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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.

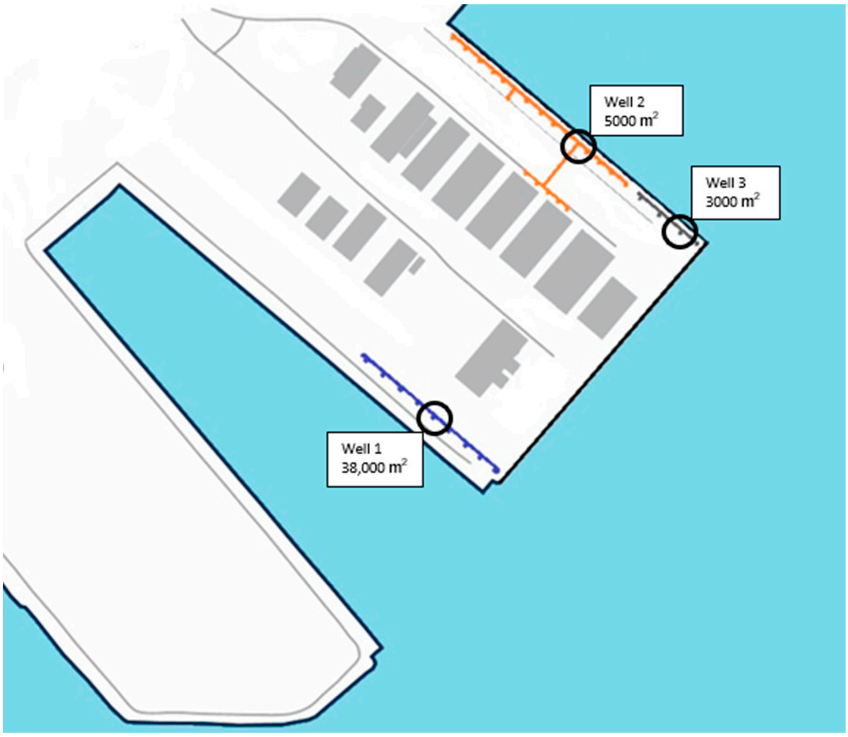

Figure 1. Three stormwater wells and their catchment areas [15].

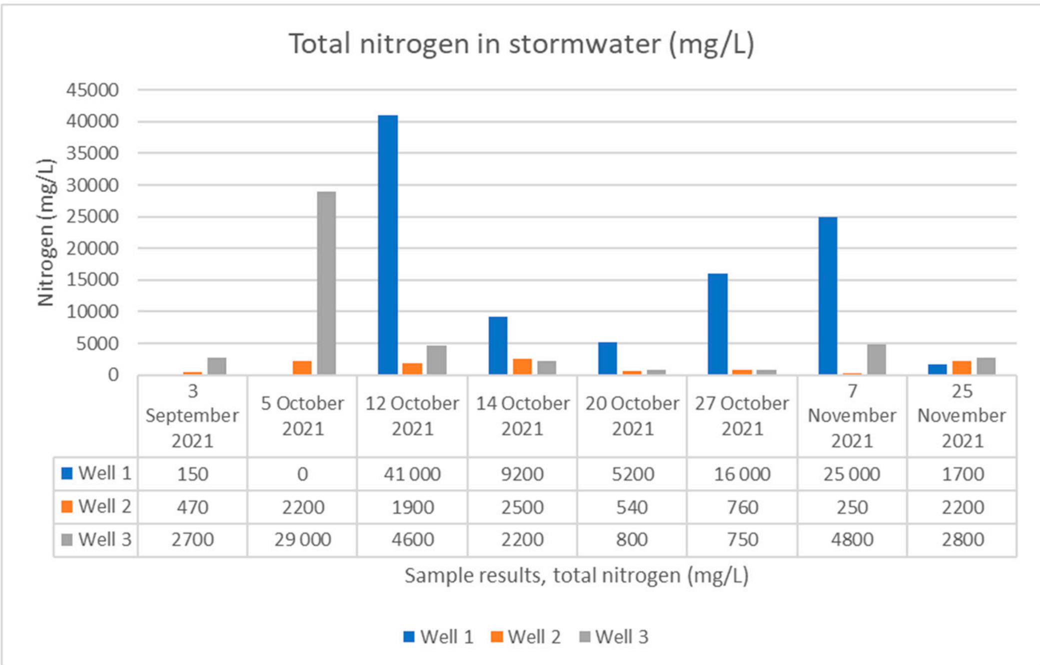

Figure 2. Total nitrogen concentration in stormwaters (mg/L). Well 1 displays highest nitrogen concentrations.

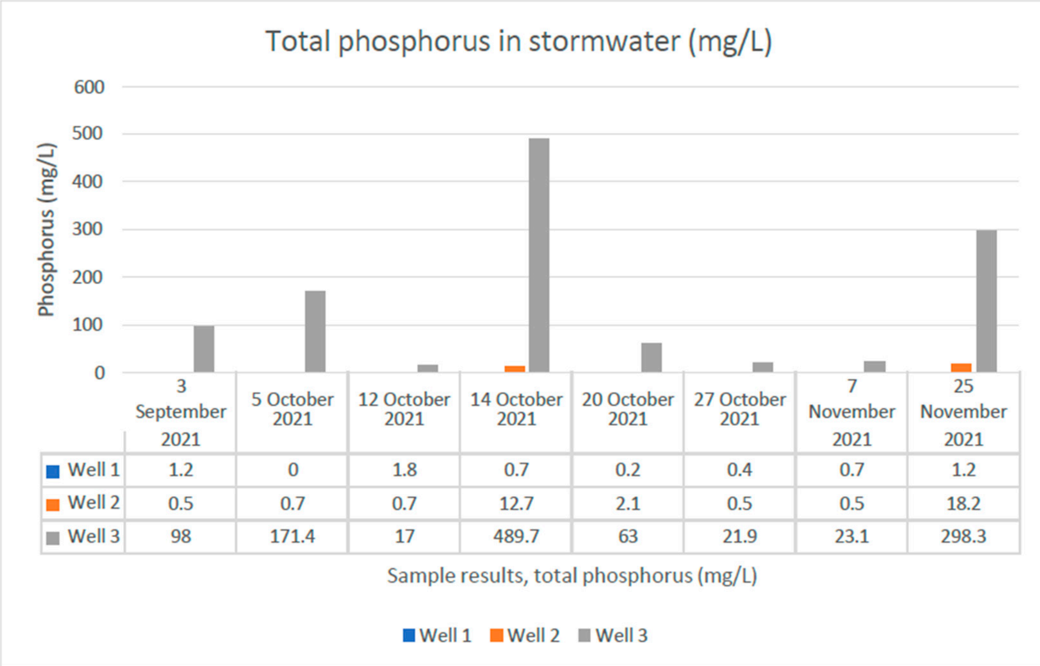

Figure 3. Total phosphorus in stormwaters (mg/L). Well 3 displays highest concentrations as most of the phosphorus fertilizers are loaded in that area.

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).

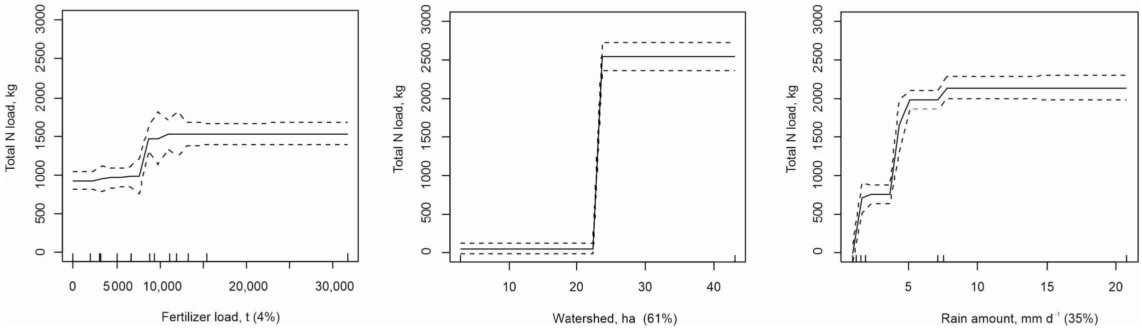

Figure 4. Standardized functional-form relationships showing the effect of environmental variables on total nitrogen discharge from fertilizer loading to the marine environment, while all other variables are held at their means. The relative contribution of each variable in the BRT model is given in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

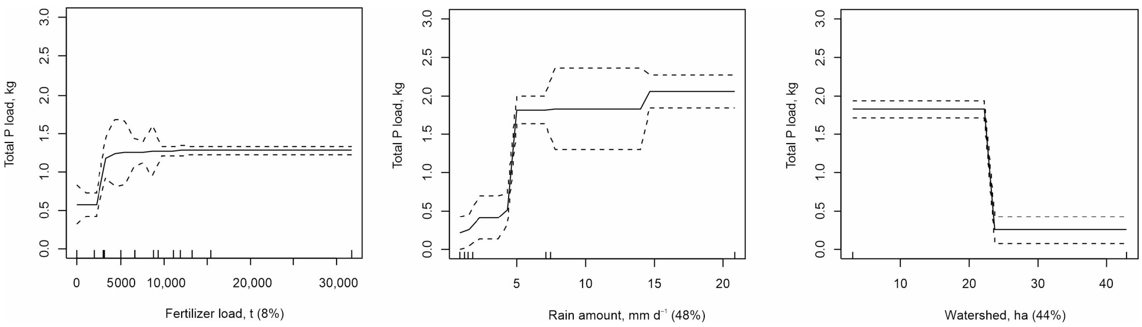

Figure 5. Standardized functional-form relationships showing the effect of environmental variables on total phosphorus discharge from fertilizer loading to the marine environment, while all other variables are held at their means. The relative contribution of each variable in the BRT model is given in 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).

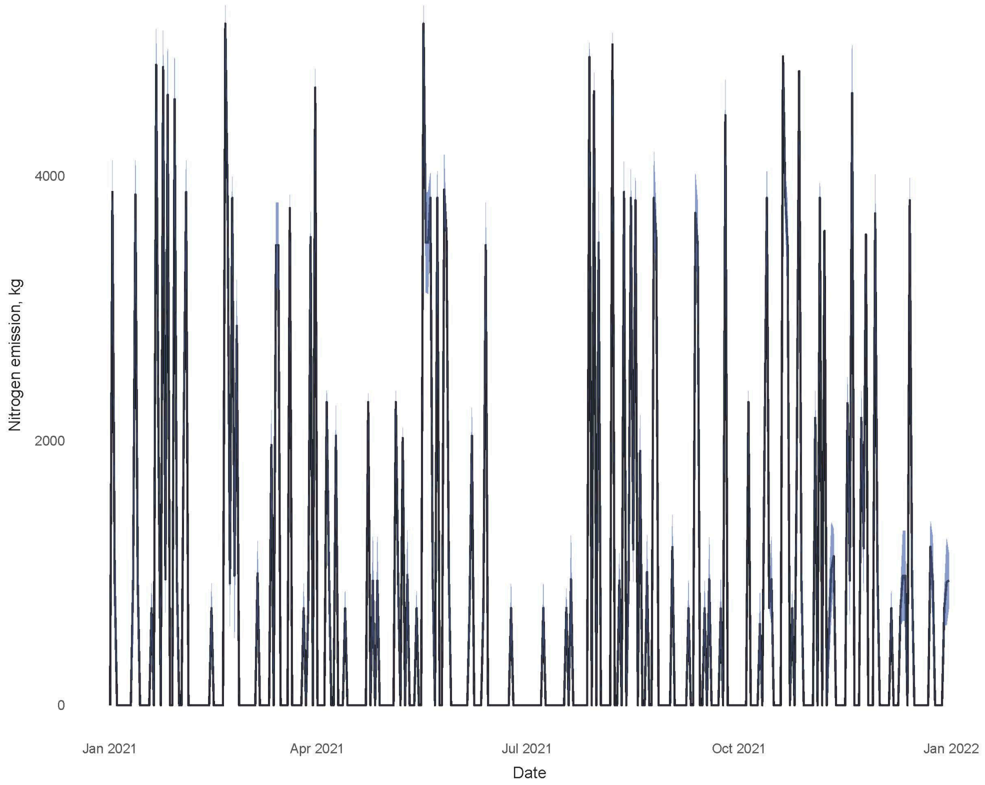

Figure 6. Predicted daily dynamics of total nitrogen discharge from fertilizer loading to the marine environment. The thicker line shows mean emissions, while the thinner line shows the standard error of these means.

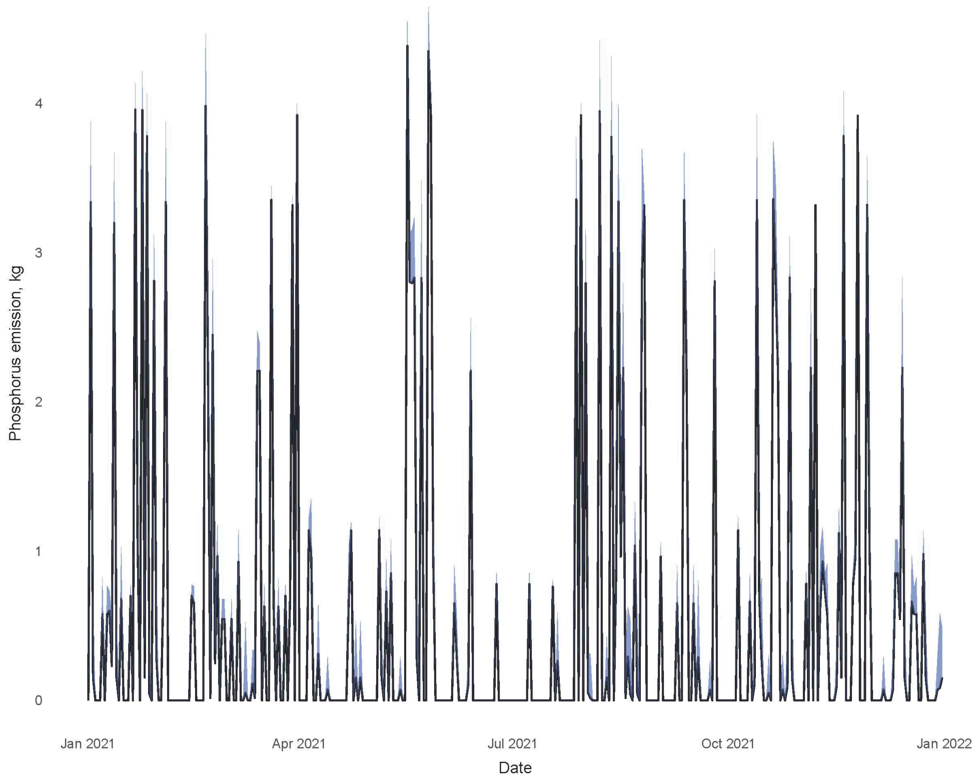

Figure 7. Predicted daily dynamics of total phosphorus discharge from fertilizer loading to the marine environment. The thicker line shows mean emissions, while the thinner line shows the standard error of these means.

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.

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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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