and municipal wastewater treatment.

In addition, it should be noted that while the loads from fertilizer application, municipal wastewater treatment plants, and industry are localized point sources, the nutrient load from ships' wastewaters is dispersed throughout the open waters of the Baltic Sea during their voyages.

Although the overall contribution of shipping to total nutrient loading is small, recent research has improved the understanding of the relative importance of different ship-generated waste streams. According to Jalkanen (2025), grey water currently represents the largest nutrient discharge pathway from ships, accounting for more than half of shipping-related nitrogen discharges and over 70% of phosphorus discharges (Figure 9). Food waste constitutes the second largest source of phosphorus, while the relative contribution of sewage has declined substantially following the implementation of stricter wastewater discharge regulations in the Baltic Sea.

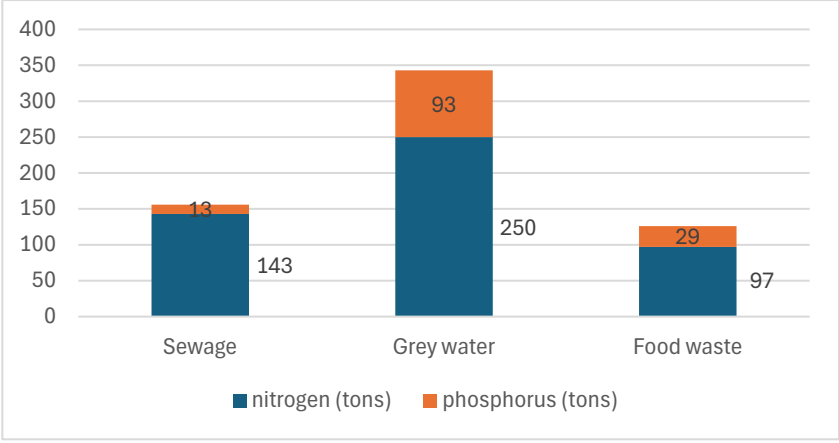


Figure 9: Grey water is the biggest identified nitrogen and phosphorus source from shipping in 2024 (adapted from HELCOM/Jalkanen, 2025).

The decline of sewage-related nutrient inputs demonstrates the effectiveness of international regulatory measures. The designation of the Baltic Sea as a MARPOL Annex IV Special Area and the subsequent requirement for passenger vessels to deliver sewage to port reception facilities have significantly reduced direct wastewater discharges from passenger ships. Consequently, the composition of shipping-related nutrient discharges

has changed, with grey water and food waste now accounting for a larger share of total nutrient inputs than sewage (Jalkanen, 2025).

The findings of this study support previous studies indicating that shipping-related nutrient inputs constitute a relatively minor source of eutrophication pressure at the Baltic Sea scale.

5.3 Comparison of the maritime and port sources to total nutrient input

The results of Article III showed that riverine inputs were the dominant source of nutrient loading to the Hamina–Kotka–Pyhtää coastal area, accounting for approximately 94% of total nitrogen inputs and 92% of total phosphorus inputs in 2021. Maritime and port-related sources together represented 3.9% of nitrogen inputs, mainly from fertilizers, and <0.1% of phosphorus input.

The source-apportionment results obtained in this study are broadly consistent with previous assessments of nutrient inputs to the Baltic Sea, confirming the dominant role of catchment-derived nutrient inputs reported in Baltic Sea-wide assessments (HELCOM, 2018; HELCOM, 2023). Other studies likewise indicate that the majority of nutrient inputs to the Baltic Sea and other semi-enclosed systems originate from rivers, with agriculture constituting the largest anthropogenic source of nutrient losses in many catchments (Alexander et al., 2008; Andersen et al., 2017; HELCOM, 2018; Murray et al., 2019; Pecio, 2024; Robertson et al., 2019; Wilewska-Bien, 2019). Agricultural sources have been estimated to account for approximately 40–60% of total nutrient loads, whereas municipal wastewater contributions are more variable but generally remain considerably higher than those from shipping.

The dominance of riverine inputs observed in the present study reflects a long-term trend in Baltic Sea nutrient management. Since the 1990s, substantial reductions have been achieved in municipal wastewater and industrial nutrient discharges through improved treatment technologies, environmental permitting, and increasingly stringent discharge requirements (HELCOM, 2018). As a result, the relative importance of point sources has declined considerably over time. In contrast, reductions in diffuse nutrient loading have progressed more slowly. Although agricultural nutrient management has been strengthened through both European Union and national measures, agriculture continues to remain the largest anthropogenic contributor to nutrient enrichment in many Baltic Sea catchments (HELCOM, 2018; HELCOM, 2023).

Similar source-apportionment patterns have been reported in other eutrophication-sensitive systems, including Lake Erie and Chesapeake Bay, where riverine and agricultural nutrient inputs remain the dominant contributors despite substantial reductions in point-source discharges (Baker et al., 2014; Boynton et al., 1995; Maccoux et al., 2016; STAC, 2019).

A key contribution of this study is its integrated source-to-sea assessment, which supports earlier findings using measured nutrient input data from all major sources within a single coastal area and adds a previously overlooked but significant source: nutrient-rich cargo operations at port.

5.4 Regulations

The results presented in Article III show that nutrient inputs in the study area are governed through a multi-level regulatory framework consisting of international conventions, EU legislation, national legislation, regional agreements, and local

environmental permits. Although all major nutrient sources are subject to some form of regulation, the regulatory stringency applied to different sources is not fully aligned with their relative contribution to nutrient loading.

The regulatory assessment revealed that the smallest evaluated source, ship-generated wastewater, is subject to the strictest regulatory control (Figure 10), whereas fertilizer cargo handling—the largest point source of nitrogen identified in the study—is regulated less stringently than several smaller point sources (Figure 11).

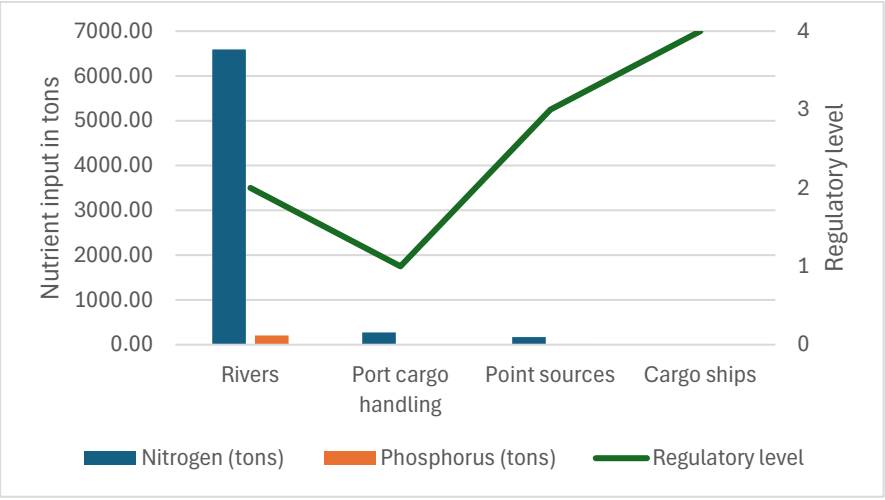


Figure10: Regulatory stringency is not fully aligned with nutrient discharge magnitude.

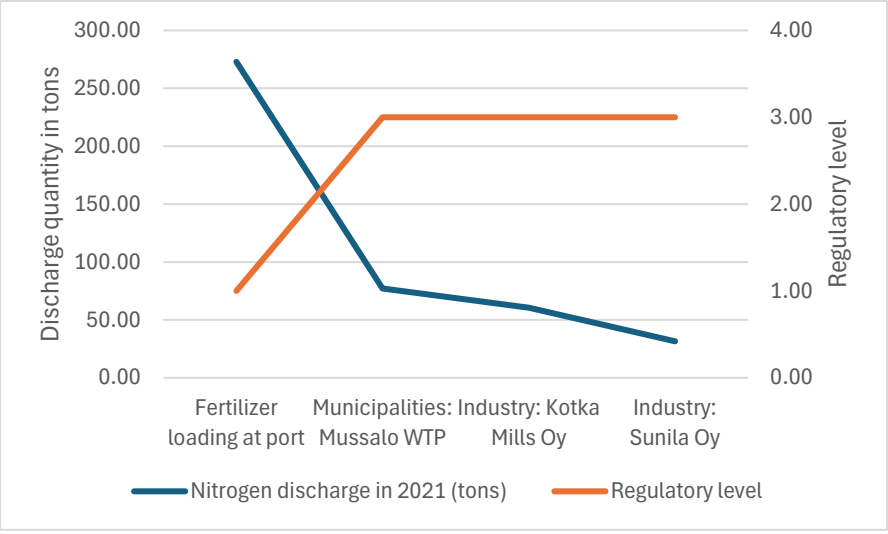


Figure 11: Biggest nitrogen contributor is regulated more loosely than other point sources.

At the same time, the largest overall contributor, riverine nutrient input originating mainly from agriculture, is covered by extensive policy frameworks but remains difficult to regulate effectively due to diffuse pathways and regulatory exceptions. These findings suggest that the relationship between nutrient pressure and regulatory control is not

always proportional. While stricter regulation may contribute to lower discharges in some cases, as demonstrated by point sources that are controlled through numerical permit limits, such conclusions cannot be directly drawn for all sources. For example, the ship wastewater estimates used in this study represent theoretical maximum discharges rather than measured releases, making it impossible to establish a direct relationship between regulatory strictness and actual discharge quantities.

Previous studies and assessments have shown that the level of regulatory control varies considerably between nutrient sources, geographical areas, and operational activities. Although international and EU legislation provide a common framework, the practical implementation of nutrient management remains largely dependent on national and local authorities. As a result, similar activities may be regulated differently across countries and even between individual facilities.

This is particularly evident in the regulation of fertilizer cargo handling. In Finland, environmental permit requirements for fertilizer operations vary between ports despite similar environmental risks. In the Port of HaminaKotka, the permit conditions were originally based on the relatively small fertilizer throughput at the time of permitting. Although throughput volumes have subsequently increased, the permit conditions have largely remained unchanged. Consequently, the stringency of regulation is influenced by historical permitting decisions and site-specific regulatory assessments rather than by a consistent evaluation of nutrient loading potential. Similar differences can be expected in other Baltic Sea countries where environmental permitting systems and regulatory practices differ.

A comparable situation exists in maritime wastewater regulation. Internationally, ship sewage discharges are governed primarily through MARPOL Annex IV, while additional restrictions may be introduced at the national level. Because shipping is inherently international and marine waters transcend national borders, harmonized international regulation is generally considered the most effective governance mechanism. However, substantial differences remain between countries. Finland has introduced national restrictions that prohibit the discharge of untreated sewage from ships in territorial waters and will progressively restrict greywater discharges. Other Baltic Sea countries generally rely on MARPOL requirements without additional national restrictions. Consequently, the regulatory classification of shipping-related nutrient inputs would vary significantly if the same assessment framework were applied in another country. In the present study, greywater discharges received the highest regulatory stringency score 4 due to Finnish legislation, whereas the same source would receive the lowest regulatory control score 0 elsewhere.

The effectiveness of nationally imposed wastewater discharge restrictions may also be limited by the international nature of shipping. While Finnish legislation prohibits sewage discharges within Finnish territorial waters, vessels operating on international routes may legally discharge stored wastewater outside Finnish territorial waters where MARPOL requirements permit such discharges. Consequently, national restrictions do not necessarily reduce total nutrient releases to the Baltic Sea.

The study also highlights the challenges associated with regulating diffuse agricultural nutrient sources. Despite being the dominant contributor to riverine nitrogen and phosphorus inputs, agriculture remains difficult to regulate effectively. Numerous policy instruments, agri-environmental schemes, and nutrient management requirements exist, yet exemptions and implementation challenges may reduce their effectiveness in practice. This finding is broadly consistent with previous studies demonstrating that

agricultural nutrient losses remain one of the most difficult nutrient sources to control despite decades of policy development.

The results also reveal a governance challenge related to fertilizer cargo operations. Several technically feasible and cost-effective measures are available for reducing nutrient losses during cargo handling, and best-practice recommendations are well established. However, in many cases these measures remain voluntary rather than mandatory. As a result, their implementation depends largely on operator commitment rather than regulatory requirements. From a policy perspective, this suggests that authorities should systematically evaluate existing mitigation recommendations and consider incorporating the most effective and technically feasible measures into mandatory permit conditions where appropriate.

More broadly, the findings illustrate a recurring challenge in Baltic Sea nutrient governance. The most effective measures for reducing nutrient inputs are generally well known, and organizations such as HELCOM have identified a wide range of scientifically supported mitigation options. However, HELCOM itself has limited authority to impose binding requirements. The implementation, enforcement, and prioritization of nutrient reduction measures remain largely the responsibility of national and regional authorities. Consequently, regulatory approaches and environmental outcomes may differ substantially between jurisdictions even when shared environmental objectives exist.

The results of this study highlight a recurring challenge in coastal eutrophication management: the dominant nutrient sources are often diffuse and difficult to regulate, whereas smaller but more manageable sources at the land–sea interface tend to receive disproportionate analytical and regulatory attention. Studies from estuaries and coastal seas worldwide emphasize that effective nutrient management requires not only addressing the largest sources but also identifying leverage points where targeted interventions can yield measurable local benefits.

5.5 Nutrient Governance and Regulatory Implications

The results of this dissertation suggest that current nutrient governance in the Baltic Sea region is not always aligned with the relative environmental significance of different nutrient sources. While some comparatively minor nutrient sources are subject to stringent regulation, other locally significant sources receive less regulatory attention. Similar governance challenges associated with fragmented responsibilities, institutional complexity and uneven implementation have been identified in broader Baltic Sea environmental governance research (Valve et al., 2017; Grönholm, 2020; Cederqvist et al., 2020). To improve the effectiveness of eutrophication management, regulatory efforts should focus on better aligning governance measures with actual nutrient pressures. The following recommendations are derived from the key findings of this study.

First, nutrient-rich cargo handling at port should be better recognized in permitting and monitoring systems. The findings demonstrate that fertilizer cargo handling can constitute a locally significant source of nitrogen loading, yet this source remains largely absent from conventional nutrient inventories and is typically regulated through environmental permits that do not include explicit nutrient discharge limits. Recent voluntary initiatives, including best environmental practice (BEP) and best available technology (BAT) guidelines developed for fertilizer shipping and port operations, provide practical measures for reducing nutrient losses (John Nurminen Foundation, 2024; Utriainen et al., 2020). However, voluntary measures alone may not ensure

consistent implementation across ports. A more systematic approach could involve harmonized environmental permit requirements, clearer nutrient monitoring obligations, and consideration of nutrient discharge limits for fertilizer handling activities. Such measures would improve the visibility of port-related nutrient sources and facilitate more consistent management practices throughout the Baltic Sea region (Gilek & Karlsson, 2016; Tynkkynen et al., 2014).

Second, the regulation of ship-generated wastewater should remain primarily based on harmonized international frameworks rather than increasingly fragmented national requirements. The results indicate that ship wastewater contributes only a negligible share of total nutrient loading, yet it is subject to the strictest regulatory controls among the nutrient sources assessed. At the same time, the regulatory approach remains uneven across the Baltic Sea region: while passenger ship sewage discharges are strictly regulated under MARPOL Annex IV, greywater is largely unregulated internationally, and some countries, such as Finland, have introduced additional national restrictions.

The international nature of shipping limits the effectiveness of nationally imposed discharge prohibitions. Although Finnish legislation prohibits sewage discharges within Finnish territorial waters and will extend restrictions to greywater, vessels operating on international routes may legally discharge stored wastewater outside Finnish waters where MARPOL requirements permit such discharges. As a result, national restrictions may shift the location of discharges rather than substantially reduce total nutrient inputs to the Baltic Sea.

Ship wastewater is already governed through MARPOL Annex IV and complementary HELCOM agreements, which were specifically developed to address nutrient discharges in the Baltic Sea as a shared marine ecosystem (IMO, 2021; HELCOM, 2023). These frameworks provide a common regulatory basis for all Baltic Sea states and are better aligned with the transboundary character of shipping and marine pollution.

Fragmented national requirements may also increase administrative complexity and reduce regulatory predictability for vessels operating between different Baltic Sea countries. Therefore, future regulatory development should primarily build on existing international instruments, ensuring a coherent Baltic Sea-wide approach while maintaining a level playing field for maritime operators (HELCOM, 2023; Ringbom, 2018).

Third, Future nutrient reduction efforts should focus more strongly on agriculture, where the largest reduction potential remains. Riverine inputs, originating largely from diffuse catchment sources, accounted for more than 90% of both nitrogen and phosphorus inputs in the study area. Despite decades of nutrient reduction efforts, diffuse agricultural loading remains the dominant source of nutrient enrichment in the Baltic Sea. Similar conclusions have been reported in Baltic Sea-wide assessments, which identify agriculture as the largest anthropogenic source of nutrient inputs to the marine environment (HELCOM, 2018; HELCOM, 2023). In contrast, substantial reductions have already been achieved in municipal and industrial point-source discharges through permit-based regulation, technological improvements, and increasingly stringent discharge limits. This suggests that future nutrient reduction potential is likely to be greatest within the agricultural sector (Andersen et al., 2017).

5.6 Limitations of the study

This dissertation focuses on nutrient discharges from selected maritime and port-related activities in a single coastal case-study area. Although the Hamina–Kotka–Pyhtää region contains several major nutrient source categories and therefore provides a suitable

environment for comparative analysis, the results cannot be directly generalized to all Baltic Sea ports. Port infrastructure, cargo composition, operational practices and environmental permit requirements vary considerably between ports.

The study focused on fertilizer cargo handling and cargo ship wastewater because these sources could be quantified with a reasonable level of confidence. Several other potential nutrient pathways, such as food waste, cargo residues, dredging activities, construction projects, ballast water and bilge water, were excluded due to limited available data and their relatively minor contribution to nutrient loading according to existing literature. Similarly, only nutrient discharges to water were assessed, while atmospheric emissions and other environmental impacts of maritime activities were outside the scope of the dissertation.

The wastewater assessment was limited to cargo ships. Passenger vessels typically generate substantially larger quantities of wastewater than cargo vessels, but regular passenger traffic is absent from the case-study port. Consequently, the results should be interpreted primarily as an assessment of cargo shipping rather than all shipping activities in the Baltic Sea. However, passenger vessels' black water discharges to the Baltic Sea has been prohibited by MARPOL since 2023, reducing that nutrient source remarkably (Jalkanen et al., 2024).

The regulatory analysis examined the formal level of regulatory control rather than regulatory effectiveness in practice. The developed classification framework compares regulations, permits and discharge restrictions, but it does not assess compliance, enforcement practices or actual environmental outcomes. Therefore, the results describe differences in regulatory structure rather than the effectiveness of individual regulatory systems.

The regulatory comparison is also influenced by geographical and temporal factors. For example, the prohibition of ship-generated sewage discharges from cargo vessels in Finnish territorial waters currently represents a national requirement rather than a Baltic Sea-wide regulation. In contrast, MARPOL Annex IV establishes strict wastewater requirements for passenger vessels throughout the Baltic Sea Special Area. The study also considers Finland's future prohibition of greywater discharges, which will enter into force in 2030. As this requirement was already adopted during the final stages of the research, it was included in the regulatory assessment despite not yet being fully implemented.

Similarly, environmental permit requirements are not uniform even within Finland. While the fertilizer terminals in the ports of HaminaKotka and Kokkola operate without explicit nutrient discharge limits, the fertilizer terminal in Uusikaupunki is subject to numeric nutrient-related permit conditions (Regional State Administrative Agency, 2015). Such differences illustrate that regulatory comparisons inevitably simplify a more complex governance landscape.

Despite these limitations, the study provides one of the first integrated assessments combining quantified maritime nutrient sources, port-related nutrient discharges and regulatory analysis within a common source-to-sea framework. The limitations primarily affect the extent to which the results can be generalized, but they do not alter the main conclusion that nutrient loads and the strictness of regulatory controls are not always aligned.

6 Conclusions

6.1 Main conclusions

This dissertation examined selected maritime and port-related nutrient sources in a Finnish Baltic Sea coastal case-study area and evaluated whether the regulatory attention given to these sources corresponds to their measured or estimated environmental significance. The study addressed three research questions concerning the identification of maritime and port-related nutrient sources (RQ1), their relative significance compared with other nutrient sources (RQ2), and the alignment between nutrient pressures and regulatory frameworks (RQ3). Three main conclusions can be drawn.

Regarding RQ1 (Sources), the study identified the principal maritime and port-related nutrient sources relevant to the study area. The analysis focused on ship-generated black and grey waters and fertilizer cargo handling as nutrient pathways with a direct connection to nitrogen and phosphorus discharges. Other ship-related discharges, including ballast water and bilge water, were reviewed but considered negligible from a nutrient-loading perspective. The results show that maritime nutrient sources are not environmentally uniform. While nutrient inputs from cargo ships' black and grey waters were found to be very small, fertilizer cargo handling emerged as a previously overlooked but locally significant source of nutrient loading. These findings demonstrate that assessments of maritime nutrient inputs should extend beyond ship wastewater and include port-related activities that may contribute directly to coastal nutrient enrichment.

Regarding RQ2 (Significance), the results show that riverine inputs remain by far the dominant source of nutrient loading to coastal waters, accounting for more than 90% of total nitrogen and phosphorus inputs in the study area. Against this background, nutrient discharges from cargo ships' black and grey waters are negligible compared with total nutrient inputs to Baltic Sea coastal waters. Even if all ship-generated wastewater were delivered ashore, the resulting reduction in total nitrogen and phosphorus inputs would remain below 0.1%. Furthermore, ship wastewater discharges are dispersed along shipping routes across the open sea rather than concentrated in coastal hotspots. In contrast, fertilizer cargo handling was identified as a locally significant point source, contributing approximately 4% of the total nitrogen load in the studied coastal area and exceeding several regulated industrial and municipal point sources. Unlike ship wastewater, these discharges occur directly in sensitive coastal waters. Importantly, several technically feasible and cost-effective mitigation measures already exist, including improved cargo handling practices, enclosed systems, and enhanced stormwater management. Despite this, fertilizer-related nutrient losses remain largely overlooked in both research and regulation.

Regarding RQ3 (Regulations), the results reveal inconsistencies between environmental pressure and regulatory control. Ship-generated wastewater is subject to extensive regulation and increasing restrictions despite contributing only a very small share of total nutrient inputs. At the same time, fertilizer cargo handling, which can cause locally significant nutrient discharges, remains comparatively weakly regulated and is often governed through environmental permits lacking explicit nutrient discharge limits. The findings therefore suggest that regulatory attention is not always proportional to environmental significance. From a governance perspective, ship wastewater regulation

should continue to be based primarily on internationally harmonised MARPOL and HELCOM frameworks rather than increasingly fragmented national requirements, and greater attention should be given to improving the regulation and monitoring of port-related nutrient discharges.

More broadly, the dissertation demonstrates that nutrient sources are often studied, monitored, and regulated through separate sectoral frameworks. This fragmentation can contribute to an incomplete understanding of nutrient sources and their relative significance. By integrating source quantification with regulatory analysis, the study shows the value of a source-to-sea perspective for identifying both overlooked nutrient sources and potential inconsistency between nutrient pressures and governance responses.

Finally, the results confirm that the greatest nutrient pressures on the Baltic Sea continue to originate from diffuse land-based sources, particularly agriculture and forestry. While point-source and shipping-related discharges have been substantially reduced over recent decades, progress in reducing diffuse nutrient losses has been considerably slower. The findings therefore suggest that future eutrophication policies should focus more strongly on sources with the greatest reduction potential and align regulatory effort more closely with environmental pressures.

6.2 Future research and development needs

Future research should expand the empirical assessment of fertilizer-related nutrient losses across different Baltic Sea ports, cargo types, handling technologies, and stormwater management systems. Comparative studies are needed to determine whether the findings from the Port of HaminaKotka represent a site-specific phenomenon or a more widespread nutrient pathway within the port sector.

Second, future studies should improve the estimation of actual ship-generated wastewater discharges by integrating vessel traffic data with information on port reception facility use, onboard storage capacities, treatment performance, and vessel discharge practices. Such analyses would provide a more accurate understanding of the contribution of ship wastewater to nutrient loading in the Baltic Sea.

Third, the regulatory assessment framework developed in this thesis could be applied across other Baltic Sea countries to examine how differences in national legislation, permitting systems, and enforcement practices influence the alignment between nutrient pressures and regulatory control.

Finally, future research should evaluate the environmental effectiveness and cost-efficiency of mitigation measures aimed at reducing nutrient discharges from port operations. Particular attention should be given to enclosed fertilizer handling systems, improved dry-cleaning practices, stormwater collection and treatment, nutrient recovery technologies, and harmonized monitoring and reporting requirements across ports.

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Abstract

Nutrient Discharges from Maritime Activities in the Baltic Sea -Sources, Significance and Regulatory Implications

Eutrophication remains the most severe environmental pressure affecting the Baltic Sea and is primarily driven by excessive nitrogen and phosphorus inputs from human activities. While nutrient loading from agriculture, wastewater treatment plants, and industry has been extensively studied, maritime and port-related nutrient sources are rarely compared with the land-based sources within a common analytical framework. In addition, the relationship between the environmental significance of different nutrient sources and the regulatory frameworks governing them remains insufficiently understood. This dissertation addresses these gaps by identifying and quantifying the selected maritime and port-related nutrient sources, assessing their significance in relation to total nutrient loading, and evaluating whether existing regulation corresponds to observed nutrient pressures.

The dissertation is based on three peer-reviewed studies and applies an integrated source-to-sea and governance-oriented approach. The research follows a case-study design focused on the Hamina–Kotka–Pyhtää coastal area in the eastern Gulf of Finland, an area containing major riverine, industrial, municipal, maritime, and port-related nutrient sources within the same coastal system. First, nutrient discharges from fertilizer cargo handling were quantified through intensive stormwater monitoring combined with machine-learning-based modelling to capture spatial and temporal variability. Second, the theoretical maximum nutrient generation from cargo ships' black and grey waters was calculated using vessel traffic data, voyage characteristics, crew estimates, and established emission factors. Third, these maritime and port-related nutrient sources were evaluated alongside riverine, municipal, and industrial inputs in a comparative source apportionment, coupled with an analysis of the regulatory instruments governing each source category.

The results showed that riverine inputs dominated nutrient loading in the studied coastal area, accounting for 93.7% of total nitrogen inputs and 91.7% of total phosphorus inputs. Fertilizer cargo handling contributed 3.9% of total nitrogen and 0.1% of phosphorus loading, whereas cargo ships' black and grey waters accounted for less than 0.1% of both nutrients. These findings demonstrate that fertilizer cargo handling is the most significant maritime-related nutrient source identified in the study area, while nutrient inputs from cargo ship wastewater are negligible compared with riverine and major land-based point sources.

The regulatory analysis revealed substantial differences in regulatory treatment among nutrient sources. Cargo ships' black and grey water, despite its very limited contribution to nutrient loading, was subject to the highest level of regulatory control in the studied area. In contrast, fertilizer cargo handling, which generated considerably larger nitrogen discharges and exceeded the nitrogen loads of individual industrial and municipal point sources, was regulated mainly through operational requirements and environmental permits without explicit nutrient discharge limits. The results indicate that regulatory attention is not always aligned with the relative environmental significance of nutrient sources.

The dissertation demonstrates the value of combining nutrient source quantification with governance analysis within a common source-to-sea framework. The findings improve understanding of maritime and port-related nutrient discharges in the Baltic Sea and highlight the importance of aligning regulatory attention more closely with environmental pressures. The results further support the view that the regulation of ship-generated wastewater should remain based primarily on harmonized international frameworks, such as MARPOL and HELCOM, rather than increasingly fragmented national regulations, reflecting the transboundary nature of maritime traffic.

Lühikokkuvõte
Merendustegevusest tulenev toitainekoormus Läänemeres: allikad, olulisus ja regulatiivsed mõjud

Läänemere eutrofeerumine on endiselt üks suurimaid merekeskkonna probleeme. Selle peamine põhjus on inimtegevusest tulenev liigne lämmastiku- ja fosforikoormus. Põllumajandusest, reoveepuhastitest ja tööstusest pärinevat toitainete koormust on põhjalikult uuritud, kuid merendus- ja sadamategevuse osakaalu kogukoormuses ei ole seni piisavalt hinnatud. Samuti ei ole selge, kas eri toitaineallikate keskkonnamõju ja nende suhtes kehtivate nõuete rangus on omavahel kooskõlas. Doktoritöös hinnatakse merendus- ja sadamategevusest pärinevat toitainete koormust, selle osakaalu kogukoormuses ning seda, kas kehtivad nõuded vastavad tegelikule keskkonnamõjule.

Doktoritöö põhineb kolmel eelretsenseeritud teadusartiklil ning käsitleb toitainete liikumist nende tekkekohast mereni koos keskkonnajuhtimise meetmetega. Juhtumiuuring viidi läbi Hamina–Kotka–Pyhtää rannikualal Soome lahe idaosas. Selles piirkonnas jõuavad samasse rannikumere süsteemi toitained jõgedest, tööstusest, reoveepuhastitest, laevaliiklusest ja sadamategevusest.

Esiteks hinnati sadamas väetiste käitlemisel tekkivaid lämmastiku- ja fosforiheitmeid. Selleks seirati põhjalikult sademevett ning kasutati masinõppel põhinevat mudelit, et kirjeldada heitmete muutlikkust ajas ja ruumis. Teiseks arvutati kaubalaevadel tekkiva mustvee ehk tualettreovee ja hallvee ehk pesemisest, köögist ning muudest olmetegevustest pärineva reovee suurim võimalik toitainete kogus. Arvutused põhinesid laevaliikluse andmetel, reiside kestusel, meeskondade hinnangulisel suurusel ning kirjanduses esitatud heitmeteguritel. Kolmandaks võrreldi merendus- ja sadamategevusest pärinevat toitainete koormust jõgede, reoveepuhastite ja tööstusest tuleneva koormusega. Samuti hinnati eri toitainete allikate suhtes kehtivaid õigusnõudeid ja muid keskkonnajuhtimise meetmeid.

Tulemused näitasid, et uuritud rannikuala toitainete koormuses valitsesid jõgedest pärinevad sisendid. Need moodustasid 93,7% kogu lämmastiku- ja 91,7% fosforikoormusest. Väetiste käitlemine sadamas andis 3,9% lämmastiku- ja 0,1% fosforikoormusest. Kaubalaevade musta ja halli vee osakaal jäi mõlema toitaine puhul alla 0,1%. Seega oli väetiste käitlemine sadamas uurimisala tähtsaim merendusega seotud toitainete koormus. Kaubalaevade reoveest pärinev koormus oli aga jõgedest ja peamistest maismaa punktallikatest pärineva koormusega võrreldes tühine.

Õigusnõuete analüüs näitas, et eri toitainete allikaid reguleeritakse väga erinevalt. Kaubalaevade must- ja hallvee käitlemisele kehtivad ranged nõuded, kuigi nende osa uurimisala toitainete kogukoormuses on väga väike. Väetiste käitlemist sadamas reguleeritakse peamiselt tegevusnõuete ja keskkonnalubade kaudu, kuid toitainete heitkogustele otseseid piirnorme ei ole. Samas põhjustab väetiste käitlemine sadamas märksa suurema lämmastikukoormuse kui laevade reovesi ning selle koormus ületab ka mõne tööstusettevõtte ja reoveepuhasti oma. Seega ei vasta eri allikatele seatud nõuete rangus alati nende tegelikule keskkonnamõjule.

Doktoritöö näitab, et toitainete koormuse arvuline hindamine koos keskkonnajuhtimise analüüsiga annab terviklikuma ülevaate sellest, kust toitained pärinevad, kuidas need merre jõuavad ja kuidas nende heidet piiratakse. Tulemused aitavad paremini mõista Läänemere merendus- ja sadamategevusest pärinevat

toitainete koormust. Samuti näitavad need, et õigusnõuded tuleks senisest paremini siduda eri allikate tegeliku keskkonnamõjuga.

Uuring toetab seisukohta, et laevadel tekkiva reovee käitlemise nõuded peaksid põhinema eelkõige ühtsetel rahvusvahelistel kokkulepetel, nagu MARPOL ja HELCOM. Liiga erinevad riiklikud nõuded võivad muuta süsteemi killustatuks, samas kui laevaliiklus on oma olemuselt piiriülene.

Appendix 1

Publication I

Lappalainen, S.-T., Kotta, J., Tombak, M.-L., & Tapaninen, U. (2024). Using Machine Learning Methodology to Model Nutrient Discharges from Ports: A Case Study of a Fertilizer Terminal. Journal of Marine Science and Engineering, 12(1), 143. https://doi.org/10.3390/jmse12010143

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Article

Using Machine Learning Methodology to Model Nutrient Discharges from Ports: A Case Study of a Fertilizer Terminal

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Abstract: Marine eutrophication is a pervasive and growing threat to global sustainability. Thereby, nutrient discharges to the marine environment should be reduced to a minimum. When fertilizers are loaded to the vessels in ports, a significant amount of nutrients are released into the sea, but so far these actions have received little attention. Here, we employed the Boosted Regression Trees modeling (BRT) to define the relationships between fertilizer loading, the loading area, rain intensity, nutrient discharge, and the marine environment, and then used the established relationships to predict the daily nutrient discharge due to fertilizer loading. The studied subject was a port in the Gulf of Finland, where significant amounts of both nitrogen and phosphorus are loaded to vessels. BRT models accounted for a significant proportion of the variability of nutrient discharge. As expected, the nutrient discharge increased with the number of fertilizers loaded and the intensity of rain. On the other hand, with the increasing loading area, the total nitrogen discharge increased, but the total phosphorus discharge decreased. The latter result may be due to the different characteristics of the loading areas of different terminals. The model predicted that at the studied port, the total nitrogen and phosphorus discharge to the marine environment due to fertilizer loading was 272,906 and 196 kg per year, respectively. Importantly, the developed model can be used to predict the nutrient loads for different future scenarios in order to propose the best mitigation methods for nutrient discharges to the sea.

Keywords: nitrogen and phosphorus discharges; green port; fertilizers; BRT models; eutrophication

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1. Introduction

Eutrophication is one of the main environmental threats to the Baltic Sea. Eutrophication, a consequence of excessive nutrient input, particularly nitrogen and phosphorus, disrupts marine ecosystems by promoting excessive algal growth and triggering hypoxic conditions. This phenomenon results in the decline of species diversity, deterioration of water quality, and adverse impacts on fisheries, ultimately undermining the stability and functionality of marine ecosystems [1]. The main contributor to the nutrient load is agriculture and it has the greatest potential for reduction. Other sources include point sources in the upper reaches of rivers, municipal sources and wastewater treatment plants, and industry and transport [2].

Shipping contributes roughly 0.3% of the total phosphorus and 1.25–3.3% of the total nitrogen inputs to the Baltic Sea [3], and potential sources include fertilizer transfer, food waste disposal, gray and black water discharges, bilge and scrubber water discharges, and the discharge of treated ballast water [4–9].

Annually, over 45 million tons of fertilizers are transported via cargo ships at Baltic Sea ports [10]. With an estimated cargo loss of 0.05% during handling operations [11], approximately 22,000 tonnes of fertilizers may inadvertently enter the sea each year. The primary causes of fertilizer loss include ship loading and unloading processes (particularly when employing antiquated techniques), temporary open storage, and inadequate

stormwater management at port facilities [10]. Fertilizers are managed in more than 70 ports in the Baltic Sea region [10], with the largest quantities in 2019 being handled at Klaipeda (13 million tonnes), Saint Petersburg (9), Vyborg (4), Gdynia (2), Gdansk (2), HaminaKotka (2), Szczecin (1.7), Tallinn (1.6), Rostock (1.6), Police (1.3), Liepaja (1.1), and Uusikaupunki (0.9) [12].

Fertilizer discharges from shipping to the Baltic Sea are not currently regulated. While MARPOL Annex V controls the cargo residues from dry bulk carriers classified as harmful to the marine environment (HME), fertilizers do not fall under this category and can be discharged at sea if over 12 nautical miles from land [11]. According to Finnish National Environmental Protection Act Law [13], an environmental permit is needed for activities with pollution risks. The case port has an environmental permit [14] for fertilizer loading activities, which requires certain operational measures. However, no limits are set for cargo emissions or discharges. The updated Baltic Sea Action Plan [2] establishes nitrogen and phosphorus reduction targets, with actions related to shipping and ports to decrease the nutrient loads from dry bulk fertilizer handling. Thus, although fertilizer terminals are recognized as significant sources of nutrient load, no systematic and reliable monitoring of discharges have been conducted. Neither have the total nutrient loads to the sea from the discharges from fertilizer loading in port areas been systematically assessed.

To fill this gap, this study aimed to quantify the spatio-temporal variability of nutrient discharges due to fertilizer loading. The main research questions of this study are as follows: (1) How can nitrogen and phosphorus discharges from fertilizer loading be estimated? (2) How much phosphorus and nitrogen in kg was generated by the loading/unloading of fertilizers? (3) How can nitrogen and phosphorus discharges be reduced at the port? To answer the questions, the quantities of nitrogen and phosphorus discharges from the identified sources (rainwater) were measured, the environmental variables affecting these emissions were identified and measured (fertilizer application area, rainfall intensity), and a model relating environmental variables and nutrient emissions was built to assess the daily nitrogen and phosphorus emissions at the fertilizer application site over the course of a year. The results were compared with previous studies of nitrogen and phosphorus sources.

This paper is organized as follows: Section 1 is an introduction that gives the reader an overview of the study, and presents the research questions and background of this study based on a literature review. Section 2 consists of the methodology for carrying out the monitoring of nitrogen and phosphorus emissions in the fertilizer load area and the construction of a model for predicting daily nutrient discharges in the area. The results are presented in Section 3, and in Section 4, the results are discussed and compared to other studies. Conclusions and recommendations for action and further research are described in Section 5.

2. Materials and Methods

2.1. Field Measurement

The case port is the Port of HaminaKotka, a general port in the Gulf of Finland. There are multiple cargo types handled in the port, such as containers, roro, liquid bulk, and dry bulk. In the port, the total annual volume of fertilizers loaded to ships in 2021 was 2.33 million tons, and in 2022, it was 2.49 million tons. Most of the fertilizers in 2022 was urea, the other types being several types of phosphates. The fertilizers arrive to the port by trains and are unloaded to storage halls before loading to ships. There are three berth areas where fertilizers are loaded, each equipped with a separate stormwater line. At two berth areas, the cargo is loaded using conveyor belts, and at one berth, the fertilizers are loaded by grabbers.

In the field study, stormwater samples were collected during rainfall from stormwater wells at each of the three loading berths. In Figure 1, the sample wells are marked with black rings and their pipelines are marked with blue (well 1), orange (well 2), and gray (well 3) to give an overview of each catchment area. The same colors are used in Figures 2 and 3 respectively. We took samples at the onset of rain and then every 2–4 h. In total,

58 samples were collected from the wells over 8 rainy days in autumn 2021. The aggregate sample from each day was analyzed by an accredited laboratory, SGS Finland, using the Kjeldahl method. The analyzed components were total phosphorus, phosphate phosphorus, total nitrogen, and salinity. Salinity was analyzed to find out if the sea water through the stormwater outlet pipes had an effect on the results.

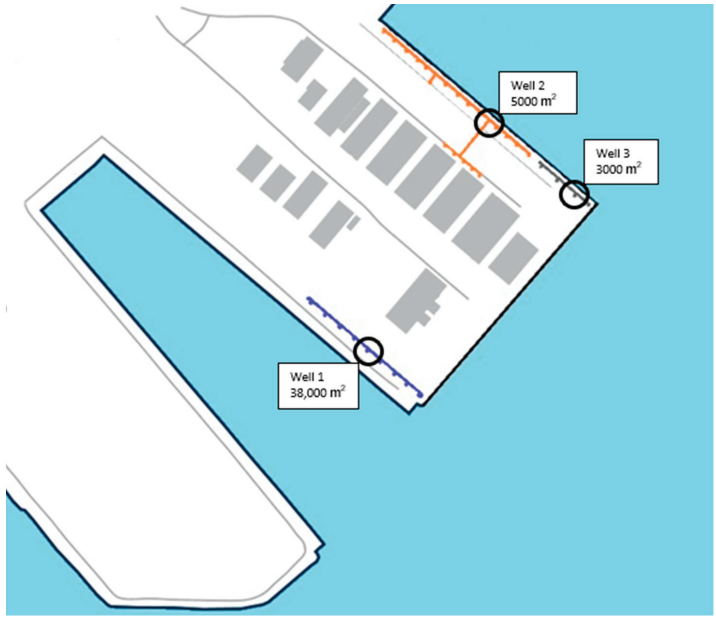


Figure 1. Three stormwater wells and their catchment areas [15].

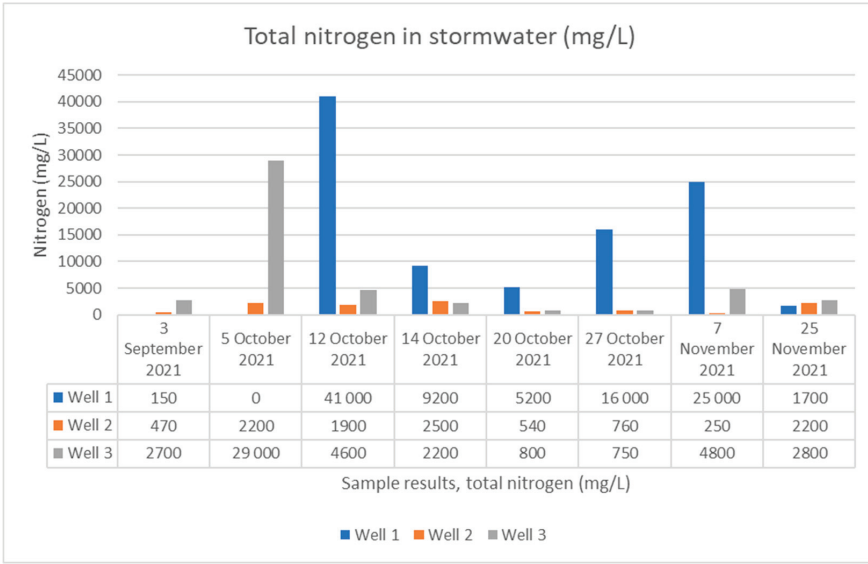


Figure 2. Total nitrogen concentration in stormwaters (mg/L). Well 1 displays highest nitrogen concentrations.

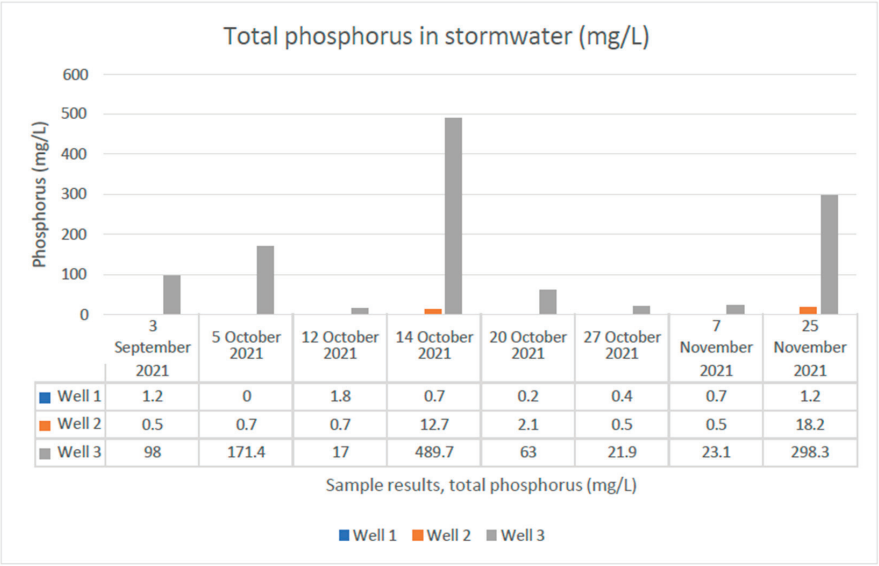


Figure 3. Total phosphorus in stormwaters (mg/L). Well 3 displays highest concentrations as most of the phosphorus fertilizers are loaded in that area.

The analysis results for nitrogen, phosphorus, and phosphate phosphorus carry a margin of error. Given the notably high nutrient concentrations, the water samples required dilution to facilitate analysis. Thus, a 15% margin of error is associated with the analysis method for nutrient concentrations.

2.2. Modeling Nutrient Discharges

When modeling the nutrient discharges, we identified the influencing environmental variables, utilized these predictors to construct the model, and made predictions for unmonitored spatial extents and time periods. For fertilizer loading at ports, nutrient discharges to the sea are primarily influenced by factors such as the loading area (catchment area), quantity of loaded fertilizers, loading timing, and rainfall intensity.

The catchment area sizes for three loading areas were acquired from a prior port stormwater monitoring report [15], measuring 38,000 m^2, 5000 m^2, and 3000 m^2. The stormwater outlet pipe heights were 1.19 m, 1.27 m, and 0.8 m above sea level. Although sea water may have reached the lowest outlet, no substantial impact on the results was observed.

The rain data were obtained from the Statistics Service of the Finnish Meteorological Institute [16]. The 2021 rain statistics included an hourly observation of rainfall and rain intensity. The observation station was located 5.5 km from the loading berths.

The field of modeling faces a challenge in developing a theoretical framework that can transcend traditional paradigms, particularly in light of the concept of "complex realism". To address this challenge, machine learning techniques provide a sophisticated tool that can aid in improving our understanding of the relationships between the environment and processes of interest. Unlike traditional methods, machine learning algorithms do not start with a predefined data model; instead, they learn the relationship between a response and its predictors [17]. However, it is crucial to incorporate a mechanistic understanding when selecting environmental variables for the model in order to identify and quantify the relationships between the environment and the process of interest.

A novel predictive modeling technique known as Boosted Regression Trees (BRT) combines the strengths of both machine learning and statistical modeling. BRT does not require prior data transformation or the elimination of outliers and is capable of

fitting complex nonlinear relationships. Thresholds and unimodal responses, which are common in real-world data, pose analytical challenges to traditional methods. However, these complexities can be addressed more effectively by applying machine learning and artificial intelligence techniques. Furthermore, the method avoids overfitting the data and provides robust estimates, which are essential in many applications. Moreover, BRT can automatically detect and model the interactive effects between predictors, making it particularly useful in identifying the multitude of interactions between environmental variables. Due to its strong predictive performance, BRT is increasingly being used in various fields [18,19]. Overall, BRT provides a promising approach for many disciplines by offering a powerful and flexible tool for analyzing the complex relationships between a response and its predictors.

The BRT modeling technique was used to build a model relating environmental variables to nutrient emissions at the fertilizer application site, and this model was then used to assess the daily nutrient emissions at the site over the course of a year. BRT modeling iteratively develops a large ensemble of small regression trees constructed from random subsets of the data. Each successive tree predicts the residuals of the previous tree to gradually increase the predictive power of the overall model [18]. When fitting a BRT, the learning rate and tree complexity must be specified. The learning rate determines the contribution of each successive tree to the final model as it progresses through iterations. The tree complexity determines whether only main effects (tree complexity = 1) or also interactions (tree complexity > 1) are included. Finally, the learning rate and tree complexity together determine the total number of trees in the final model. Following the suggestions of Elith et al. [18], the model learning rate was kept at 0.1 and the tree complexity at 5 for both models. It was also checked that the final models had more than 1000 trees. Nevertheless, the selection of model parameters had only a marginal effect on model performance, with optimal models improving predictions by less than 1%. Model performance was evaluated by using the cross-validation statistics calculated during model fitting [19].

3. Results

The results of the stormwater nutrient monitoring revealed significant variations in nutrient amounts depending on the loading area, fertilizer type, rainfall, and date. The highest nitrogen and phosphorus concentrations were observed immediately after ship loading operations. Figure 2 shows the daily total nitrogen concentrations for each well. All three terminals loaded nitrogen fertilizers (primarily urea), with well 1 generally exhibiting the highest nitrogen concentrations. The maximum concentration, 41,000 mg/L, was recorded on 12 October after ship loading occurred that day. Well 3 showed the second highest result, approximately 29,000 mg/L, on 5 October, also after ship loading on the same day. The result of well 1 for 5 October is not available as the well was submerged and inaccessible.

Figure 3 presents the daily total phosphorus concentrations for each well. Phosphorus fertilizers were not loaded in the well 1 area, resulting in minimal phosphorus readings. Well 3, handling the most phosphorus fertilizers, displayed the highest phosphorus concentrations. The largest values were 489.7 mg/L on 14 October, following ship loading the previous day (13 October), and 298.3 mg/L on 25.11 after loading on 24 November. Similarly to nitrogen, the result for well 1 on 5 October is not available as the well was submerged and inaccessible.

The BRT models accounted for more than 80% of the variability in the discharge of nutrients into the sea. As expected, nutrient export increased with fertilizer loading and rainfall intensity. However, most of the variability in discharge was due to rainfall intensity, and the relative contribution of loadings was small, estimated only at 4–8% of the total variability. On the other hand, with the increasing loading area, the amounts of total nitrogen discharge increased, but the phosphorus discharge decreased (Figures 4 and 5).

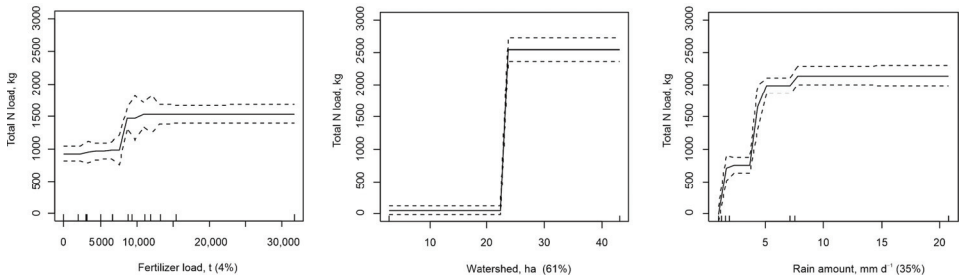


Figure 4. Standardized functional-form relationships showing the effect of environmental variables on total nitrogen discharge from fertilizer loading to the marine environment, while all other variables are held at their means. The relative contribution of each variable in the BRT model is given in brackets after the variable name on the *x*-axis. Upward tickmarks on *x*-axis show the frequency of distribution of data along this axis.

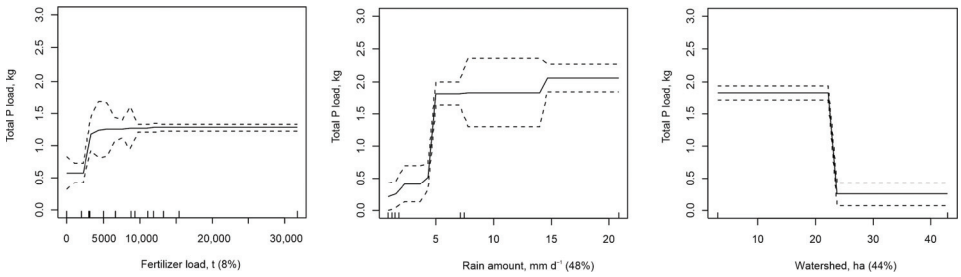


Figure 5. Standardized functional-form relationships showing the effect of environmental variables on total phosphorus discharge from fertilizer loading to the marine environment, while all other variables are held at their means. The relative contribution of each variable in the BRT model is given in brackets after the variable name on the *x*-axis. Upward tickmarks on *x*-axis show the frequency of distribution of data along this axis.

When the model was used to assess the daily nutrient emissions at the site, the estimated total nitrogen and phosphorus discharge from fertilizer loading to the marine environment was 272,906 and 196 kg per year, respectively. The daily variability of nitrogen and phosphorus discharges to the marine environment due to fertilizer loading at the port mainly reflected the peaks of rainfall, with heavier rainfall resulting in higher nutrient emissions to the sea (Figures 6 and 7).

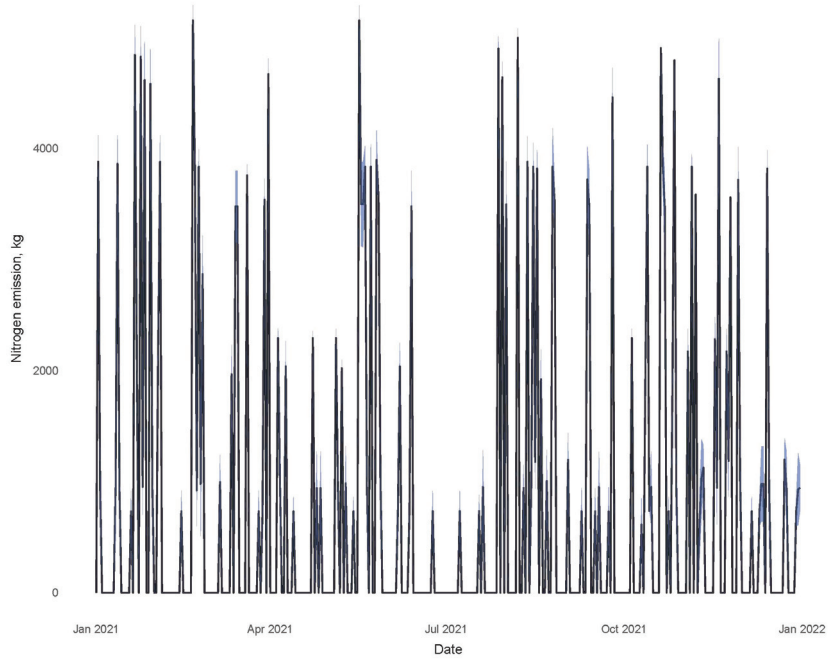


Figure 6. Predicted daily dynamics of total nitrogen discharge from fertilizer loading to the marine environment. The thicker line shows mean emissions, while the thinner line shows the standard error of these means.

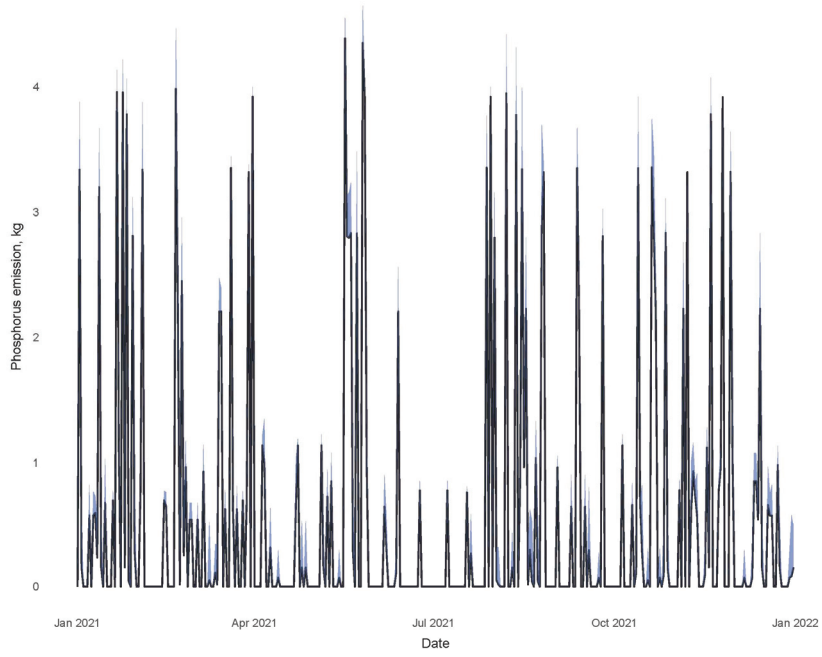


Figure 7. Predicted daily dynamics of total phosphorus discharge from fertilizer loading to the marine environment. The thicker line shows mean emissions, while the thinner line shows the standard error of these means.

4. Discussion

Our study focused on three key research questions: firstly, developing a method to estimate nitrogen and phosphorus emissions from fertilizer application; secondly, quantifying the total amount of these nutrients generated through both fertilizer application and removal; and thirdly, investigating strategies for mitigating these emissions.

Our approach combined in situ monitoring and modeling to provide robust estimates of emissions. We measured nitrogen and phosphorus emissions directly from identified sources, such as rainwater, and identified and measured key environmental variables that influence these emissions, including the area of fertilizer application and rainfall intensity. We then developed a model relating these environmental variables to nutrient emissions. Using this combined approach, our model estimated that the total nitrogen and phosphorus emissions from fertilizer application to the marine environment were 272,906 kg and 196 kg per year, respectively. This methodology not only provided accurate daily estimates, but also provided a comprehensive annual overview of nutrient emissions, demonstrating the effectiveness of integrating direct monitoring with predictive modeling in environmental studies.

The present study demonstrates that machine learning modeling methods are effective tools for predicting the complex realism of various processes, and are capable of reproducing non-linear relationships and identifying tipping points indicative of abrupt discontinuous shifts. The BRT model revealed that as the loading area increased, the total nitrogen discharge increased, while the phosphorus discharge decreased. This latter finding may be attributed to differences in the characteristics of the loading areas utilized by terminals.

Our model effectively integrates spatial and temporal dimensions by using training data from three different loading areas with different catchment characteristics and by collecting nutrient concentration samples at different times. This design captures the essential spatial and temporal variability of nutrient inputs to the sea, which is influenced by factors such as the catchment area, fertilizer application rate, loading timing, and rainfall intensity. By incorporating these spatial and temporal factors as independent variables, our model is able to predict nutrient loads for areas and periods beyond the scope of existing monitoring. This approach significantly improves the robustness and accuracy of our predictions. However, it is important to note that our results, based on data from one specific port, should not be extrapolated to other ports without additional data from those sites. Thus, the current model can be employed in the same port for hindcasting nutrient emissions in previous years or conducting scenario analyses for future port management. Additionally, the model can be applied in other ports, provided it is re-parametrized and validated using port-specific monitoring data. This is necessary due to the unique catchment areas, fertilizer loading management, and rainfall characteristics that distinguish individual ports. Despite this limitation, our study serves as a valuable demonstration of how pollutant loads can be effectively predicted in scenarios where monitoring data do not cover all spatial and temporal extents.

This study relies on actual monitoring measurements of water nutrient concentrations in stormwater, which were used to train the BRT model and estimate the total annual load over one year. Inaccuracies may arise due to the limited number of stormwater samples employed for model training relative to the observed spatio-temporal variability of nutrient concentrations in stormwater. Another source of error stems from nutrient analyses. Thus, it is expected that increasing the sample size can enhance confidence in the results. Despite the considerable variability in the training data and the relatively small sample size, the BRT model showed a high level of accuracy, accounting for over 80% of the variability in the nutrient discharges to the sea. This is further demonstrated by the very small margins of error, as shown in Figures 4 and 5. These results highlight the effectiveness of machine learning algorithms in capturing complex patterns and relationships that may not be fully captured by traditional statistical methods. Therefore, while sample size is a consideration, the robust performance of our model mitigates this potential limitation.

Prior to this study, the sampling efforts in the case port were limited to annual samples as per environmental permits. The present study conducted intensive sampling to provide a comprehensive analysis of stormwater quality. The obtained results were then compared with the annual stormwater sampling data collected by the Water and Environment Association of the River Kymijoki [15]. The phosphorus concentrations observed in the stormwater wells in this study were found to be consistent with the previously reported results. However, notable differences were observed in the nitrogen concentrations, with one stormwater well exhibiting significantly higher levels in this study.

For many nutrient sources entering the Baltic Sea, the nutrient concentrations are relatively low. However, passenger ship wastewater and fertilizer stormwater represent point sources with higher concentrations. Consequently, it is crucial to collect sewage waters from passenger ships using port reception facilities, as mandated by the International Maritime Organization IMO in 2011 [20]. On the other hand, the total annual amount of nitrogen in the sewage waters of all 2355 cargo ships calling at the case port in 2020 was only 0.7 tons [21], whereas the BRT modeling estimates an annual nitrogen load of 273 tons from the fertilizer loading area. When comparing these loads to other sectors, the annual nitrogen load at the fertilizer site is equivalent to the emissions produced by 9000 tons of caged finfish in the sea [22]. Presently, Estonia's total aquaculture fish production, including freshwater systems, amounts to less than 1000 tons annually [23], and aquaculture expansion is hindered by the Baltic Sea's heavy eutrophication. Therefore, it is essential to develop and implement mitigation measures to eliminate nutrient sources related to fertilizer loading.

The updated Baltic Sea Action Plan [2] establishes reduction targets for nitrogen and phosphorus for the Baltic Sea countries, necessitating numerous actions to meet these goals. For shipping and ports, this includes minimizing nutrient loads from dry bulk fertilizer handling operations. According to the results of this study, the amount of nitrogen discharged to the sea via stormwaters during fertilizer loading contributes to 15% of the total reduction target set by HELCOM at that coastal area.

General techniques have been identified to reduce the emissions during loading, as described by Coalition Clean Baltic in 2019 [24]. Enclosing conveyors, chutes, and telescoping arm loaders is a simple yet effective measure to reduce dust emissions and further discharges to the sea. Another effective approach is to reduce the distance between the equipment and ship holds, which helps to minimize the freefall of material. In addition, it is recommended to suspend unloading and handling operations during unfavorable weather conditions, such as rain and wind, which can increase the run-off or blowing dust. Dust suppression techniques such as bag house filters, screw conveyors, and vacuum collecting equipment can also be introduced wherever practical. Finally, the regular sweeping of the bulk storage and access/egress areas, and handling swept material, is an important measure to prevent nutrients' introduction into the Baltic Sea. The combination of these techniques can help to mitigate the impact of loading and unloading activities on air and water quality in port areas.

In recent years, substantial progress has been made in developing environmentally friendly methods for dry bulk handling in ports. Two Baltic ports have investigated potential solutions to reduce the environmental impact of fertilizers in the WISA (Water Innovation System Amplifier) project [25]. Between 2017 and 2020, the project initiated preventive measures and successfully implemented new processes. In the Port of Åhus, several actions were undertaken, including terminal operator education on the environmental impact of products, spill prevention measures, enhanced cleaning processes and equipment, and spillage reduction initiatives during crane operations. Additionally, the Port of Åhus introduced environmental monitoring, conducting individual meetings with companies operating within the harbor area. The prevention measures described provided good improvements, as the discharge of nitrogen and phosphorus via stormwater was reduced by 60–70%.

In the case port of this study, the implementation of mitigating measures has been discussed with the loading terminals. It has been emphasized to the terminals that compliance with the environmental permit is essential, requiring the covering of stormwater wells during the loading process, ensuring the proper closure of loading grabs, and conducting a thorough cleaning of the berth after loading operations. Furthermore, to validate the effectiveness of the implemented measures, it is recommended to conduct a reassessment of the stormwater sampling period to determine if the discharge levels have indeed been reduced.

In the near future, it is crucial to implement measures to prevent the continued release of emissions into the sea, emphasizing the need for comprehensive actions by all stakeholders. However, the challenge lies in the absence of regulations specifically targeting the reduction of nutrient input to the sea, rendering all actions voluntary. Fertilizers, classified as non-Hazardous Materials (non-HME), are not regulated by the MARPOL convention, and existing environmental permits lack maximum limits for fertilizer discharges into the sea. As a step forward, HELCOM is currently developing recommendations for fertilizer ports to minimize their environmental impact. To enhance effectiveness, it is crucial to investigate alternative regulatory approaches, including potential modifications to environmental permitting processes. The consideration of making mitigation methods mandatory, while also considering their financial feasibility, is paramount. For the operating terminals, implementing mitigation measures, such as containment bags, filters, and weather-related operational breaks, may currently be perceived as economically challenging. In the long run, such measures could prove beneficial for both reducing environmental impacts and aligning with the increasingly stringent demands from stakeholders.

5. Conclusions

In conclusion, our study demonstrates that marine eutrophication, a critical and expanding challenge to global sustainability, necessitates significant reductions in nutrient discharges into marine ecosystems. Employing Boosted Regression Trees (BRT) modeling, we have quantified the daily nutrient discharge attributable to fertilizer loading in a Gulf of Finland port within the Baltic Sea. The BRT model effectively accounted for a substantial portion of nutrient discharge variability and estimated an annual discharge of 272,906 kg of nitrogen and 196 kg of phosphorus due to fertilizer loading. These findings underscore the importance of enhancing the environmental sustainability of the fertilizer loading process, which exhibits the highest potential for reducing nitrogen and phosphorus discharges at the studied port. As such, we recommend that authorities, port managers, shipping companies, and loading terminals collaborate to implement strategies aimed at mitigating fertilizer-induced nutrient loading in the Baltic Sea, ultimately promoting a healthier and more sustainable marine environment.

Author Contributions: Conceptualization, S.-T.L. and J.K.; methodology, J.K.; validation, S.-T.L., J.K., M.-L.T. and U.T.; formal analysis, J.K.; investigation, S.-T.L., J.K. and M.-L.T.; resources, S.-T.L. and J.K.; data curation, S.-T.L. and J.K.; writing—original draft preparation, S.-T.L., J.K., M.-L.T. and U.T.; writing—review and editing, S.-T.L., J.K., M.-L.T. and U.T.; visualization, S.-T.L.; supervision, J.K. and U.T.; project administration, U.T. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The main factors contributing to the nutrient discharges to the sea are the loading area (catchment area), quality and quantity of loaded fertilizers, loading timing, and rainfall intensity. Collected field measurement data were also used for the modeling. Catchment area data were acquired from a prior port stormwater monitoring report [15]. The rain data were obtained from the Statistics Service of the Finnish Meteorological Institute [16]. Field measurement analysis data are described in the results section (Figures 2 and 3). The initial analysis results are not public information but can be requested from the authors. Detailed information on the quality

and quantity of the loaded fertilizers and the loading schedules are confidential information of the operating fertilizer terminals. The authors of this article do not have permission to share that data as such.

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Conflicts of Interest: The authors declare no conflicts of interest.

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Appendix 2

Publication II

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Nitrogen and Phosphorus Discharges from Cargo Ships' Black and Grey Waters—A Case Study of a Baltic Sea Port

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Abstract: Shipping is a vital component of global trade. However, shipping activities have negative environmental impacts, including emissions to air and water. The Baltic Sea is severely affected by eutrophication, mainly due to nutrient inputs, especially nitrogen and phosphorus. Understanding the contributions of various nutrient sources is essential for informed environmental regulation. The aim of this research is to quantify the nutrient content of black and grey water discharged from cargo ships in the Baltic Sea in order to assess their contribution to the total nutrient load. Specifically, this research examines the nitrogen and phosphorus loadings from ships calling the port of HaminaKotka and addresses key questions regarding nutrient generation, discharge proportions, emission shares by ship type, and their importance compared to other sources. Using a methodology based on ship data and nutrient production estimates, this study found that 2545 cargo ships generated a total of 781 kg of nitrogen and 134 kg of phosphorus in their effluents during their voyages to the port in 2021. However, only a small fraction (0.5%) of the cargo ships discharged their wastewater at port reception facilities. This study concludes that nutrient discharges from cargo ships' wastewaters are relatively small, contributing less than 0.06% phosphorus and 0.01% nitrogen to the total load in the area. This result indicates that the impact of cargo ships' wastewater on the eutrophication of the Baltic Sea is smaller than previously thought. The methodology used in this study can be applied in other ports and regions to assess nutrient discharges from cargo ships' wastewaters on a wider scale. Further research is recommended to assess the effectiveness of on-board treatment systems, the impact of other contaminants in wastewater, and the development of port reception facilities to facilitate proper wastewater management in the maritime trade.

Keywords: wastewaters; nitrogen and phosphorus; sewage; black and grey waters; sewage treatment plant; port reception facilities; eutrophication; nutrients

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1. Introduction

More than 80% of world trade is carried out with sea-going vessels [1]. Waterborne transport is one of the anthropogenic pressures that has an environmental impact on aquatic ecosystems [2]. The Baltic Sea, with its area of 370,000 km^2, is small in a global perspective, but it is also one of the world's largest reservoirs of brackish water, which makes it ecologically unique [3]. The Baltic Sea is also one of the busiest maritime regions globally, with up to 15% of the world's cargo traffic being handled within its waters. At any given time, approximately 2000 ships are present in the Baltic marine area, with a monthly passage of roughly 3500–5500 vessels through its waters [4].

The Baltic Sea has all the symptoms of nutrient overload [5]. Since it is connected with the Atlantic Ocean only via the narrow strait of Denmark, complete water exchange takes around 30 years [6]. The nine countries that border the Baltic Sea have worked hard to reduce nutrient flows through the Baltic Marine Environmental Protection Commission in

Helsinki—also known as the Helsinki Commission (HELCOM)—and, since 2008, through the European Union's Marine Strategy Framework Directive [3].

In open sea areas—like the Baltic Sea—the eutrophication caused by the extensive input of nutrients leads to excessive algae growth and oxygen depletion [6]. About 75% of the nitrogen load and at least 95% of the phosphorus load enter the Baltic Sea via rivers or as direct waterborne discharges. The main contributor to the nutrient load is agriculture. Other sources are point sources in the upper parts of rivers, municipal sources, wastewater treatment plants, industry, and transport [7]. About 25% of the nitrogen load comes in the form of atmospheric deposition. Today, eutrophication is regarded as the most severe threat to the Baltic Sea [3]. About 100 million tons of nitrogen and 4.5 million tons of phosphorus have entered the Baltic Sea since the 1850s, with more than half of it being deposited during the recent fifty years [8].

Recent modelling suggests that shipping contributes about 0.3% of the total phosphorus and between 1.25% and 3.3% of the total nitrogen input to the Baltic Sea [9]. According to various studies [2,6,10,11], potential sources of nitrogen and phosphorus discharges from shipping activities include loading and unloading of fertilizers, food waste, grey and black water, and possibly bilge and scrubber water and treated ballast water [12]. Fertilizers are the main contributor to the nutrient input to the Baltic Sea from port and shipping activities [13]. In 2020, ships' black water discharges to the Baltic Sea amounted to 0.98 million cubic meters, and the input of sewage-based nitrogen was 364 tons. Greywater discharges were estimated to amount to 3.4 million cubic meters. In particular, almost 75% of grey water discharges in European waters come from passenger ships [10].

This study evaluates the contribution of cargo ships' wastewaters to the nutrient load of the Baltic Sea and furnishes authorities with pertinent data for environmental regulatory deliberations. Specifically, this study examines the nutrient content of black (sewage) and grey water from cargo ships. Black water comprises human waste from toilets, while grey water encompasses wastewater from sinks, showers, and galleys, excluding sewage. While cruise, passenger, and ro-pax vessels are significant contributors to marine sewage, their discharges are subject to stringent regulations.

We have focused on the Finnish port of HaminaKotka with the aim of evaluating the quantity of nutrient loads of wastewaters from ships that visit this port. Our research questions are as follows:

1. How much phosphorus and nitrogen (in kilograms) has been generated on board cargo ships (from black and grey water) during their voyages in the Baltic Sea to the designated port?
2. What proportion of the wastewater is discharged into the port?
3. What are the emission shares from different ship types?
4. How significant are these emissions in relation to all sources of nitrogen and phosphorus discharges in the area?

To find the answers to these questions, the quantities of nitrogen and phosphorus from black and grey waters were calculated and compared to the amount of waste discharged to port and to previous studies of nitrogen and phosphorus sources in the area. This study provides detailed data on different ship types and illustrates the variability within these categories, recognizing that different ship types—and even specific ships within a type—may contribute differently to nutrient loads. This approach improves the understanding of the contributions by ship type and the variability within and between these types.

This paper is structured as follows: Section 1 provides an introduction, giving an overview of this study and outlining the research questions. It also presents the background of this topic based on a literature review. Section 2 describes the methodology used to assess on-board nitrogen and phosphorus production. The results are presented in Section 3. Section 4 discusses the results and compares them with the results of other studies. Finally, Section 5 presents the conclusions and recommendations for future actions and research.

The case study port, HaminaKotka, is the biggest general cargo port in Finland based on cargo traffic volumes [14]. There are several cargo types handled in the port: dry bulk,

liquid bulk, roro, containers, general cargo, gas, project shipments, and cruise traffic. The port serves as a hub in the Baltic Sea area and in Europe, and there are regular shipping lines to it all over the world [15]. It is part of the Trans-European Transport Network TEN-T core network [16]. The location of the port and main cargo traffic routes are shown in Figure 1.

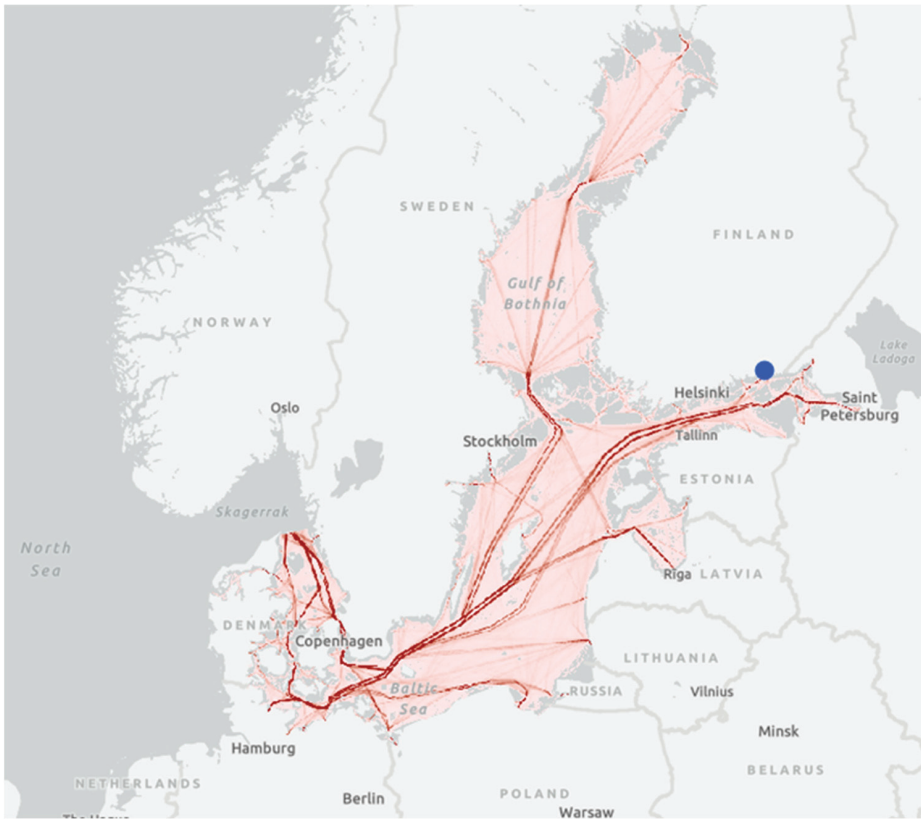


Figure 1. Cargo ship traffic intensity in the Baltic Sea in 2021 [17]. Case study port HaminaKotka is marked with blue spot.

The port is located in the area of Hamina-Kotka-Pyhtää. In this coastal area, the main contributors are the local rivers, contributing to 6593 tons of nitrogen and 207 tons of phosphorus in 2021. However, the water quality of the Kymijoki River has improved in recent years, with phosphorus concentrations in the river water now being lower than those in seawater. The proportion of total loading to this coastal area from the Kymijoki River had increased slightly from the previous year, comprising approximately 73% of phosphorus and 88% of nitrogen in 2021 [18,19].

In addition, four significant point sources were identified in the Hamina-Kotka-Pyhtää area: two forest industry factories, municipal wastewater treatment plant, and fertilizer loading berth at port [13,19]. A share of the main point sources of nitrogen and phosphorus in the Hamina-Kotka-Pyhtää area are shown in Figures 2 and 3.

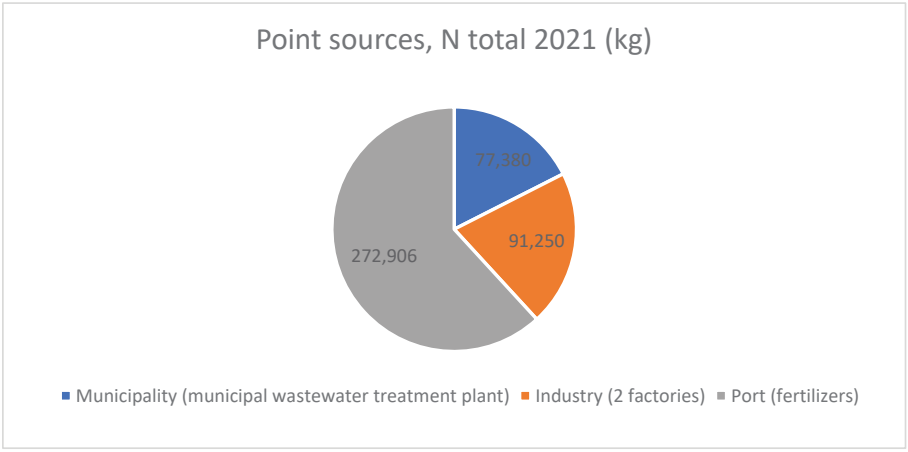


Figure 2. Point sources of nitrogen in Hamina-Kotka-Pyhtää coastal area 2021. Adapted from Ref. [13,19].

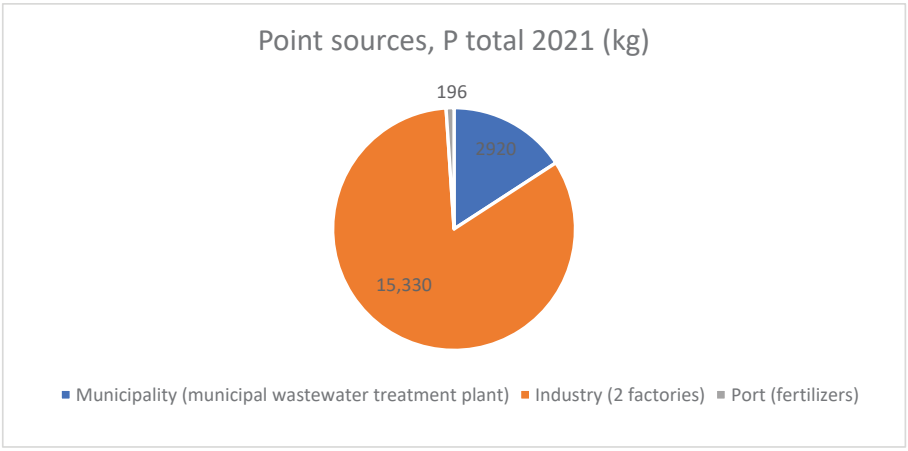


Figure 3. Point sources of phosphorus in Hamina-Kotka-Pyhtää coastal area 2021. Adapted from Ref. [13,19].

The maximum allowable input (MAI) of nitrogen and phosphorus to the Baltic Sea was agreed in 2013 at the Copenhagen Ministerial Declaration [20], whereas the MAI in the Gulf of Finland is agreed to be 101,800 tons for nitrogen and 3600 tons for phosphorus from all sources. The most recent assessment, carried out in 2021, showed that the agreed reductions were not being met.

The most important regulation for preventing pollution from ships is the International Convention for the Prevention of Pollution from Ships (MARPOL)—agreement by the International Maritime Organisation (IMO). Marpol Annex IV contains regulations regarding ships' black waters (sewage) [21]. There are no regulations concerning grey waters. According to Annex IV, cargo ships are allowed to discharge untreated sewage to the Baltic Sea if the distance to nearest land is more than 12 nautical miles. If the sewage is comminuted and disinfected, it may be discharged more than 3 nautical miles from the nearest land, provided that the ship is under way and travelling at a speed of at least 4 knots. If the ship has an approved wastewater treatment system, there are no restrictions for sewage disposal [6].

For passenger vessels, the regulations are stricter. Sewage discharge to the Baltic Sea is only permitted if the ship has an approved and certified wastewater treatment plant according to IMO resolution MEPC.227(64), which stipulates a reduction of 70% in nitrogen levels and of 80% in phosphorus levels. Passenger ships not equipped with an on-board sewage treatment facility according to the specifications must discharge the sewage (black water) to a port reception facility [22].

To ensure that ships can globally comply with MARPOL requirements, there are also requirements for port reception facilities [21]. A port shall have adequate reception facilities for oily wastes, wastes containing noxious liquid substances, sewage, garbage, exhaust gas cleaning residues, and cargo residues. However, the delivery of sewage to port reception facilities (PRFs) is voluntary for ships.

The "No special fee" system, commonly implemented in most Baltic ports [23], requires ports to levy a waste fee on ships irrespective of whether they offload any waste at port reception facilities (PRFs) or not. This fee remains constant regardless of the quantity of waste discharged at PRFs. The aim of this system is to incentivize ships to deposit all waste at the port. By paying the obligatory fee, ships gain permission to dispose of various types of waste, including domestic waste like food waste, oily waste from machinery spaces, and sewage, at the port.

Environmental regulations are becoming stricter. The EU, IMO, national authorities, ports, and other organizations are stepping up their efforts to impose further restrictions and improve the monitoring of discharges at sea. For example, as the use of exhaust gas cleaning systems (scrubbers) on ships increases, many countries and ports are restricting their use due to the water pollution they cause [24]. Nevertheless, certain discharges, such as non-hazardous materials to the environment (non-HMEs) containing cleaning water and grey water, remain unregulated. Due to the lack of regulations on grey water and the relatively loose regulations on sewage discharges from cargo ships, this study is essential to evaluate the volume of nutrient discharges from these ships in order to assess the severity of the issue.

2. Materials and Methods

This study evaluates the quantities of nitrogen and phosphorus generated during sea voyages in the Baltic Sea by all individuals on board of the cargo ships that arrived at the case port in 2021. To perform this calculation, the following data were required:

- Number of vessels and vessel types;
- Distance from the previous port (in the Baltic Sea) to the case port;
- Speed of the vessels;
- Number of crew members on board;
- Daily amount of nitrogen and phosphorus in grey water and black water typically produced per person.

According to vessel statistics provided by the port, there were 2545 cargo ship calls in the case port in 2021 [25]. In total, 40% were general cargo vessels, 20% were tankers, 17% container vessels, 16% roro vessels, and 6% were bulk carriers. Distance in nautical miles from the previous port in the Baltic Sea was calculated using a calculation tool by Marine Traffic [26]. If the previous port was outside the Baltic Sea, the distance was calculated from the entrance of the Baltic Sea (Skagen). The average speed of each vessel was estimated using the information by Agarwal [27]. The average travelling time of each ship across the Baltic Sea to the case port was then calculated. The average number of crew on board the ships was estimated using data by Finnish Transport and Communications Agency [28] and additional information provided by the port.

The amount of nitrogen and phosphorus in daily generation of grey water (GW) and black water (BW) per person in different ship types was estimated based on a study by Jalkanen et al. [10]. The fixed emission factor of 16 g N and 1.6 g P per person and day that was used for black water is comparable to land-based estimates of 12.5 g N and 1.4 g P per person per day [29]. To verify these estimated figures, several samples were taken in the

port of HaminaKotka during 2021–2023 from cargo vessels wastewaters. According to the water sample analysis reports, the nutrient content of wastewater from cargo ships is generally equivalent to that of household wastewaters [30]. The data used in calculation are presented in Table 1 below.

Table 1. Data of vessels calling the port in 2021.

Ship Type	Number of Ships [25]	Ships' Speed [27]	Persons On Board [28]	P in GW [10]	P in BW [10]	N in GW [10]	N in BW [10]
Container	431	20	19	1.9	1.6	4.4	16
Tanker	501	15	17	1.9	1.6	4.4	16
Bulk carrier	151	14	15	1.9	1.6	4.4	16
Tug	6	10	4	1.9	1.6	4.4	16
General cargo	1042	12	10	1.9	1.6	4.4	16
Roro	414	19	17	1.9	1.6	4.4	16

The equation used in this calculation to find out the amount of produced N and P in black and grey waters for each ship was as follows:

$$\text{Nutrient [g]} = \text{Individual contribution [g/d]} \times \text{crew members [persons]} \times \text{distance to port [nautical miles]/speed [nautical miles/d]}$$

In addition to the quantity of the produced nitrogen and phosphorus, we studied how many vessels discharged their wastewaters to the port reception facilities [25].

3. Results

The calculation showed that the crew members in the 2545 cargo ships calling the case port in 2021 generated a total of 134 kg of phosphorus and 781 kg of nitrogen in their wastewaters during their voyages from the previous Baltic port to the port studied in this case report. The results of the calculation of cargo ships' wastewaters in kilograms are presented in Table 2.

Table 2. Amount of nitrogen and phosphorus in cargo ships' wastewaters in 2021.

2021	Nitrogen (kg)	Phosphorus (kg)
Black water (sewage)	612.9	61.3
Grey water	168.5	72.8
TOTAL	781.4	134.1

The average amount of nitrogen produced in wastewaters per ship is 0.3 kg, and the average amount of phosphorus produced in wastewaters per ship is 0.05 kg. These nutrient discharges, if discharged in the sea, are not local, as the regulations restrict discharging the wastewater near the shore. These discharges are either discharged to the open sea off the coast somewhere in the Baltic Sea, treated on board in a sewage treatment plant, or stored in holding tanks and discharged in port reception facilities.

General cargo ships and tankers accounted for the majority of emitting cargo ships. In contrast, specialized cargo ships accounted for relatively few emissions compared to other ship types. In addition, there was considerable variability in emissions within this specific category of ships (Figures 4 and 5).

In the port of HaminaKotka, only 13 vessels delivered their wastewaters to PRFs in 2021 [25]. Considering the total of 2545 ships that visited the port in that year, this represents only 0.5% of the ships that discharged their sewage in the port. There are no fixed reception facilities in the port, but sewage is received from ships by vacuum trucks [31].

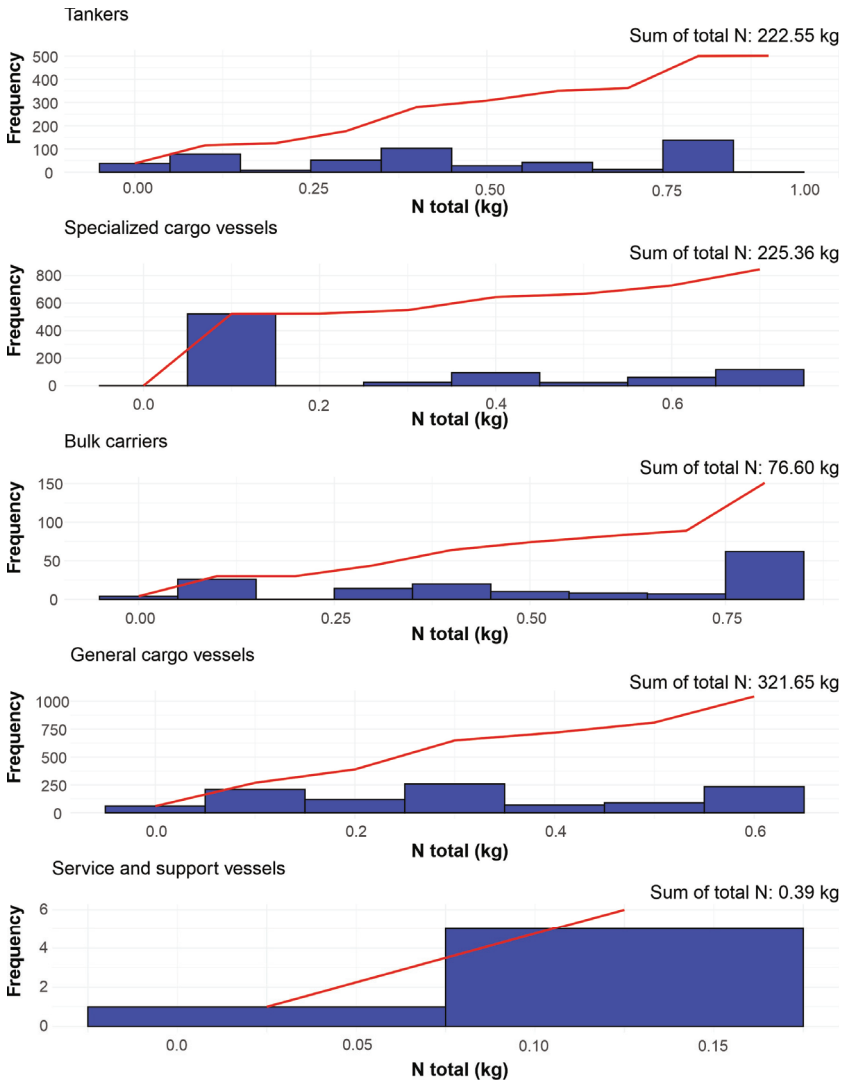


Figure 4. Estimated frequency distribution and total annual nitrogen discharges by ship type at the studied port. The red line represents the cumulative load of nutrient discharges.

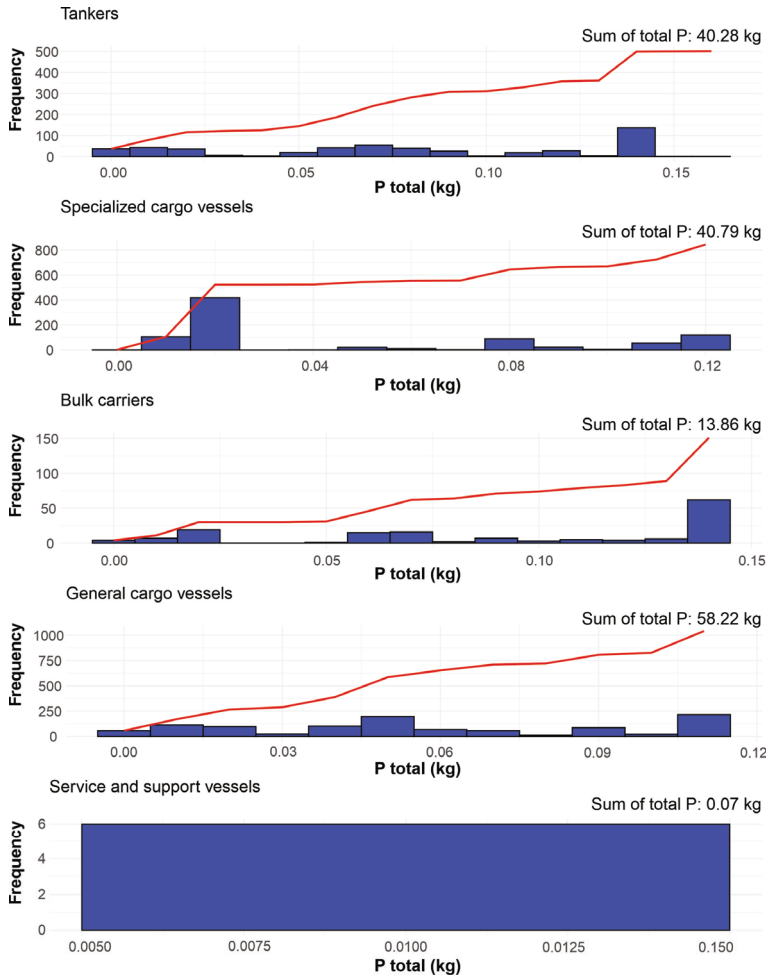


Figure 5. Estimated frequency distribution and total annual phosphorus discharges by ship type at the studied port. The red line represents the cumulative load of nutrient discharges.

4. Discussion

In this study, we calculated the theoretical maximum quantities of nitrogen and phosphorus deposited in the Baltic Sea by the cargo vessels visiting the case study port over one year. We also compared the results to the total load to assess the significance of this nutrient source. The results indicate that the contribution of cargo ships' wastewaters to the total nutrient load is minimal. While the total nutrient discharges from various sources in the coastal area amounted to 6761 tons of nitrogen and 225 tons of phosphorus, the load from cargo ships' wastewaters was only 0.781 tons of nitrogen and 0.134 tons of phosphorus. This means phosphorus emissions from cargo ships' wastewaters account for just 0.06% of the total, and nitrogen emissions represent only 0.01%. Additionally, it should be noted that while the loads from fertilizer application, municipal wastewater treatment plants, and industry are localized point sources, the nutrient load from ships' wastewaters is dispersed throughout the open waters of the Baltic Sea during their voyages.

The results indicate that the main sources of wastewater-based nutrient discharges are general cargo and tanker vessels. However, there is considerable variability in nutrient loads within these groups, suggesting that management strategies should take this

variability into account. Using the outcomes of this study, the port can determine specific terminals where investments in port reception facilities for cargo vessels would yield the most significant impact.

It is unclear how many vessels employed on-board sewage treatment systems before releasing the wastewaters to the sea or later discharged them to other ports' PRFs. If these mitigating measures are utilized, the actual emissions are even smaller than indicated in this study. However, only few vessels discharged their wastewaters at the HaminaKotka port, despite this service being free of charge. This suggests that most ships do not utilize this option. In contrast, passenger vessels are required to use port reception facilities for wastewater. With tightening environmental regulations on the horizon, significant changes to wastewater discharge processes on-board cargo ships and at cargo ports are anticipated.

The significance of this study lies in its detailed analysis of nutrient loads from cargo ships, an area that has been unclear. While various studies have shown that the nutrient discharges from passenger ships are significant, it was not understood that those from cargo ships remain minor. With stricter environmental regulations anticipated for cargo ships, the results of this study provide valuable insights, highlighting areas where interventions—such as the development of efficient nutrient treatment systems on board and the design of future port reception facilities—can be implemented to minimize these nutrient discharges. The methodology used in this study can be adapted and applied in other ports and regions, providing a scalable solution for assessing and managing nutrient emissions from cargo ships on a wider scale. This approach not only enhances local environmental protection efforts but also contributes to a more comprehensive understanding of maritime environmental impacts globally.

This study is partly based on calculations and estimations. There may be inaccuracies due to a limited number of samples or generic data that were used as a source for calculations. The ships' speed and number of crew were estimates based on the literature. While there may be variations in the actual number of crew and speed, the overall magnitude of the results remains consistent. The estimated production and concentrations of nitrogen and phosphorus were verified with an analysis of actual samples.

5. Conclusions

This study addressed questions about the generation and discharge of phosphorus and nitrogen from cargo ships in the Baltic Sea. In particular, it focused on quantifying the amounts of these nutrients contained in black and grey water and assessing the proportion of wastewater discharged during a ship's voyage to a given port. It also looked at the contribution of different types of ships and assessed the significance of these emissions in relation to other sources of nutrient discharges in the area.

Our research questions were as follows:

1. How much phosphorus and nitrogen (in kilograms) was generated on board of the cargo ships (from black and grey water) during their voyages in the Baltic Sea to the designated port?
2. What proportion of the wastewater is discharged into the port?
3. What are the emission shares from different ship types?
4. How significant are these emissions in relation to all sources of nitrogen and phosphorus discharges in the area?

We found that the proportion of emissions from cargo ships' effluent is only a small fraction of the total nutrient load in the area. The cargo ships produced 781 kg of nitrogen and 134 kg of phosphorus in their effluents during their voyages to the case port, which equals only 0.06% phosphorus and 0.01% nitrogen of the total load in the area. Tankers and general cargo vessels had the biggest shares of emissions, and only 0.5% of the cargo ships discharged their wastewaters to PRFs. According to the results, the impact of cargo ships' wastewaters on the eutrophication of the Baltic Sea is smaller than previously thought. Moreover, these nutrients are primarily dispersed across the Baltic Sea rather than being discharged into local waters. However, with anticipated tightening of environmental

regulations, significant changes to the wastewater discharge processes of cargo ships and ports can be expected.

Further research is needed to assess the effectiveness of on-board sewage treatment systems in mitigating nitrogen and phosphorus discharges to the sea, as well as to quantify the proportion of treated versus untreated effluent. Additionally, the composition and environmental impact of other contaminants present in wastewaters, such as bacteria and traces of medication, require further investigation.

Another proposal for further research is to investigate the effectiveness of port reception facilities (PRFs). Current PRF availability and infrastructure vary significantly among ports, ranging from fixed to mobile facilities, with occasional absence or high costs. It should be kept in mind that passenger vessels are the main producers of wastewaters at sea. These emissions are strictly regulated and, generally, passenger terminals are equipped with fixed PRFs accordingly.

Author Contributions: Conceptualization, S.-T.L.; methodology, S.-T.L. and J.K.; validation, S.-T.L., U.T. and J.K.; formal analysis, S.-T.L., U.T. and J.K.; investigation, S.-T.L.; data curation, S.-T.L., U.T. and J.K.; writing—original draft preparation, S.-T.L. and U.T.; writing—review and editing, S.-T.L., J.K. and U.T.; visualization, S.-T.L.; supervision, U.T. and J.K.; project administration, U.T. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The main data used in this study are available from public sources. Ship speed, average number of crew per ship type, and nutrient production per person can be found in the literature. Detailed information on port-specific ship calls and information on the ships that delivered their wastewaters to the case port are not publicly available. The authors of this article do not have permission to publish these data. Data on ship calls can be obtained from Traficom or the Port of HaminaKotka. Sample analysis results can be obtained from the Baltic Sea Action Group.

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Appendix 3

Publication III

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Article

Maritime and Port Contributions to Coastal Nutrient Loading in the Baltic Sea: Apportionment and Regulatory Implications

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Abstract

Eutrophication caused by excessive nitrogen and phosphorus input remains the most severe environmental threat to the Baltic Sea. While nutrient sources in general are widely studied and regulated, the relative importance of maritime nutrient inputs and their regulatory treatment remain insufficiently integrated into land-based nutrient assessments. This study applies a load-based source apportionment approach and quantifies the maritime- and port-related nutrient inputs to a Baltic Sea coastal system, in relation to other nutrient contributors (riverine, municipal, and industrial sources). Additionally, the stringency of the regulatory frameworks governing each source is assessed using a qualitative regulatory classification scale and compared to the proportion of each nutrient source. The results show that riverine inputs dominate total nutrient loading, accounting for over 90% of both nitrogen and phosphorus. Maritime sources contribute only a small share overall. However, fertilizer cargo handling constitutes the largest nitrogen point source, while ship wastewater inputs are negligible. In contrast, ship wastewater is subject to the strictest regulatory controls, whereas fertilizer handling operates under permits lacking explicit nutrient discharge limits. The findings reveal a governance mismatch between nutrient pressures and regulatory focus and highlight the need to better align nutrient management priorities with actual environmental pressures in semi-enclosed seas.

Keywords: eutrophication; sustainability; nitrogen; phosphorus; governance; environmental permit; fertilizers; catchment; point source; sewage; grey water; nutrient; regulations

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1. Introduction

1.1. State of the Baltic Sea

The Baltic Sea is a shallow, semi-enclosed sea in northern Europe with limited exchange with the World Ocean and minimal tides. Situated between maritime and continental climate zones and influenced by the North Atlantic and Arctic, it exhibits strong climatic variability. Large river inflows from its extensive catchment create a pronounced salinity gradient, from about 20 in the Danish Straits to less than 2 in the northern and eastern areas, resulting in brackish conditions with marine species dominating in the southwest and freshwater species in the northeast [1].

The catchment area is roughly four times larger than the sea itself, covering nearly 20% of Europe and spanning from temperate, densely populated regions to subarctic areas. It encompasses parts of 14 countries and is home to approximately 85 million people [1]. It

is one of the most intensively trafficked maritime regions worldwide with approximately 3500–5500 ships sailing its waters each month [2].

The Baltic Sea Region has experienced prolonged periods of excessive fertilizer application, particularly from the 1950s to the 1990s, alongside substantial urban nutrient inputs [3]. As a densely populated and highly utilized marine area, the sea is strongly influenced by human activities, including agriculture, aquaculture, fisheries, river regulation, chemical pollution, tourism, and coastal management [4].

High external nutrient loads have resulted in widespread eutrophication, including recurrent phytoplankton and cyanobacterial blooms, reduced water clarity, and oxygen depletion (hypoxia) in bottom waters [5]. These impacts are amplified by the long residence time: because the Baltic Sea is connected to the Atlantic Ocean only through the narrow Danish Straits, complete water exchange takes around 30 years [6], slowing recovery once nutrients accumulate. Eutrophication is currently considered the most serious environmental pressure affecting the Baltic Sea [7], posing a persistent challenge to the environmental sustainability of coastal ecosystems and maritime activities in the region.

1.2. Nutrient Sources

The majority of nutrient inputs to the Baltic Sea originate from the surrounding catchment. Long-term assessments indicate that approximately 75% of nitrogen and at least 95% of phosphorus loads reach the sea via riverine inflows or direct waterborne discharges. Agriculture constitutes the dominant source, while additional contributions arise from upstream point sources, municipalities, wastewater treatment plants, industry, and transport [7].

Model-based estimates indicate that shipping accounts for about 1–3% of total nitrogen and less than 1% of total phosphorus inputs to the Baltic Sea [8,9]. These estimates primarily account for ship-generated wastewater discharges and atmospheric deposition originating from ship emissions. However, several potentially relevant maritime and port-related nutrient pathways are poorly represented in regional nutrient inventories. These include fertilizer and other nutrient-containing cargo handling in ports, contaminated stormwater runoff from terminal areas, and operational discharges regulated under maritime conventions [9,10].

Fertilizer cargo handling deserves particular attention. Annually, more than 45 million tons of agricultural fertilizers are handled in Baltic Sea ports [11], often in close proximity to sensitive coastal waters. Empirical data on nutrient losses during loading, unloading, and storage operations remain scarce, and such discharges are typically absent from river-based monitoring programmes and national nutrient load compilations. As a result, port-related nutrient inputs may be underestimated despite their potentially high local relevance [10].

In contrast, ship-generated sewage discharges have been studied more extensively. Recent estimates indicate that ship-borne black and grey water discharges to the Baltic Sea have decreased markedly following regulatory restrictions, particularly for passenger vessels [9,12].

In addition to maritime point-source reductions, land-based point-source discharges have been substantially reduced since the 1990s in the Baltic Sea but also in other sea areas [13]. Diffuse agricultural sources remain the dominant contributor, particularly for nitrogen, and continue to challenge eutrophication management across the Baltic Sea region and globally [14–18].

1.3. Regulatory Context

Nutrient inputs to the marine environment are governed through multiple regulatory layers. Marine-source discharges are primarily regulated through international conventions,

which are implemented to and complemented by national legislation. Land-based nutrient discharges are regulated through European Union directives and national legislation, and major point sources are controlled through environmental permits that specify monitoring and reporting obligations. Ports are affected by both maritime and shore regulations. In addition, nutrient sources are subject to Baltic Sea wide regional requirements.

Ship-generated sewage (black water) is regulated internationally under MARPOL Annex IV [19] and, in certain areas, by additional national requirements. Since the prohibition of sewage discharge from passenger vessels to the Baltic Sea by MARPOL Annex IV, both black water and grey water discharge has decreased by approximately 50% [9]. In the studied Finnish coastal waters, the discharge of sewage—including treated effluent—is prohibited from all ships under the Maritime Environmental Protection Act since 1 July 2025 [20]. Greywater is not regulated internationally under MARPOL Annex IV, but national rules may apply; in Finnish territorial waters, discharge of greywater will be prohibited from 1 January 2030 [20]. Operational discharges and wastes beyond wastewater are regulated mainly under MARPOL Annex V (garbage), including provisions for food waste and cargo residues [19]. Cargo residues that are not classified as harmful to the Marine Environment (HME) can be discharged to the Baltic Sea under certain conditions. Fertilizers are not classified as HME despite their well-known potential to contribute to eutrophication. Consequently, fertilizer residues can be discharged at sea when regulatory distance and operational requirements are met [19].

Land-based nutrient inputs are addressed through European Union and national water and agriculture policy. The EU Nitrates Directive constrains nitrogen and phosphorus use and management on agricultural land [21], and the EU Water Framework Directive [22] establishes objectives and programmes of measures for achieving good ecological status in surface waters through coordinated monitoring, planning, and programmes of measures implemented at the river basin level.

Implementation of these directives occurs through national legislation and policy in-struments. In Finland, agricultural nutrient management measures include restrictions on fertilizer use, phosphorus balance requirements for cultivated fields, and other agri-environmental measures designed to limit nutrient losses from agricultural land to rivers and ultimately to coastal waters such as the Baltic Sea. In 2023, the Finnish national legislation governing the use of phosphorus-containing fertilizers in agriculture was tightened [23]. The regulation imposes stricter limits on the application of mineral phosphorus fertilizers to reduce the risk of phosphorus runoff into watercourses. The National Phosphorus Decree tightened restrictions on mineral phosphorus fertilizers but allows higher phosphorus application to cultivated fields through manure under certain conditions, raising concerns about its effectiveness in preventing long-term phosphorus accumulation in soils and subsequent runoff [24].

Municipal wastewater treatment plants and industrial facilities that discharge to water operate under environmental permits. These permits typically specify numeric limits for nitrogen and phosphorus, require routine monitoring, and oblige operators to report results to the competent authority [25].

In addition to EU and national measures, the Baltic Sea coastal states cooperate through the Baltic Marine Environment Protection Commission (Helsinki Commission, HELCOM) to achieve a good environmental status of the Baltic Sea. HELCOM regulates nutrient input mainly by giving recommendations, setting regional reduction targets, coordinating policies among Baltic countries, monitoring pollution levels, and promoting best practices [7].

HELCOM's nutrient reduction approach defines Maximum Allowable Inputs (MAI) and allocates reduction responsibilities among countries. For the Gulf of Finland, the MAI is 101,800 t of nitrogen and 3600 t of phosphorus annually [26]. In 2022, total nitrogen

input to the Gulf of Finland was 126% of the MAI, and total phosphorus was 137% of the MAI [27]. According to HELCOM, the required annual reductions in nutrient inputs to the Gulf of Finland are 6000 tons of nitrogen and 200 tons of phosphorus The Country-Allocated Reduction Target (CART) for the Gulf of Finland is 1199 t of nitrogen and 146 t of phosphorus per year [28].

Beyond regulatory programmes, non-governmental initiatives support practical nutrient reduction measures. For example, Baltic Sea Action Group (BSAG) [29], the John Nurminen Foundation [30], and Race for the Baltic [31] coordinate projects and voluntary commitments that target hotspots such as wastewater treatment upgrades, manure and nutrient recycling solutions, and catchment restoration measures, complementing public policy and accelerating implementation.

1.4. Research Gap and Rationale

A comprehensive, source-to-sea assessment of nutrient inputs to coastal waters is currently lacking. In particular, port- and shipping-related discharges are seldom evaluated alongside traditional land-based sources in a unified framework. Fertilizer and other nutrient-contributing cargo handling discharges are typically absent from published nutrient load assessments and official discharge databases, despite evidence that they can be locally important inputs.

Different nutrient sources are regulated by separate regulatory frameworks and layers and monitored by separate authorities. A systematic mapping of regulatory overlaps and gaps is therefore needed to understand how differing regimes influence nutrient inputs.

1.5. What We Study

The case study focuses on the Hamina–Kotka–Pyhtää coastal waters on the Finnish coast of the eastern Gulf of Finland. This region was selected for four main reasons.

The first reason is that the eastern Gulf of Finland is among the most severely impacted areas in the Baltic Sea in terms of nitrogen and phosphorus loads [27,28], making the area particularly relevant for detailed investigation.

Second, the Hamina–Kotka–Pyhtää area reflects the broader Baltic Sea system well, as it encompasses all major, commonly identified sources of nutrient loading within a single, well-defined area. The area receives nutrient inputs from the Kymi River (via several branches) and from smaller local rivers [32,33], as well as direct coastal discharges from municipal and industrial point sources [32,34,35]. In addition, the area hosts intensive maritime activities associated with one of the largest ports in Finland, which represents a potential source of nutrient inputs related to shipping operations and cargo handling [10,36].

Third, uniquely detailed data on cargo handling—typically unavailable elsewhere—is accessible for this region. Fertilizer cargo-related nutrient discharges were quantified in our previous study [10], allowing us to now integrate these with other relevant datasets to produce a comprehensive assessment of total nutrient inputs.

Finally, the regulatory framework governing the area spans international, EU-level, regional, and national layers, providing a comprehensive context for regulatory analysis.

Figure 1 shows the location of the study area in the Gulf of Finland and studied nutrient sources: red dot marks a riverine diffuse source, purple square marks a land-based point source, orange square marks maritime or port-related point source. Rivers (red dots) from west to east are Taasia, Kymi/Ahvenkoski, Kymi/Pyhtää, Kymi/Koivukoski, Kymi/Korkeakoski, Summa, Vehka. The point sources (purple and orange squares) from north to south are Stora Enso: Sunila Mill, Kotkamills Oy, Mussalo Wastewater treatment plant, fertilizer berth at the Port of HaminaKotka Oy and maritime traffic.

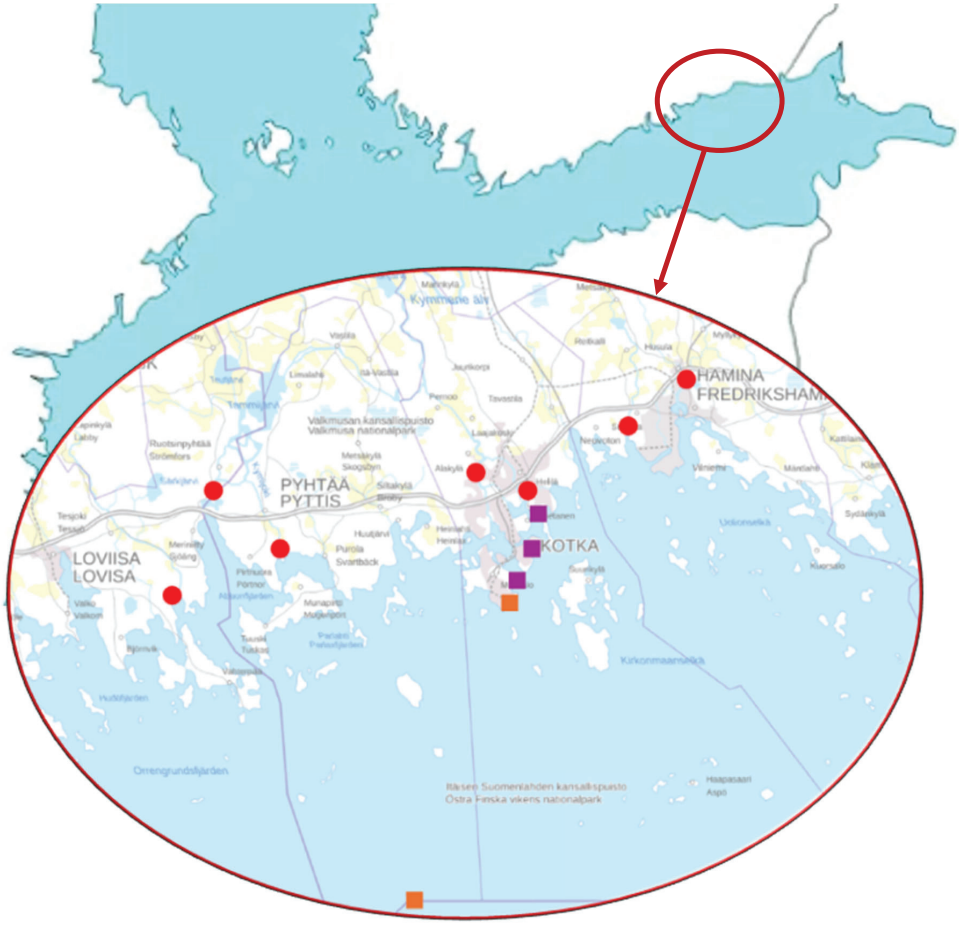


Figure 1. Nutrient sources in the Pyhtää–Kotka–Hamina region in 2021.

The Port of HaminaKotka is the biggest general port in Finland, with annual cargo throughput of 12–18 million tons [37]. Its berths are distributed in Hamina–Kotka region and it hosts about 2500 ship calls annually. Around 2–3 million tons of fertilizers are loaded to ships in Mussalo annually [37,38], most of them being nitrogen fertilizers such as urea.

Mussalo Wastewater Treatment Plant collects and treats wastewaters from the cities and counties of Kotka, Kouvola, Pyhtää and Hamina with 156,000 habitants [39] and in several additional industrial facilities [32]. It is the fourth biggest wastewater treatment plant in Finland, treating over 10 million cubic meters of water annually [34]. Other industrial nutrient point-source contributors are Stora Enso, Sunila Mill, which handles the wastewaters of the former pulp mill, and the paper and cartonboard factory Kotkamills Oy [35].

This study (i) quantifies total nitrogen and phosphorus inputs to the Hamina–Kotka–Pyhtää coastal waters in 2021 and apportions them among riverine inputs, land-based point sources, port cargo handling, and ship operations; (ii) maps the regulatory instruments and permits governing each source category; and (iii) identifies potential governance gaps where loads are substantial but controls or monitoring are weak or where loads are negligible but controls are strict. The main focus is on the maritime-related nutrient sources, including port operations. Port activities can be viewed as both land-based point sources

and maritime-related sources, as they occupy an intermediate position in terms of both the origin of the discharge and regulatory framework.

Our research questions are as follows:

RQ1. What are the shares of maritime and port activities in relation to total nutrient input?

RQ2. Which regulations and permits control each studied nutrient source?

RQ3. Based on the results, are there regulatory gaps related to the discharges?

To find the answers to these questions, we evaluated nutrient discharges from identified maritime and shore sources using previous studies and measurements, surveyed the related regulations and compared the nutrient load sources to related regulations to identify overlaps and potential gaps.

This paper is structured as follows: Section 1 provides an introduction, giving an overview of this study and outlining the research questions. It also presents the background of this topic based on a literature review. Section 2 describes the methodology used to assess the total nutrient input and the contribution of shipping and port activities. The results are presented in Section 3. Section 4 discusses the results and compares them with the results of other studies. Finally, Section 5 presents the conclusions and recommendations for future actions and research.

2. Materials and Methods

2.1. Study Area and Scope of the Assessment

This case study focuses on nutrient inputs in the Hamina–Kotka–Pyhtää coastal waters during the year 2021 and compares annual nitrogen and phosphorus loads from three main source categories:

(i) Riverine inputs (representing combined diffuse and upstream point sources);
(ii) Local land-based point sources (municipal wastewater treatment and industrial facilities);
(iii) Maritime-related sources, separating diffuse ship waste waters from fertilizer cargo handling point source at port terminals.

The analysis was limited to the most significant and quantifiable nutrient sources. Minor or poorly quantifiable sources, such as food waste from ships and solid cargo residues, were excluded. It is nevertheless acknowledged that fertilizer residues deposited on ship decks during loading and unloading operations may constitute a locally relevant nutrient source; however, reliable quantitative estimates for this pathway are currently unavailable.

Nutrient discharges from industries, municipalities, and agricultural activities located in the lower reaches of the river catchments were included in the riverine input category, as their discharges reach the coastal waters indirectly via river transport. In contrast, industries and municipalities discharging treated effluents directly into the coastal waters were assessed separately as land-based point sources. Wastewaters generated on board cargo ships were included in the analysis even though they are not necessarily discharged in the immediate vicinity of the study area. These loads were considered to illustrate the potential theoretical maximum nutrient input associated with all cargo vessels visiting the ports within the study area.

In addition to quantifying nutrient loads, the study examines the regulatory context governing each identified nutrient source. This includes: (iv) international, regional, and national regulatory frameworks applicable to the different source categories; and (v) environmental permits.

To ensure transparency and reproducibility, a detailed traceability table is provided as Supplementary Materials. For each quantified nutrient source, the table specifies the dataset used, temporal coverage, spatial location, sampling frequency or calculation basis,

analytical method, and key assumptions underlying the annual nitrogen and phosphorus load estimates.

2.2. Data Sources

The assessment integrates multiple complementary data sources to quantify nutrient inputs and to support the regulatory analysis. The data sources comprise: (i) regional nutrient load data produced by environmental authorities [33]; (ii) environmental monitoring reports [32,40,41]; (iii) peer-reviewed scientific literature on maritime nutrient discharges and mitigation measures, including the authors' previous studies [10,34]; (iv) European Union, international, and national legislation governing nutrient discharges from both land-based and maritime activities [19–23]; and (v) environmental permits of operators located in the study area [42–45].

As this study is based on observational data, "*n*" refers to the number of observations, reports, or time steps underlying each annual estimate. These include monitored time series such as monthly river measurements, operational or compliance reports such as quarterly wastewater treatment plant reports, modeled daily estimates for fertilizer terminal discharges, and annual estimates derived from the literature for ship-generated wastewater. The distinction between raw observations, aggregated annual values, and secondary estimates is documented in the traceability table in the Supplementary Materials of this article.

2.3. Analytical Approach to Nutrient Source Apportionment

The analysis applied a load-based nutrient source apportionment approach consistent with the HELCOM Pollution Load Compilation (PLC) methodology. Annual nitrogen and phosphorus loads from riverine, land-based point, and maritime-related sources were compiled from monitoring data, operator reports, and previous studies, harmonized to comparable units, and assessed using a comparative load assessment. This approach enables a transparent comparison of the relative magnitude of nutrient inputs from different source categories without modelling nutrient transport or ecological responses.

The compiled nutrient loads were further benchmarked against HELCOM Country-Allocated Reductions Targets (CART) to contextualize their relative significance with respect to regional eutrophication reduction targets in the Gulf of Finland set to Finland. This comparison provides a policy-relevant reference for assessing the contribution of local nutrient sources in relation to basin-scale environmental objectives and the sustainability of nutrient management strategies in semi-enclosed seas.

2.4. Unit Harmonization, Uncertainty and Limitations

All nutrient inputs were harmonized to annual nitrogen and phosphorus loads (tons year^{-1}) to enable comparison across heterogeneous data sources. Where monitoring data were reported as concentrations and flows, annual loads were calculated by aggregation over the study year. Reported annual discharges from permits and operational reports were used directly. Modeled or estimated sources were calculated using published coefficients and assumptions applied consistently for the year 2021.

Uncertainty varies by source category. Riverine and land-based point-source loads are based on regulatory monitoring and are primarily subject to analytical and flow-measurement uncertainty. Fertilizer terminal discharges include an estimated analytical uncertainty of approximately 15% due to dilution requirements during sample analysis. Ship-generated wastewater loads represent theoretical maximum estimates based on published per capita generation rates, vessel characteristics, and operational assumptions. Given the compilative nature of the study and the heterogeneity of data sources, uncer-

tainty is reported in the supplemented traceability table descriptively by category instead of through formal error propagation or inferential statistical analysis.

Double counting between source categories was avoided by assigning nutrient loads to mutually exclusive pathways. Riverine loads include all upstream diffuse and point-source inputs transported to the coast via rivers and exclude discharges entering coastal waters directly. Municipal and industrial point sources were included only when effluents were discharged directly into the coastal area. Fertilizer terminal discharges represent on-site stormwater and cargo handling losses and do not overlap with river monitoring stations or municipal drainage systems. Ship-generated wastewater loads were treated separately and represent potential offshore discharges distributed across the Baltic Sea rather than localized coastal inputs.

2.5. Regulatory Analysis

In parallel, the regulatory analysis was informed by the DPSIR (Drivers–Pressures–State–Impact–Response) framework, focusing on the linkage between nutrient pressures and regulatory responses. To compare the relative stringency of regulatory control applied to different nutrient sources, a qualitative regulatory classification scale ranging from 0 to 4 was developed for this study using predefined criteria based on the presence and strength of legally binding regulatory instruments. The scale reflects the type and strength of regulatory instruments governing nutrient discharges, ranging from the absence of direct controls to explicit discharge prohibitions (Table 1). Regulatory sources consulted included international conventions, European Union directives, national legislation, and site-specific environmental permits. Each source category was assigned a regulatory level corresponding to the most stringent applicable instrument. Ambiguous cases were handled conservatively by assigning the lower regulatory level unless explicit numeric discharge limits or prohibitions were present.

Table 1. Qualitative regulatory classification scale.

Regulatory Level	Criteria
0	No restrictions
1	No numerical discharge limits Monitoring and mitigation requirements
2	Numerical discharge or input limits by regulations in general Monitoring and mitigation requirements
3	Specific numerical discharge limits by environmental permits Monitoring and mitigation requirements
4	Discharge prohibited

Level 0 depicts that there are no regulatory instruments directly addressing nutrient releases from the source category. Level 1 implies that environmental requirements focus on operational practices or preventive measures (e.g., cargo handling procedures, stormwater management), without numeric nutrient discharge limits. Level 2 indicates that nutrient discharges are addressed through broader policy instruments or management programmes (e.g., catchment-level water protection programmes or agricultural nutrient management rules). Numeric limits exist based on the rules, but a specific environmental permit is not required. Level 3 signals that environmental permits establish source-specific numeric discharge limits for nitrogen and/or phosphorus, combined with monitoring, reporting, and regulatory oversight. Level 4 shows that regulatory frameworks include explicit discharge prohibitions or highly restrictive rules governing discharges.

3. Results

3.1. Nutrient Load Quantification

The total input of nitrogen was 7035 tons, and the input of phosphorus was 225 tons in 2021. Across all assessed sources, riverine inputs dominated total nutrient loading to the Hamina–Kotka–Pyhtää coastal waters in 2021 (93.7% of nitrogen and 91.7% of phosphorus). Local land-based point sources contributed 2.4% of nitrogen and 8.1% of phosphorus. Maritime-related sources accounted for the remaining small fraction: port activities contributed 3.9% of nitrogen and 0.1% of phosphorus, whereas ship wastewaters contributed <0.1% of both nutrients (Table 2; Figures 2 and 3).

Table 2. Nitrogen and phosphorus discharges in Hamina–Kotka–Pyhtää coastal area in 2021.

Nitrogen Source	Nitrogen (Tons)	Point Source	Data Sources	Phosphorus Source	Phosphorus (Tons)	Point Source	Data Sources
Kymi River Ahvenkoski	3171.03	no	[32,33]	Kymi River Ahvenkoski	89.49	no	[32,33]
Kymi River Koivukoski	1352.25	no	[32,33]	Kymi River Korkeakoski	38.45	no	[32,33]
Kymi River Korkeakoski	1325.21	no	[32,33]	Kymi River Koivukoski	32.83	no	[32,33]
Taasia River	283.97	no	[32,33]	Taasia River	25.86	no	[32,33]
Fertilizer loading at port	272.90	yes	[10]	Summa River	12.37	no	[32,33]
Summa River	256.93	no	[32,33]	Industry: Kotkamills	8.03	yes	[32]
Kymi River Pyhtää	114.94	no	[33]	Industry: Sunila Mill	7.43	yes	[41]
Vehka River	87.90	no	[32,33]	Vehka River	4.50	no	[32,33]
Municipalities: WWTP	77.20	yes	[40]	Kymi River Pyhtää	3.37	no	[33]
Industry: Kotkamills	60.59	yes	[32]	Municipalities: WWTP	2.81	yes	[40]
Industry: Sunila Mill	31.54	yes	[41]	Fertilizer loading at port	0.20	yes	[10]
Ships' Black waters	0.61	yes	[36]	Ships' Grey Waters	0.07	yes	[36]
Ships' Grey Waters	0.17	yes	[36]	Ships' Black waters	0.06	yes	[36]
Total Nitrogen load	7035.24			Total Phosphorus load	225.45		

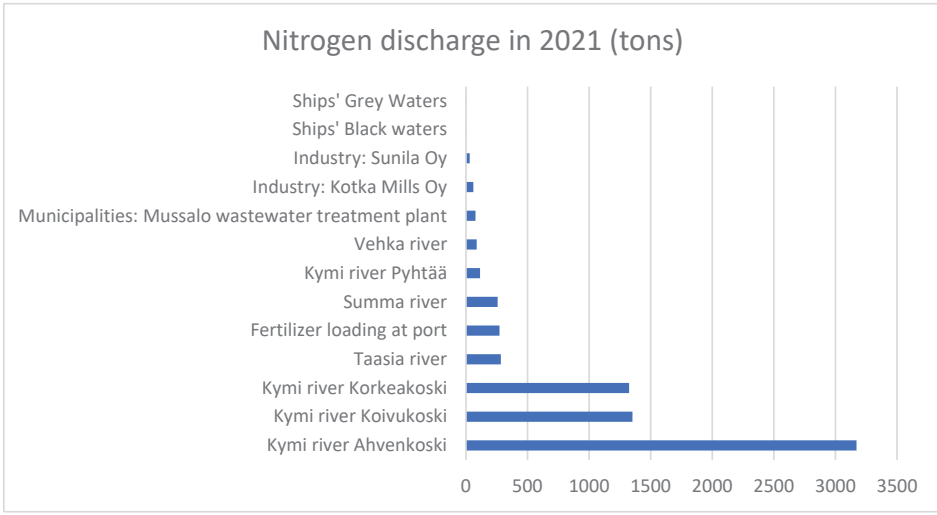


Figure 2. Comparison of the nitrogen discharge quantities [10,30,32,33,36,41].

Figure 2 illustrates that the largest branches of the Kymi River are by far the dominant sources of nitrogen discharge. However, one point source—fertilizer cargo loading—is among the riverine sources in terms of magnitude. Ship wastewater contributes only a very small share compared to the other sources. Figure 3 shows that, in addition to the largest branches of the Kymi River, the smaller Taasia River is also a major contributor to

phosphorus loading. Similar to the nitrogen loads, ship wastewater represents only a very minor share of the total phosphorus load.

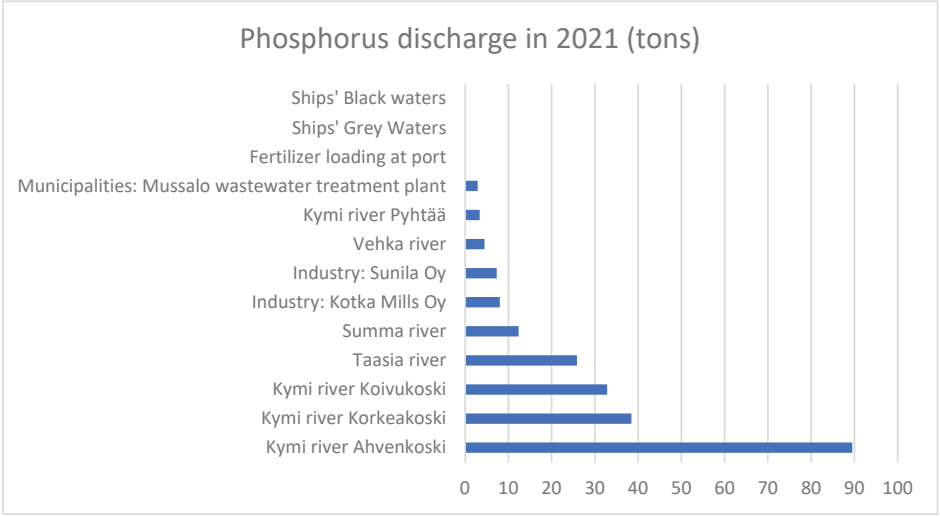


Figure 3. Comparison of the phosphorus discharge quantities [10,30,32,33,36,41].

3.2. Regulatory Mapping

The regulatory mapping revealed substantial differences in how nutrient discharges from the assessed source categories are governed. To compare the relative stringency of regulatory control applied to different nutrient sources, a qualitative regulatory classification scale (0–4) was developed for this study (see Section 2). The scale reflects the type and strength of regulatory instruments governing nutrient discharges, ranging from the absence of specific regulation (0) to strict regulatory control with explicit discharge prohibitions (4).

Riverine nutrient loads entering the Hamina–Kotka–Pyhtää coastal area originate from both point sources and diffuse agricultural sources within the catchment area. Upstream municipal wastewater treatment plants and industrial facilities discharging into rivers operate under environmental permits that establish facility-specific limits for nitrogen and phosphorus discharges. In contrast, diffuse agricultural discharges within the catchment are regulated primarily through nutrient management requirements, such as restrictions on fertilizer application. These measures regulate agricultural practices rather than establishing quantified discharge limits for nutrients. Consequently, riverine nutrient loads entering coastal waters are controlled indirectly through catchment-level management measures rather than through direct limits on total riverine nutrient inputs. Because riverine nutrient loads originate from a combination of sources subject to both numerical permit limits and more general practice-based regulations, this source category was assigned a score of 2 on the regulatory scale.

Three major point sources (Mussalo wastewater treatment plant, Sunila Milland Kotkamills) discharging directly into coastal waters are regulated through environmental permits issued by Finnish environmental authorities. These permits include explicit numeric limits for nitrogen and phosphorus discharges and may require advanced nutrient removal technologies. Permit conditions also include monitoring and reporting requirements that enable regulatory authorities to verify compliance. Compared with other nutrient sources in the study area, these sources are therefore subject to direct and

quantifiable regulatory control. Accordingly, these point sources were assigned a score of 3 on the regulatory scale.

Fertilizer cargo handling at port is subject to environmental permits that require preventive measures and monitoring but do not impose numeric nitrogen or phosphorus discharge limits; therefore, this source category was assigned level 1.

Ship-generated wastewater is regulated through a multi-level framework consisting of international maritime conventions and national implementation measures. MARPOL Annex IV restricts the discharge of sewage but does not regulate grey water. From the perspective of international regulation alone, grey water discharges would therefore correspond to level 0. However, national regulations in Finland impose stricter requirements: the discharge of sewage from ships is prohibited in Finnish coastal waters, and the discharge of grey water is scheduled to be prohibited from 2030 onwards. Considering this stricter national regulatory framework, ship-generated wastewater was assigned the highest regulatory score of 4.

Table 3 summarizes the main regulatory frameworks governing nutrient discharges from the different source categories analyzed in this study.

Table 3. Regulatory mapping of major nutrient source categories in the study area.

Source Group	Source Category	Examples in This Study	Main Regulatory Instruments	Regulatory Level (0–4)
Land-based sources	Riverine and diffuse catchment inputs including point sources via rivers	Kymi River branches; Taasia, Summa and Vehka Rivers	EU Water Framework Directive programmes of measures; Nitrates Directive; national agri-environmental regulations, environmental permits for industrial facilities along the river with numeric nitrogen and phosphorus discharge limits	2
	Municipal point sources	Mussalo wastewater treatment plant	Environmental permit with numeric nitrogen and phosphorus discharge limits; monitoring and reporting obligations	3
	Industrial point sources	Kotkamills; Sunila Mill	Environmental permit with numeric nitrogen and phosphorus discharge limits; monitoring and reporting obligations	3
Maritime and port-related sources	Port cargo handling	Fertilizer loading terminals; contaminated stormwater	Environmental permits for port and terminal operations; operational requirements (generally without numeric nutrient limits)	1
	Ship sewage (blackwater)	Cargo vessel sewage	MARPOL Annex IV; national prohibition of sewage discharge in Finnish territorial waters	4
	Ship greywater	Cargo vessel greywater	(greywater not regulated under MARPOL Annex IV); national prohibition in Finnish territorial waters from 2030	4

Figure 4 illustrates that rivers and fertilizer handling represent the largest sources of nitrogen input in the studied coastal area. In contrast, ship-generated wastewater is subject to the most stringent regulatory control, particularly when accounting for the forthcoming prohibition of grey water discharges in Finnish territorial waters. Figure 5 demonstrates a similar pattern for phosphorus inputs, where sources contributing relatively small nutrient loads are regulated more strictly than larger contributors.

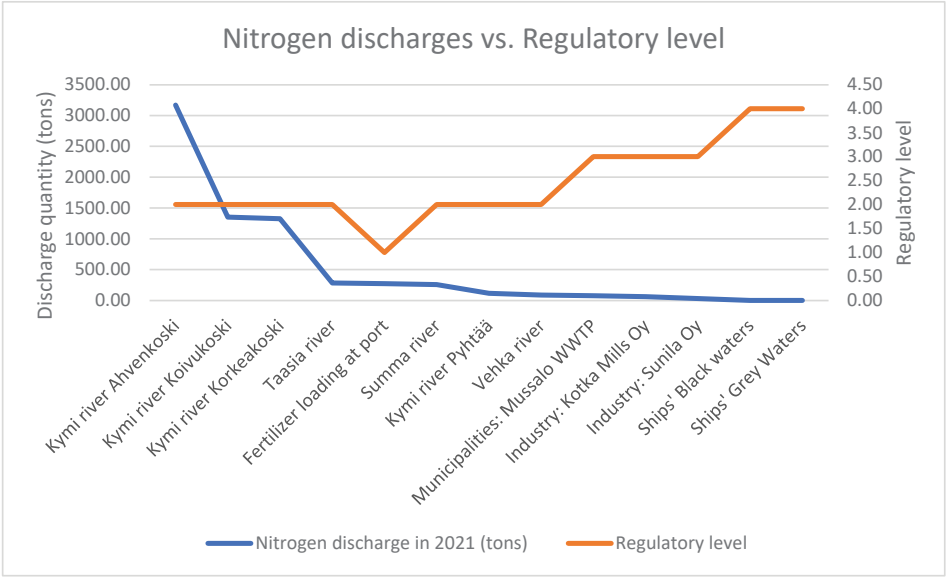


Figure 4. Nitrogen input quantity compared to the regulatory level of each source.

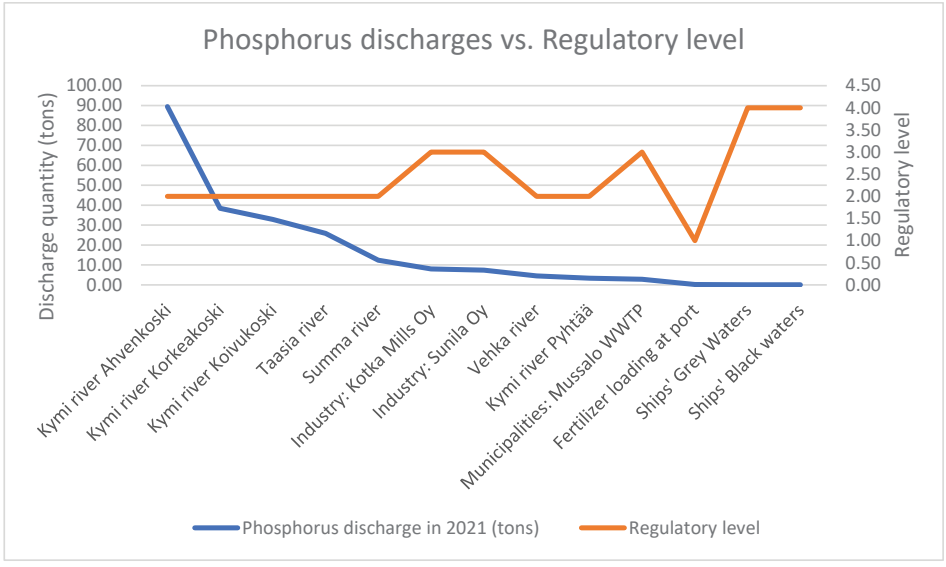


Figure 5. Phosphorus input quantity compared to the regulatory level of each source.

Figure 6 highlights a mismatch between nutrient load apportionment and regulatory stringency regarding the point sources. Fertilizer handling accounts for a larger share of

nitrogen input than the other assessed point sources combined, yet it is subject to a lower level of regulatory control compared with others. In contrast, Figure 7 indicates that for phosphorus inputs the distribution of loads is more closely aligned with the regulatory level applied to each point source.

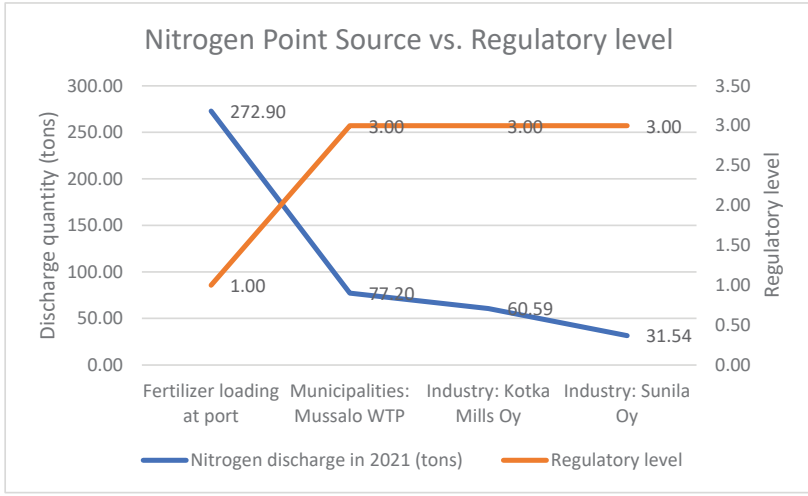


Figure 6. Nitrogen input from point sources compared to how strictly they are controlled.

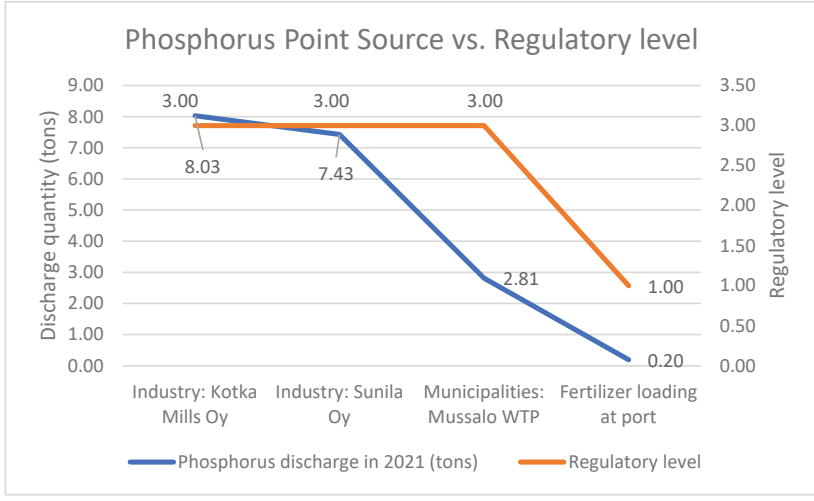


Figure 7. Phosphorus input from point sources compared to how strictly they are controlled.

4. Discussion

4.1. Contextualizing Maritime Contribution

The main findings of this study regarding nutrient apportionment (RQ1) were the following:

- Riverine inputs dominate total nutrient delivery by 94% of N (nitrogen) and 92% of P (phosphorus) in 2021;
- Ships' wastewaters are minor contributors in magnitude (<0.1% of N and <0.1% of P) and distributed outside coastal waters;

- Fertilizer cargo loading at port contributes 3.9% of N and 0.1% of P, being the biggest identified point source of nitrogen exceeding other point sources combined.

The dominance of riverine nutrient inputs observed in the Hamina–Kotka–Pyhtää coastal waters is consistent with long-term assessments in the Baltic Sea and other semi-enclosed coastal systems. Numerous studies have demonstrated that land-based sources, particularly agriculture and upstream diffuse inputs, account for the majority of nitrogen and phosphorus loads delivered to coastal waters, in which agriculture commonly contributes roughly 40 to 60% of total nutrient loads and municipal wastewater remains much more variable but still far larger than shipping in most systems [14,16,36,46–51]. Despite significant reductions in municipal and industrial discharges since the 1990s, nutrient legacies in soils and continued diffuse losses from catchments remain the primary drivers of eutrophication pressure in the Baltic Sea.

What distinguishes this study from earlier assessments is the integration of maritime and port-related nutrient pathways into the source apportionment. While shipping-related nutrient inputs have been examined at the basin scale using modeling approaches [8,9], such analyses typically focus on ship-generated wastewaters and atmospheric deposition and do not resolve port cargo handling or terminal-level discharges.

Empirical studies of ship sewage and grey water confirm that these inputs are quantitatively small, contributing approximately <0.1–3% for both nitrogen and phosphorus [36,47,52,53]. The present results corroborate these findings for the eastern Gulf of Finland. In addition, it should be noted that while the loads from fertilizer application, municipal wastewater treatment plants, and industry are localized point sources, the nutrient load from ships' wastewaters is dispersed throughout the open waters of the Baltic Sea during their voyages.

In contrast, fertilizer cargo handling at ports emerges as a locally significant nutrient source that is largely absent from regional nutrient inventories. Previous work has demonstrated that nutrient losses from fertilizer terminals can be substantial under certain operational and meteorological conditions and may constitute a non-negligible fraction of local nitrogen inputs [10]. The present study confirms that, while small in relation to total catchment loads, fertilizer handling represents the largest maritime-related nitrogen source and the largest identified point source in the study area. This finding aligns with broader observations that spatially concentrated sources, even when modest in absolute terms, can play a disproportionate role in shaping coastal water quality, particularly in semi-enclosed systems with limited water exchange [13,54].

4.2. Regulatory Implications

The main findings of this study regarding the regulatory framework and gaps regarding nutrient discharges (RQ2 and RQ3) were the following:

- Nutrient inputs to the study area are governed by a multi-layered regulatory framework spanning international conventions, EU legislation, national laws, and local environmental permits.
- Regulatory stringency is not aligned with the magnitude of nutrient pressures: sources contributing the largest nutrient loads are often regulated less strictly than sources with minor quantitative importance.
    - Diffuse agricultural sources, which dominate total nitrogen and phosphorus inputs via rivers, remain ineffectively regulated despite extensive policy frameworks.
    - Ship-generated wastewater contributes a negligible share of nutrient inputs but is subject to the strictest regulatory controls, including discharge prohibitions to certain ship types (passenger vessels by international MARPOL) and to certain locations (all ships in Finnish territorial waters by national legislation).

- Fertilizer cargo handling at ports constitutes the largest maritime-related nitrogen source and the largest identified nitrogen point source, yet environmental permits lack explicit nutrient discharge limits.

4.2.1. Ineffective Regulation of Dominant Diffuse Sources

The regulatory patterns observed in this case study reflect challenges documented in Baltic Sea environmental governance literature: policy frameworks are extensive and targets are clear, but the alignment between pressures and regulatory instruments is uneven, particularly where diffuse sources dominate and governance spans multiple levels [55,56]. In the studied area, the dominant nutrient inputs originate from the river system, reflecting diffuse agricultural losses and upstream point sources. Despite decades of regulation under the EU Nitrates Directive, Water Framework Directive, and the HELCOM Baltic Sea Action Plan (BSAP), agriculture remains the most challenging sector for nutrient abatement. Numerous studies demonstrate that reductions from diffuse sources are slower, more uncertain, and more costly than reductions from point sources [57–59].

Similarly, European nutrient discharge analyses show that policies aimed at point sources were more effectively implemented than those targeting diffuse sources [60]. Projected EU policy implementation to 2050 is expected to reduce domestic/industrial nitrogen discharges by 14% and phosphorus by 25%, whereas agricultural reductions are more modest at 5% for nitrogen and 2% for phosphorus [61].

4.2.2. Fertilizer Cargo Handling: An Overlooked but Manageable Source

Fertilizer cargo handling at ports represents the largest maritime-related nitrogen source and the largest identified nitrogen point source in the study area, yet it is subject to comparatively weak regulatory control. This imbalance reflects a broader governance mismatch in which port-based and land–sea interface activities lack clear nutrient-specific requirements and consistent performance standards.

Despite their localized environmental relevance, nutrient discharges associated with fertilizer loading are typically regulated through environmental permits that emphasize operational practices and general pollution prevention rather than explicit nitrogen or phosphorus discharge limits. As a result, fertilizer handling exceeds the nitrogen loads of several other point sources that are subject to stricter, limit-based regulation. This gap persists even though effective technical and operational mitigation measures—such as covered storage, enclosed conveyors, containment structures, and advanced stormwater management systems—are well established and technically feasible.

The findings illustrate a recurring governance challenge at the land–sea interface, where port activities fall between terrestrial and maritime regulatory regimes. Such boundary zones have been identified in Baltic Sea governance research as weak points in environmental management, characterized by fragmented responsibilities and diffuse accountability [62,63]. In practice, this institutional ambiguity limits the translation of nutrient reduction objectives into enforceable permit conditions for port operations.

From a policy-efficiency perspective, this regulatory gap is notable. Unlike diffuse agricultural runoff, port-related discharges are spatially confined, operationally well defined, and technically controllable. Economic and governance analyses indicate that nutrient abatement is most cost-effective when applied to sources that are observable, enforceable, and associated with clear institutional responsibility [64,65]. Strengthening port environmental permits through explicit nutrient discharge limits, systematic monitoring, and mandatory implementation of best available techniques would therefore complement catchment-scale measures and address a currently under-regulated but high-leverage source.

Finland's environmental permitting system closely resembles those of other Baltic countries, including Sweden, Denmark, Norway, Iceland, and Estonia [66], suggesting that similar regulatory gaps related to fertilizer handling potentially exist elsewhere in the Baltic Sea region.

4.2.3. Inefficiency of Additional Ship Wastewater Restrictions

In contrast to fertilizer handling, ship-generated wastewater is subject to the strictest regulatory controls despite its negligible contribution to total nutrient loads. Earlier studies show that nutrient inputs from ship wastewater were already very small prior to the most recent regulatory restrictions [8,36] and have decreased further following their implementation [9,12].

The regulatory framework governing ship wastewater is fragmented across international and national levels. Under MARPOL Annex IV, the discharge of sewage from passenger ships is prohibited in the Baltic Sea, while greywater is not regulated at the international level. Finnish national legislation, in contrast, prohibits the discharge of sewage—including treated effluent—from all ships in territorial waters and will extend the prohibition to greywater from 2030 onwards. As a result, nationally imposed requirements go beyond internationally agreed standards and apply unevenly across wastewater streams. This outcome reflects a well-documented tendency in Baltic Sea governance to prioritize sources that are administratively clear and internationally harmonized, even when their environmental impact is limited [55,65]. From a sustainability perspective, further tightening of ship wastewater regulations is unlikely to deliver meaningful additional reductions in coastal eutrophication. Moreover, increasing divergence between national maritime regulations may create compliance challenges for international shipping without proportional environmental benefit. This finding supports calls in the literature to better align regulatory effort with environmental effectiveness rather than regulatory convenience [56].

4.3. Alignment with HELCOM Targets

According the HELCOM country allocated reduction target (CART), Finland should reduce the input of nitrogen by 1199 tons and the input of phosphorus by 146 tons per year in the Gulf of Finland in order to reach good environmental status of the sea. In the studied area, achieving these targets relies mainly on reductions from agriculture and other catchment sources, complemented by improved targeted controls for locally important point sources. The importance of local contributions is illustrated by the Taasia River, a small, local catchment that alone contributed to nearly 18% of the total phosphorus CART for the whole Gulf of Finland. For nitrogen, fertilizer cargo loading at a port accounts for approximately 23% of the nitrogen CART for the Gulf of Finland. It is notable that a reduction of only 17% in total nitrogen inputs within the Hamina–Kotka–Pyhtää area would be sufficient to meet the entire nitrogen CART for the Gulf of Finland. In contrast, achieving the phosphorus reduction target would require a substantially larger reduction of approximately 65% in phosphorus inputs from the studied area.

These findings reinforce conclusions from Baltic Sea governance research: while point-source controls have delivered substantial reductions historically, achieving remaining targets—particularly for phosphorus—will depend primarily on diffuse agricultural abatement, complemented by targeted regulation of locally significant point sources [26,58,67].

5. Conclusions

This study quantified the relative contribution of maritime- and port-related nutrient sources to total nitrogen and phosphorus inputs in the Hamina–Kotka–Pyhtää coastal waters and mapped the regulatory regime governing each source category. Riverine inputs

dominated total loading in 2021, while maritime sources were minor overall; however, fertilizer cargo handling and associated stormwater runoff formed the primary maritime-related pathway and the largest identified nitrogen point source. In regulatory terms, shipborne wastewaters are subject to stringent controls, and municipal and industrial point sources operate under permits with numeric limits and monitoring. In contrast, excess amount of manure can be inserted into cultivated fields due to the manure exception in the phosphorus degree, and fertilizer terminal discharges can lack explicit nutrient limits, indicating a governance gap. Catchment-scale measures remain essential for achieving HELCOM CART objectives, and targeted permit updates for fertilizer terminals offer a practical local opportunity for additional reductions.

From a broader perspective, these results highlight a recurring challenge in coastal eutrophication management: the dominant nutrient sources are often diffuse and difficult to regulate, whereas smaller but more manageable sources at the land–sea interface tend to receive disproportionate analytical and regulatory attention. Studies from estuaries and coastal seas worldwide emphasize that effective nutrient management requires not only addressing the largest sources but also identifying leverage points where targeted interventions can yield measurable local benefits. By integrating port-related activities into the nutrient source framework, this study contributes to closing a persistent gap between basin-scale nutrient assessments and local coastal management.

The Hamina–Kotka–Pyhtää case exemplifies dynamics that extend well beyond the Baltic Sea. Many coastal regions combine large agricultural catchments, intensive port operations, and dense maritime traffic. The approach applied here, which quantifies heterogeneous nutrient sources alongside a structured regulatory comparison, provides a transferable template for identifying where governance efforts are aligned with environmental pressures and where such mismatches may weaken eutrophication mitigation in semi-enclosed coastal systems worldwide.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18083983/s1, Table S1: Traceability Table.

Author Contributions: Conceptualization, S.-T.L.; methodology, S.-T.L. and D.M.A.; validation, S.-T.L., J.K. and U.P.T.; formal analysis, S.-T.L., J.K. and U.P.T.; investigation, S.-T.L., J.K. and D.M.A.; data curation, S.-T.L., J.K., D.M.A. and U.P.T.; writing—original draft preparation, S.-T.L., J.K. and D.M.A.; writing—review and editing, S.-T.L., J.K., D.M.A. and U.P.T.; visualization, S.-T.L.; supervision, J.K. and U.P.T.; project administration, S.-T.L. All authors have read and agreed to the published version of the manuscript.

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Publication III supplementary material: Traceability Table

Nutrient source	N discharge (tons)	P discharge (tons)	Type of source	Coordinates	Time period	Data origin	Dataset reference	Method	Sampling frequency / method used for data collection and analysis
Kymi River Ahvenkoski	3171.03	89.49	Riverine (diffuse)	60.490570, 26.452550	1.1.-31.12.2021	Secondary data from environmental reports.	[32,33]	measured	Water flow is measured monthly from the measuring point shown in the Figure 1 of this study. Total nitrogen and total phophorus samples were taken by sertified environmental samplers and analysed in an acredited laboratory.
Kymi River Koivukoski	1352.25	32.83	Riverine (diffuse)	60.514243, 26.869354	1.1.-31.12.2021	Secondary data from environmental reports.	[32,33]	measured	Water flow is measured monthly from the measuring point shown in the Figure 1 of this study. Total nitrogen and total phophorus samples were taken by sertified environmental samplers and analysed in an acredited laboratory.
Kymi River Korkeakoski	1325.21	38.45	Riverine (diffuse)	60.504550, 26.931140	1.1.-31.12.2021	Secondary data from environmental reports.	[32,33]	measured	Water flow is measured monthly from the measuring point shown in the Figure 1 of this study. Total nitrogen and total phophorus samples were taken by sertified environmental samplers and analysed in an acredited laboratory.
Taasia River	283.97	25.86	Riverine (diffuse)	60.431012, 26.414484	1.1.-31.12.2021	Secondary data from environmental reports. Modelled flows may differ from measured values, but they still provide a representation of the rivers' water volumes.	[32,33]	simulated	Due to the infrequent measurement of the flow of this river, simulated flow data from the Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS), specifically the VEMALA load calculation module, is used in load estimations.
Fertilizer cargo loading at port	272.90	0.20	Port activity (point)	60.422961, 26.920638	1.1.-31.12.2021	Primary data from our previous study. The analysis results for nitrogen, phosphorus, and phosphate phosphorus carry a margin of error. Given the notably high nutrient concentrations, the water samples required dilution to facilitate analysis. Thus, a 15% margin of error is associated with the analysis method for nutrient concentrations.	[10]	measured	58 samples from storm water wells taken during an intensive period in autumn 2021. The total nitrogen and total phosphorus were analyzed in an acredited laboratory. Taking into account affecting factors (catchment area, quantity of loaded fertilizers, loading timing, and rainfall intensity) we employed a predictive modeling technique known as Boosted Regression Trees (BRT) and build a model relating environmental variables to nutrient emissions at the fertilizer application site, and this model was then used to assess the daily nutrient emissions at the site over the course of a year.
Summa River	256.93	12.37	Riverine (diffuse)	60.551491, 27.093476	1.1.-31.12.2021	Secondary data from environmental reports. Modelled flows may differ from measured values, but they still provide a representation of the rivers' water volumes.	[32,33]	simulated	Due to the infrequent measurement of the flow of this river, simulated flow data from the Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS), specifically the VEMALA load calculation module, is used in load estimations.
Kymi River Pyhtää	114.94	3.37	Riverine (diffuse)	60.463691, 26.567481	1.1.-31.12.2021	Secondary data from an environmental report.	[33]	calculated	Due to its low flow, no samples are taken from the Pyhtää branch in the joint monitoring program; instead, its contribution to the total substance load is assumed to be 2%, based on the value from 1992.

Vehka River	87.90	4.50	Riverine (diffuse)	60.575333, 27.171071	1.1.-31.12.2021	Secondary data from environmental reports. Modelled flows may differ from measured values, but they still provide a good representation of the rivers' water volumes.	[32,33]	simulated	Due to the infrequent measurement of the flow of this river, simulated flow data from the Finnish Environment Institute's Watershed Simulation and Forecasting System (WSFS), specifically the VEMALA load calculation module, is used in load estimations.
Municipalities: Mussalo WWTP	77.20	2.81	Land-based (point)	60.439611, 26.913915	1.1.-31.12.2021	Secondary data from quarterly reports to the authority by the wastewater treatment plant. No wastewater bypass events reported during the reporting period.	[40]	measured	Samples taken from incoming and outgoing water twice a month. Total nitrogen and total phosphorus analysed in an acredited laboratory. The treatment results are calculated as quarterly averages, including any bypasses and overflow events. Results are reported four times a year to the environmental authority.
Industry: Kotkamills Oy	60.59	8.03	Land-based (point)	60.468763, 26.958393	1.1.-31.12.2021	Secondary data from an environmental report.	[32]	measured	Total nitrogen and total phosphorus analysed from monthly samples taken at the mill.
Industry: Sunila Oy	31.54	7.43	Land-based (point)	60.487063, 26.959417	1.1.-31.12.2021	Secondary data from monthly environmental reports by the Sunila Oy to the environmental authority.	[41]	measured	Total nitrogen and total phosphorus analysed from monthly samples taken at the mill.
Ships' Black waters	0.61	0.06	Maritime activity (point)	Whole Baltic Sea	1.1.-31.12.2021	Primary data from our previous study. Results are compared to other studies of ship wastewaters and found to be similar in magnitude.	[36]	calculated	Calculated using the following equation: Nutrient [g] = Individual contribution [g/d] * crew members [persons] * distance to port [nautical miles] / speed [nautical miles/d].
Ships' Grey Waters	0.17	0.07	Maritime activity (point)	Whole Baltic Sea	1.1.-31.12.2021	Primary data from our previous study. Results are compared to other studies of ship wastewaters and found to be similar in magnitude.	[36]	calculated	Calculated using the following equation: Nutrient [g] = Individual contribution [g/d] * crew members [persons] * distance to port [nautical miles] / speed [nautical miles/d].

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