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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.

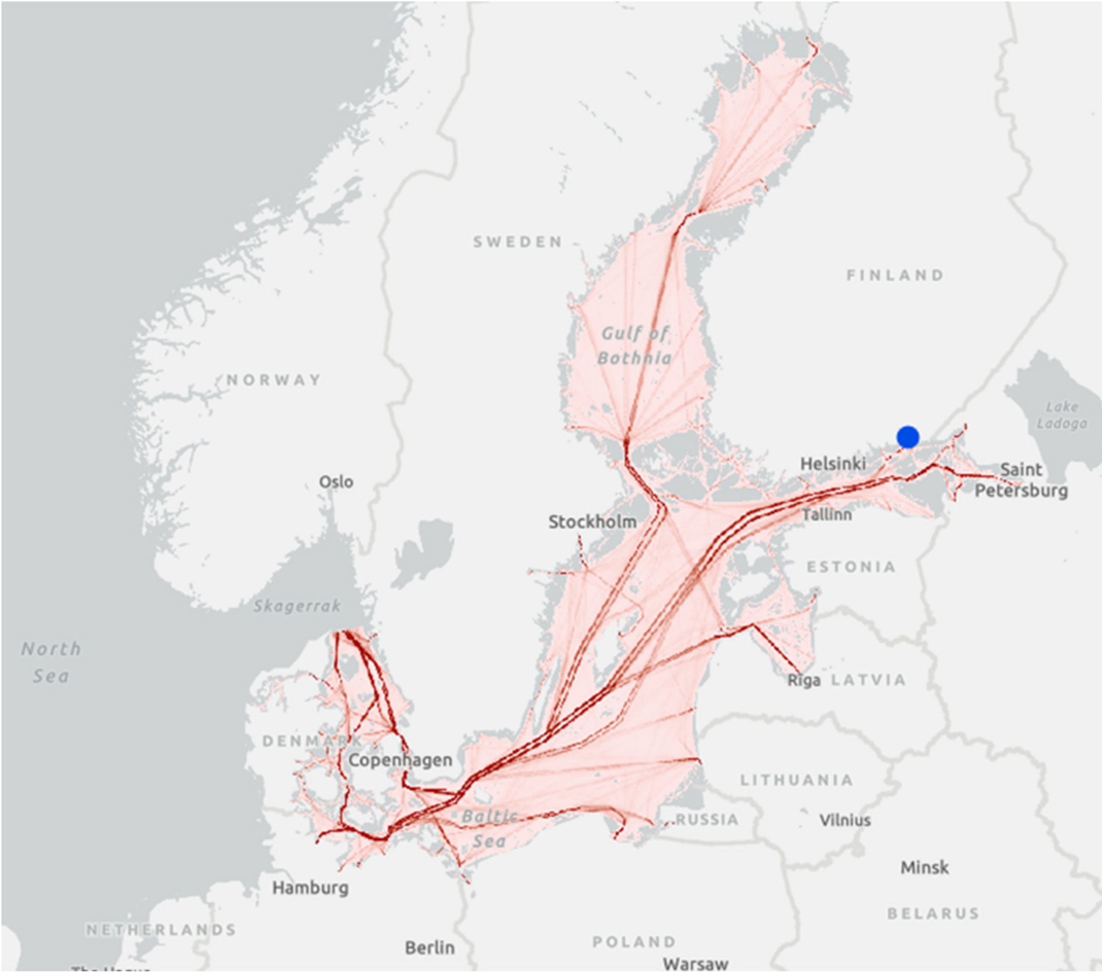

Figure 1. Cargo ship traffic intensity in the Baltic Sea in 2021 [17]. Case study port HaminaKotka is marked with blue spot.

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.

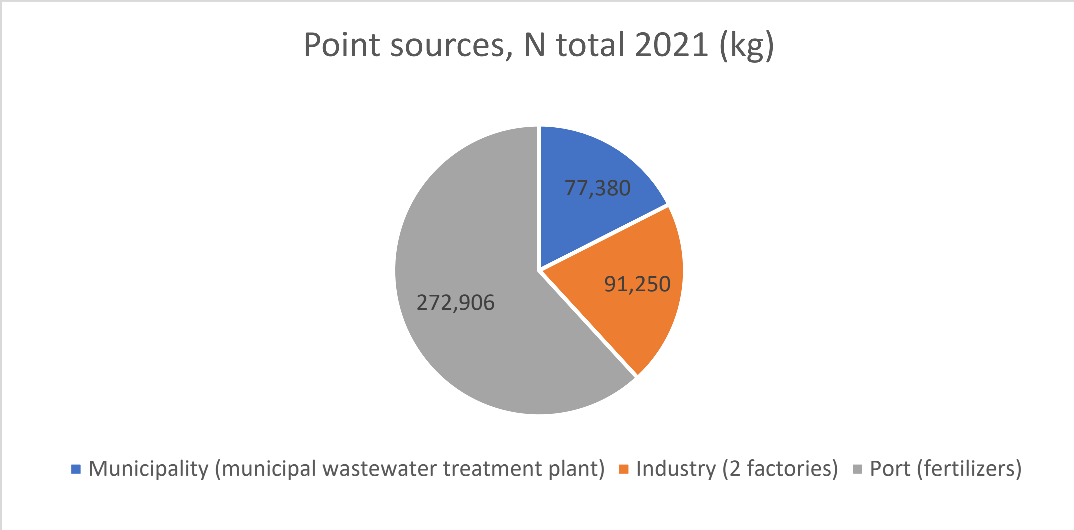

Figure 2. Point sources of nitrogen in Hamina-Kotka-Pyhtää coastal area 2021. Adapted from Ref. [13,19].

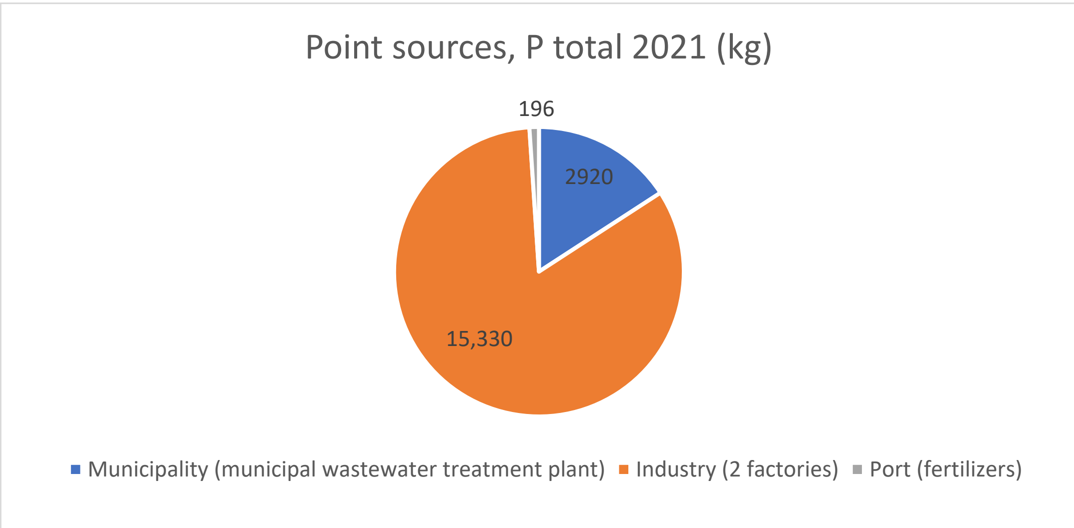

Figure 3. Point sources of phosphorus in Hamina-Kotka-Pyhtää coastal area 2021. Adapted from Ref. [13,19].

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].

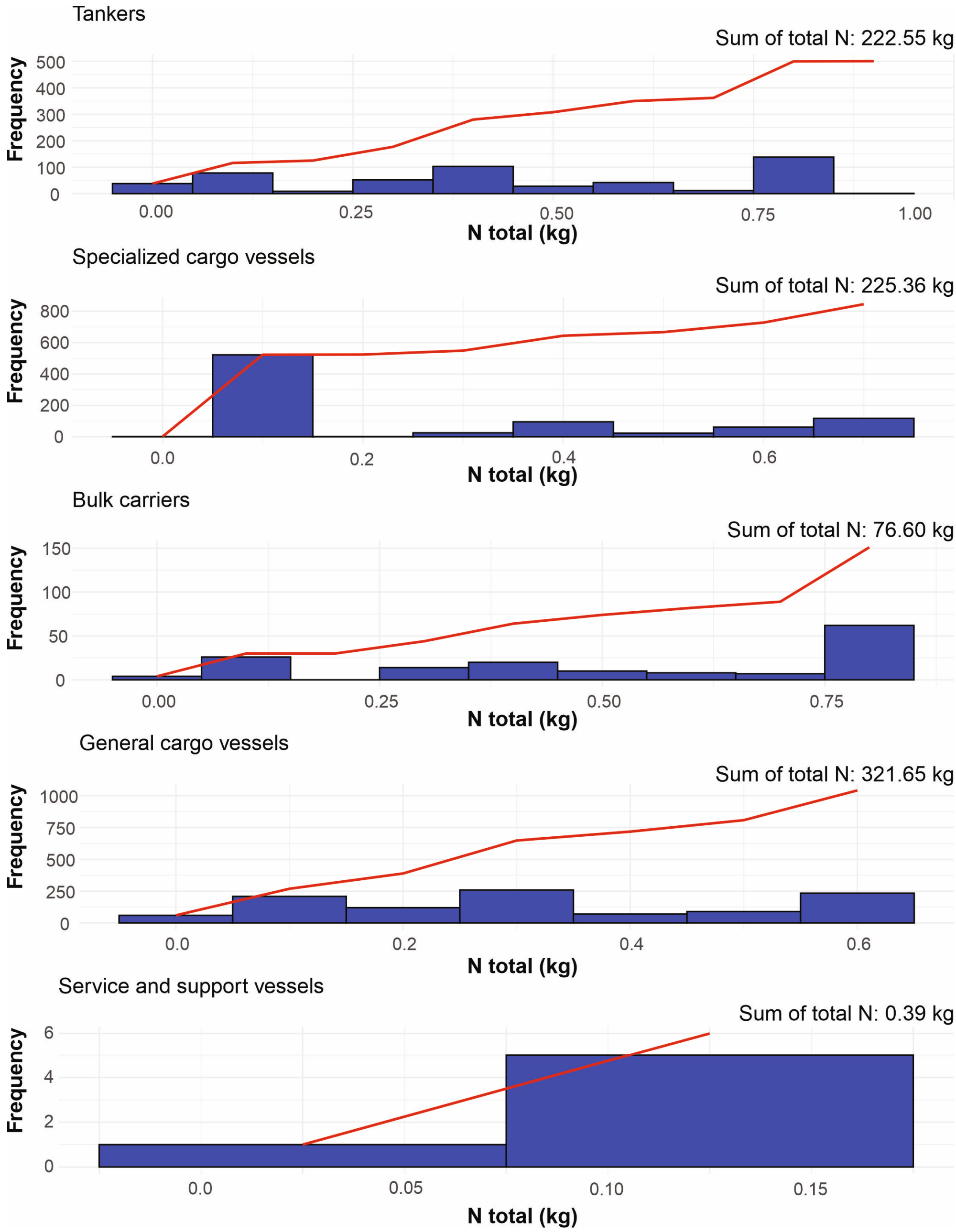

Figure 4. Estimated frequency distribution and total annual nitrogen discharges by ship type at the studied port. The red line represents the cumulative load of nutrient discharges.

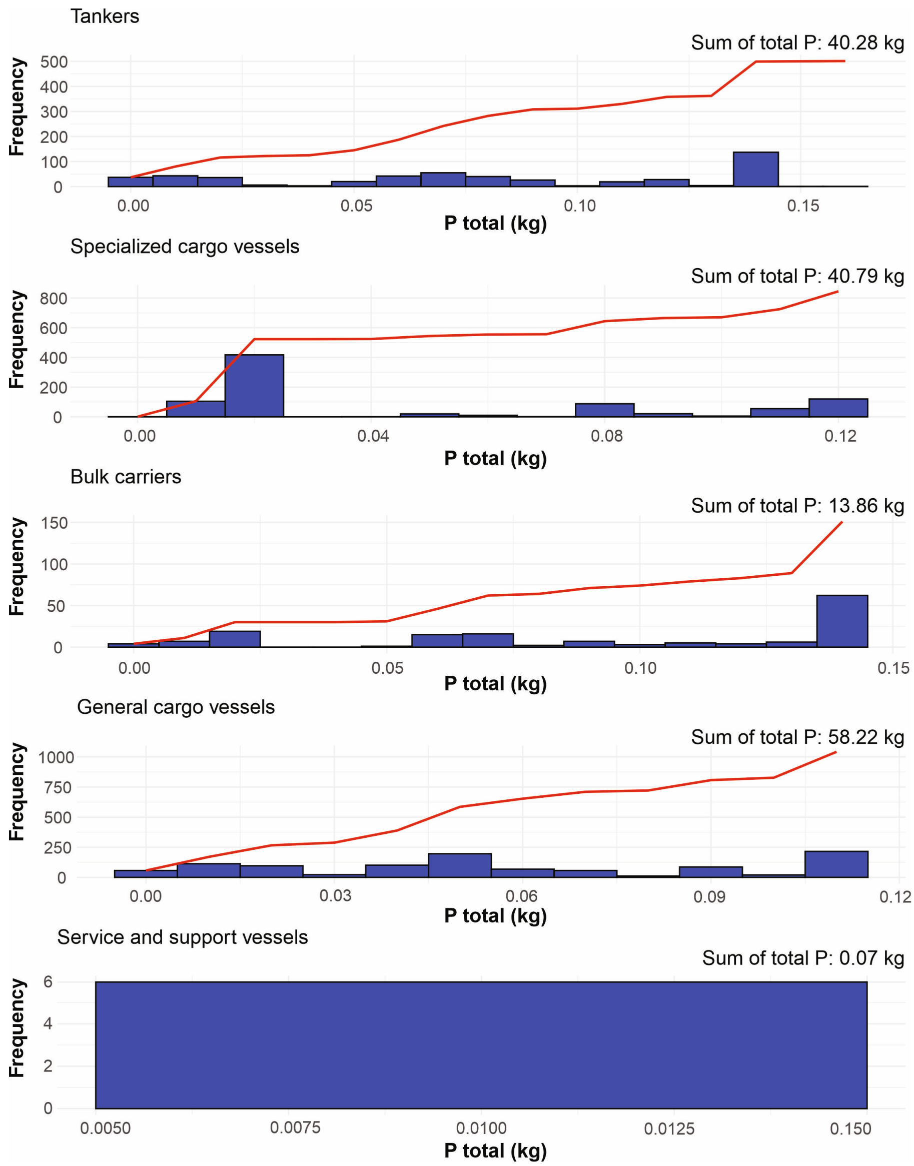

Figure 5. Estimated frequency distribution and total annual phosphorus discharges by ship type at the studied port. The red line represents the cumulative load of nutrient discharges.

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.

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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.

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

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