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Aquatic Eutrophication Potential of Fertilizer Application in Maize Cultivation in Thailand

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Abstract

Eutrophication is one of the challengeable global environmental problems driven by excessive nutrients (nitrogen and phosphorus) released to the ecosystem from various sources, mainly from fertilizer application in agricultural production systems. The life cycle assessment framework was applied to assess aquatic eutrophication potential associated with fertilizers applied in maize production in Thailand. The emissions were quantified by applying widely used updated inventory models, Product Environmental Footprint Category Rules (PEFCR) and European Monitoring and Evaluation Program/European Environmental Agency (EMEP/EEA) (2019). The characterization factors were obtained from the characterization model, IMPACT World+. Based on the midpoint level analysis, the total marine eutrophication potential from fertilizers applied in maize cultivation in 2019 was 26,514,965 kg N N-lim equivalent, while the total freshwater eutrophication potential was 50,175 kg PO_4^{3-} P-lim equivalent. The highest marine and freshwater eutrophication potentials were from Phetchabun province, while the lowest from Surin province. Nitrate emission has the highest contribution to the marine eutrophication potential at regional, provincial and country levels, followed by ammonia and nitrogen dioxide emissions. The only emission that contributes to the freshwater eutrophication potential in this study was phosphorous. The northern region has the highest contribution to the highest marine and freshwater eutrophication potentials. The results of damage level impact assessment revealed that the ecosystem damage from aquatic eutrophication potential is greater in the northern region and lower in the central region. The ecosystem damage from marine and freshwater eutrophication potentials was 331,800,510 PDF. m^2. year with the high contribution (99.8%) of marine eutrophication potential. Phetchabun was the highly contributed province to the ecosystem damage while the lowest was Surin province. These results shall be useful for the policymakers and researchers to develop the regulations to initiate emission reduction plans. The analysis of emission reduction pathways found that the 4R (right source, right rate, right time and right place) nutrient management practice would be the best and effective way to reduce the eutrophication impacts on the environment in the context of Thailand compared to the other three approaches; changing fertilizer types, fertilizer spreading techniques and the use of inhibitors/soluble salts.

Keywords : Fertilizer Application; Maize Cultivation; Marine Eutrophication Potential; Freshwater Eutrophication Potential; Ecosystem Damage; Emission Reduction

Introduction

The rapid growth of the population results in rising demand for food, thereby requiring the intensification of agricultural production. Hence, farmers tend to apply an excessive amount of fertilizers in view of the plant growth and achieving the maximum yield within a limited area and less time [1]. Excess nutrients, nitrogen (N) and phosphorous (P), applied to the field as fertilizers enter freshwater systems through leaching and runoff and are then transported to coastal areas causing eutrophication in both freshwater and marine ecosystems [2]. Eutrophication occurs naturally to some extent, but anthropogenic activities, i.e., fertilizer application in agricultural production systems, discharges from municipal wastewater treatment plants, industrial wastewater, livestock production and fossil fuel combustion, drive the eutrophication process more than that by emitting a high amount of nutrient and organic matter to the ecosystems [3]. Intensive fertilizer application in agriculture production systems is one of the key drivers of eutrophication [4]. Between 1961 and 2015, mineral fertilizer usage in Thailand was increased more than 100 times [5]. Despite the increase in fertilizer usage, the yield of maize was not increased significantly [6]. This indicates the loss of excess fertilizers into the environment due to improper management [7]. Excess nutrients accelerate the growth of algae and aquatic plants, causing massive impacts on the aquatic ecosystem. The continuous growth of aquatic plants forms a toxic algal boom that reduces water transparency and prevents sunlight penetration into deep layers of the lakes and ocean. The absence of sunlight for photosynthesis and lack of nutrients for algae and aquatic plants initiate the death of aquatic plants. Degradation of dead biomass by bacteria diminish the oxygen in deep layers of the water [8]. The continuation of this phenomenon for a long time causes the reduction of oxygen level to a point where no life is possible and end up with a dead ecosystem [9]. Phosphorous is the key nutrient controlling primary production in freshwater, while nitrogen in marine water. Thus, P is considered as the limiting nutrient in freshwater, while N is the limiting nutrient in marine water [2]. Past studies on Thai reservoirs and coastal water have shown that Thailand too encountered the impacts of aquatic eutrophication [10-12]. The life cycle assessment (LCA) is a standardized methodology used over 25 years to assess the potential environmental impacts associated with a product, a process or a system along its life cycle [13]. Eutrophication is taken into account in LCA studies considering its high contribution to the impacts on the environment. Maize is a widely grown crop throughout the world and one of five major crops produced in Thailand, occupying about 33% of the arable land [14]. The secondary data available for N and P fertilizer application in major crop productions revealed that the average inorganic N and P fertilizers applied for maize cultivation were higher than that of the cultivation of sugarcane, cassava, rice and oil palm [15-19]. Moreover, characterization-based eutrophication impact assessments have not been carried out in the context of Thailand. Thus, the main aims of the study are to assess the aquatic eutrophication potential associated with fertilizer application in maize cultivation in Thailand and to recommend possible techniques, technologies or practices to minimize the aquatic eutrophication impacts on the environment.

Methodology

The assessment of the aquatic eutrophication potential of fertilizer application in maize cultivation was performed according to the LCA framework outlined in ISO 14040: 2006 standard [23]. The LCA is performed in terms of four different phases, including goal and scope definition, inventory analysis, impact assessment and interpretation of results.

Goal and Scope Definition

The main goal of this study was to assess the aquatic eutrophication potential of fertilizer application in maize cultivation in Thailand. Maize was cultivated in 44 provinces (out of 77 provinces) in 2019. These 44 provinces belong to three regions in Thailand, northern, northeastern and central. The freshwater and marine eutrophication potentials of the inorganic fertilizer application, N fertilizer, P fertilizer, and mixes of N, P, K fertilizers were investigated. The reference unit applied for this assessment was the "*fertilizer application for maize cultivation in a province in 2019*". The reference flows were the amount of fertilizers applied for maize cultivation in a province in 2019. The system boundary of this analysis is shown in dash line (- - -) in Figure 1, and it was a "gate-to-gate" system that considered only fertilizer application process in the entire production chain.

Life Cycle Inventory (LCI)

The life cycle inventory of this study included three main data categories, such as the production of maize in each province in the year 2019, the quantity of N and P fertilizers applied to the field, and the emissions from fertilizers. The entire life cycle inventory data were obtained from secondary sources. The maize production data were gathered from the yearbook of "Agricultural Statistics of Thailand – 2019" published by the Office of Agriculture Economics (OAE) [24]. Average N and P fertilizer application rates were estimated based on the provincial N and P application data obtained from exisiting studies [19-22]. The N and P application data reflects field surveys in 20 provinces in 2015 [19]. Hence, the average N and P applied to produce 1 ton of maize was estimated on a regional basis as shown in Table 1 and applied to quantify the N and P application rates in 44 provinces.

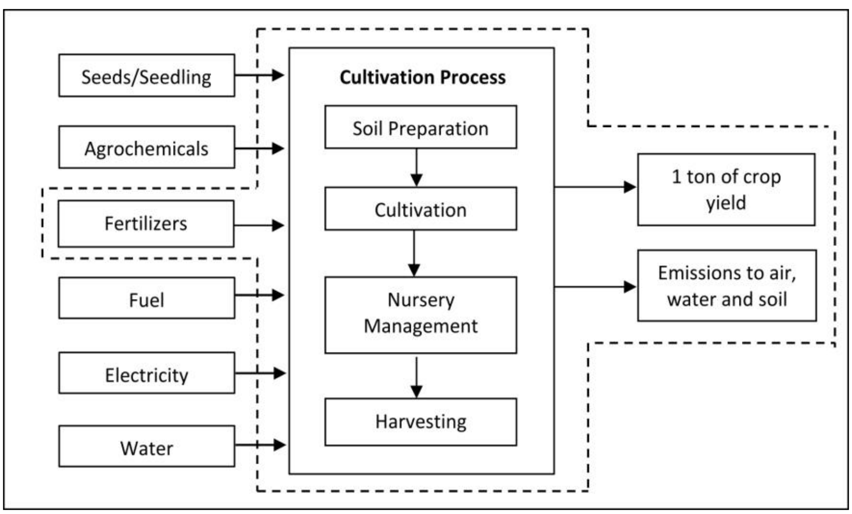

Figure 1 System Boundary

Table 1 Average N and P fertilizers applied to produce 1 ton of maize [19]

Regions (n = provinces)	Average fertilizer application to produce 1 ton of maize	
	N fertilizer (kg N)	P fertilizer (kg P)
North (n=14)	28.34 ± 4.38	7.58 ± 3.22
Northeastern (n=4)	25.60 ± 2.35	5.32 ± 1.33
Central (n=2)	29.11 ± 8.09	8.05 ± 2.09

The default emission factors (EF) of pollutants emitted from fertilizer application, which causes eutrophication, were obtained from two widely used and updated (in 2019) life cycle inventory models; European Monitoring and Evaluation Program/European Environmental Agency (EMEP/EEA) (2019) [25] and Product Environmental Footprint Category Rules (PEFCR) [26] (Table 2). The emissions from fertilizers considered in this study were ammonia (NH_3), nitrogen oxides (NO_x), nitrate (NO_3^-) and phosphorous (P). The PEFCR method was used as the main approach. Since the emission factor for nitrogen oxides (NO_x) was not available in the PEFCR method, the emission factor provided in the EMEP/EEA (2019) method was considered. The EMEP/EEA (2019) method express NO_x emission as NO_2. These EFs are applied to estimate the emissions from fertilizers applied to the field.

Life Cycle Impact Assessment (LCIA)

In life cycle impact assessment, the resulting emissions from different sources to air, water or soil compartments are translated into a potential environmental impact using a characterization model (LCIA methods). Among existing LCIA methods, the IMPACT World+ method [27] was applied to assess the aquatic eutrophication potential since it has recently updated (in 2019) spatially differentiated characterization factors (CF) for Thailand (Table 3). The importance of having a country-specific CF is because it reflects the local environmental conditions in a specific country or a region. The pollutants that do not have country-specific CF but have a high contribution to occur eutrophication, the CF at the global level, were considered.

The IMPACT World+ method addresses aquatic eutrophication by two separate impact categories; freshwater eutrophication and marine eutrophication. The impacts are expressed as freshwater eutrophication potential (FEP) and marine eutrophication potential (MEP). The P related emissions cause freshwater eutrophication, while N related emissions cause marine eutrophication [2]. Fertilizers emit different forms of N and P to different emission compartments, air, water and soil. Usually, NO_3^- enters the groundwater by leaching. The PO_4^{3-} enters groundwater and surface water via leaching and runoff, respectively, while P enters surface water through soil erosion [4].

Table 2 Emission factors [25, 26]

Emission Type	Compartment	Method	Emission Factor	Unit
NH_3	Air	PEFCR	0.120	kg NH_3 / kg N fertilizer applied
NO_x	Air	EMEP/EEA (2019)	0.040	kg NO_2/ kg N fertilizer applied
NO_3^-	Water	PEFCR	1.330	kg NO_3^-/ kg N fertilizer applied
P	Water	PEFCR	0.050	kg P / kg P fertilizer applied

Table 3 Characterization factors at midpoint and endpoint levels [27]

Substance	Emission Compartment	Spatial Resolution	Midpoint Characterisation Factor	Endpoint Characterisation Factor [PDF. m^2. year/ kg substance]
NH_3	Air	Thailand	0.108*	1.353
NO_x	Air	Thailand	0.034*	0.420
NO_3^-	Water	Global	0.158*	1.977
P	Water	Thailand	0.100**	1.145

* kg N N- lim eq/ kg substance; ** kg PO_4^{3-} P- lim/kg substance; PDF: Potentially disappeared fraction

Since freshwater ways and ground waterbody are interconnected, these N and P related pollutants would enter the freshwater bodies via leaching and runoff and are then transported to coastal water, which can cause eutrophication in freshwater and marine ecosystems [2]. Unlike nitrate, phosphate is not water-soluble, and it only moves with soil particles as it adheres to soil particles. Hence, nitrate is easily transported from freshwater to the ocean as it is soluble in water [4]. The N-related pollutants, which emit into the air (NH_3 and NO_x), are first deposited in the atmosphere and later enter into water and land through precipitation [28]. This cause eutrophication in water and acidification in the land. Thus, N release from fertilizers can cause damage to the marine ecosystem even though the land and marine water are not connected. Moreover, the consistency between the selected LCI model and the LCIA method is essential to get scientifically reliable impact scores. For example, the characterized substances and their emission compartments in the LCIA method need to be matched with the substances and emission compartments covered in the LCI method. he MEP and FEP at provincial and country-level were estimated as indicated in equation (1) [27] by multiplying N and P related emissions from fertilizers applied in each province with the characterization factors provided in Table 3.

Aquatic Eutrophication Potential = Emission × Characterisation Factor (1)

Based on the results of the impact assessment, recommendations of potential techniques, technologies, and practices to minimize the impacts from fertilizer application on the environment were proposed. The interpretation of the results of the impact assessment was discussed in the result and discussion section.

Results and Discussion

Impact Assessment Results and Interpretation

The aquatic eutrophication impacts were expressed as FEP (kg PO_4^{3-} P-lim eq.) and MEP (kg N N-lim eq.). Figure 2 and Figure 3 illustrated the total MEP and total FEP respectively for maize cultivation at the provincial level in Thailand in 2019.

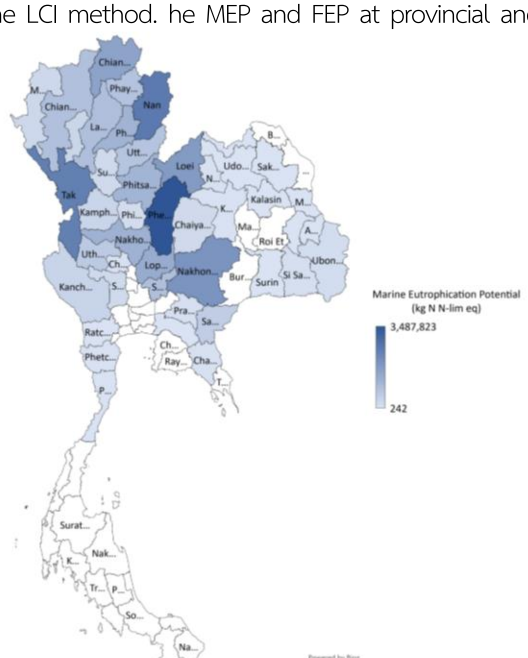

Figure 2 MEP of fertilizer application in maize cultivation in Thailand in 2019

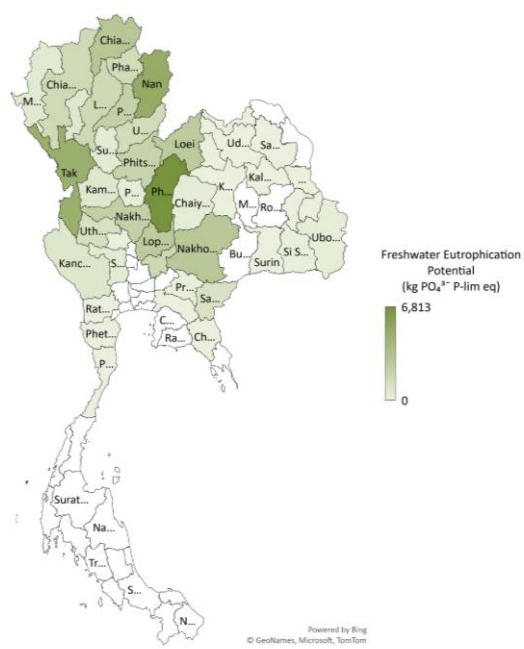

Figure 3 FEP of fertilizer application in maize cultivation in Thailand in 2019

Out of the 77 provinces in Thailand, maize was cultivated in 44 provinces only. The rest of the provinces (33), including all provinces in the southern region and several provinces in the northeastern (5) and central (14) regions, were not cultivated maize in 2019 (indicated in white colour in the map). The MEP and FEP were analyzed using midpoint CFs provided in the IMPACT World+ method. The total MEP from fertilizers applied in maize cultivation in 2019 was 26,514,965 kg N N-lim equivalent, while the total FEP was 50,175 kg PO_4^{3-} P-lim equivalent. At the country level, the top 3 provinces which have the highest MEPs and FEPs were Phetchabun (MEP:13.2%; FEP: 13.6%), Nan (MEP: 9.7%; FEP: 10%) and Tak (MEP: 9.1%; FEP: 9.4%). However, the lowest MEP and FEP were from Surin province.

The contribution of N-related emissions to the MEP at the regional level is shown in Figure 4. Among the three regions which cultivated maize, the north region has the highest contribution to the total MEP, followed by the northeastern and central regions. Total MEP has the contribution of MEPs from NO_3^- (93.6%), NH_3 (5.8%) and NO_x (0.6%) emissions. Furthermore, the study of Misselbrook et al. (2019) [29] also shows that NO_3^- emission is relatively high compared to NH_3 and NO_x emissions from fertilizers. Figure 5 indicates the contribution of P-related emissions to the total FEP. Phosphorous is the only emission that contributed to the FEP in this study. The northern region has the highest contribution to the total FEP, followed by central and northeastern regions.

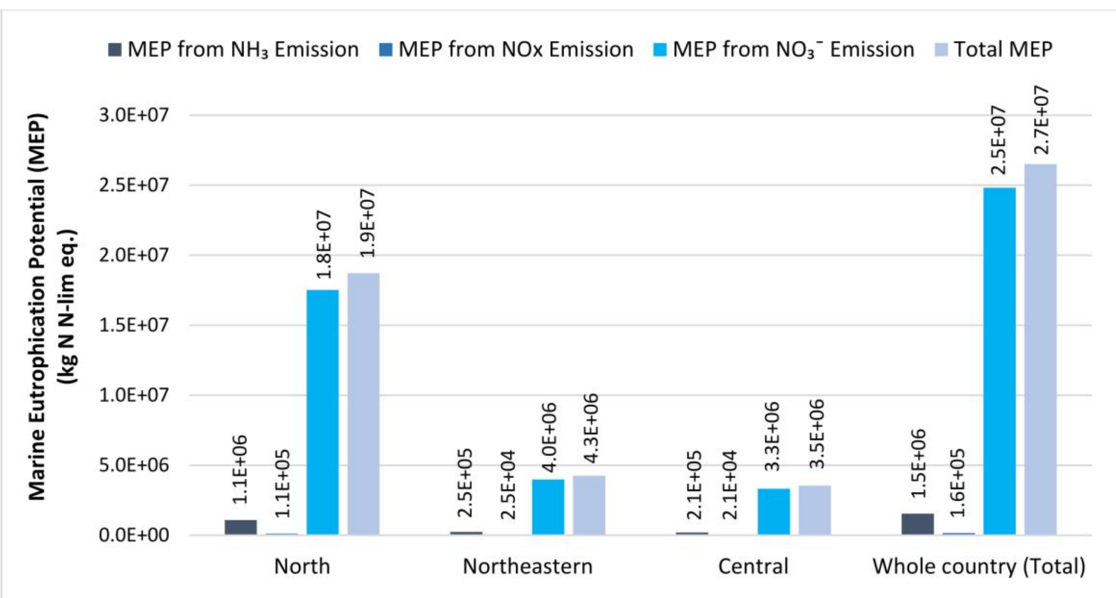

Figure 4 Contribution of N-related emissions to the total MEP

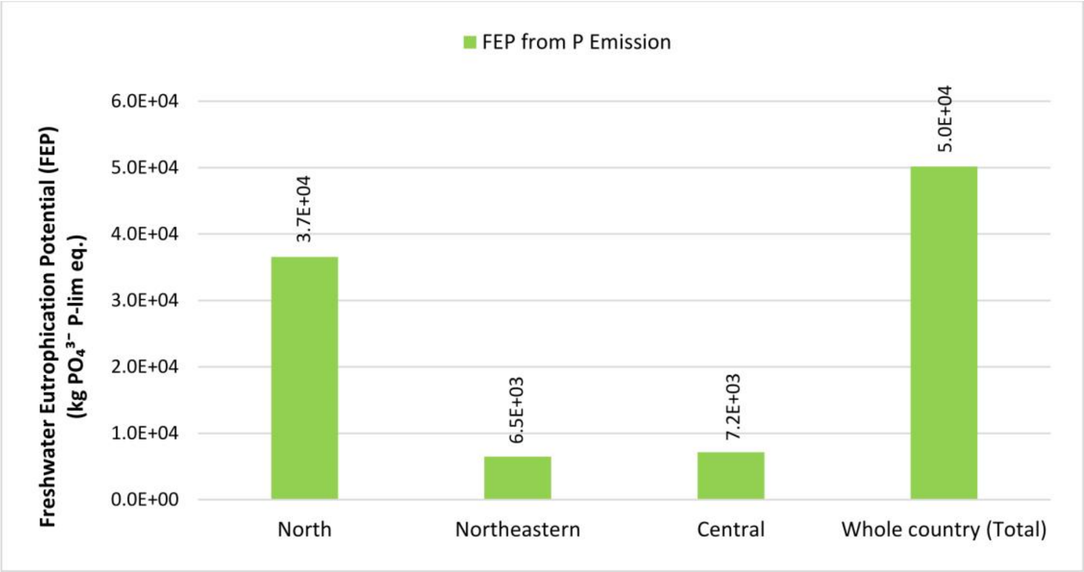

Figure 5 Contribution of P-related emissions to the total FEP

The total fertilizer application was estimated based on maize production (ton), productivity (yield) (ton/ rai) and fertilizer application rate (kg N or P/rai) in this study. The maize production and fertilizer application rate are directly proportional to the total fertilizer application, while the productivity is inversely proportional. In addition, total fertilizer application is directly proportional to both MEP and FEP. Therefore, if productivity increases, the total fertilizer application will be decreased, and MEP and FEP will also be decreased along with that. Accordingly, the region which has the highest MEP (northern) and FEP (northern) have the lowest productivity, while the regions with the lowest MEP (central) and FEP (northeastern) have the highest productivity. Similarly, the provinces with the highest MEP and FEP (Petchabun, Nan and Tak) have lower productivity at the provincial level.

Figure 6 shows the ecosystem damage associated with the impacts of marine and freshwater eutrophication.

In IMPACT World+ method, midpoint level impact categories can be further modelled and grouped into damage level impact categories (endpoint) which can be categorized into three major areas of protection (AOPs), including human health, ecosystem quality, and resources and ecosystem services. The potential of losing species richness (ecosystem damage) was analyzed using damage level CFs and expressed as a potential disappeared fraction (PDF) of species. As shown in the figure above, the northern region is the most significant contributor to ecosystem damage. The lowest contributor was the central region. Based on the endpoint level analysis, the ecosystem damage from MEP and FEP for Thailand was 332,009,061 PDF. m^2. year. MEP has the highest contribution to ecosystem damage (99.8%). At the provincial level, Phetchabun province (13.2%) was the highly contributed province to ecosystem damage, followed by Nan (9.7%), Tak (9.1%) provinces. The lowest ecosystem damages were in Surin, Yasothon, and Amnat Charoen provinces, respectively. These results shall be presented to the policymakers and researchers to develop the regulations to initiate emission reduction plans.

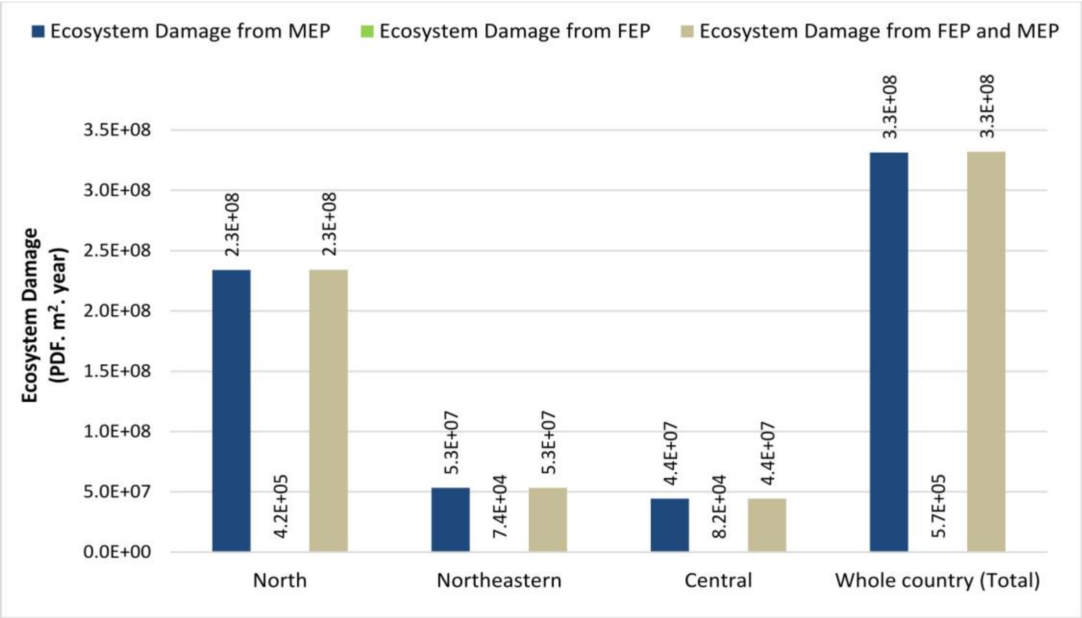

Figure 6 Contribution of MEP and FEP to the ecosystem damage

Aquatic Eutrophication Potential Reduction Pathways

The potential aquatic eutrophication impacts from fertilizers could be lessened by reducing the emissions. The emission reduction techniques, technologies or practices were categorized into four major approaches, viz., changing fertilizer types, fertilizer spreading techniques, use of inhibitors and fertilizer management practices, as shown in Table 4.

Most of the studies focused on reducing greenhouse gas emissions (N_2O) and ammonia emission from fertilizers. Hence, adequate attention has not been received in reducing other emissions (NO_x, NO_3^- and PO_4^{3-}) from fertilizers that cause eutrophication in aquatic ecosystems. The fertilizer imports statistics [39] revealed that Urea was the highly imported fertilizer in Thailand, accounting for 43.7% of the total import of fertilizers. Furthermore, Urea has a higher emission factor for NH_3 emission compared to other fertilizer types [22]. Thus, Urea was used as the reference fertilizer to estimate the emission reduction percentages of concerned fertilizers in this study. Five fertilizers were considered for the replacement of Urea. Three of them are currently being imported to Thailand (MAP, DAP, and AS), while the other two fertilizers are AN and CAN, which could be introduced to the market and farmers as low emission fertilizers. Apart from the percentage emission reduction, the cost-effectiveness of these fertilizers was considered since Thailand is a developing country. Accordingly, the costs of the MAP, DAP, AS, AN and CAN are 9,143 THB/ton, 12,049 THB/ton, 4,857 THB/ton [39], 6,016 THB/ton and 7,340 THB/ton [40] respectively. Based on the brief analysis, in the context of Urea replacement by a fertilizer imported into Thailand, MAP would be a better substitute compared to AS and DAP because of high cost and low emission reduction compared to MAP. Due to the fact that the cost of AN and CAN has no significant difference between other fertilizers currently being imported to Thailand, CAN would be a better alternative to introduce

Table 4 Emission reduction pathways

Approach	Emission reduction pathways	Type of emission	Emission reduction percentages	References
Change the fertilizer types	Replaced Urea with DAP/MAP	NH_3	-68%	[25]
	Replaced Urea with AS		-42%	
	Replaced Urea with AN		-90%	
	Replaced Urea with CAN		-95%	
Fertilizer spreading techniques	Rapid incorporation of Urea	NH_3	-50%	[30]
	Trailing hose		-30-35%	
	Trailing shoe		-30-60%	
	Shallow injector		-70-80%	
	Deep injector		-90%	
Use of inhibitors or soluble salts	Urea + NBPT	NH_3	-50%	[31]
	Urea(s) + Urease Inhibitor		-70%	[30]
	Urea(l) + Urease Inhibitor		-40%	
	Urea + Soluble Salts (Ca, Mg, K)		-33%	[32]
	Nitrification Inhibitor (DCD)	NO	-92%	[33]
		N_2O	-64%	[34]
		NO_3^-	-50%	[35]
Fertilizer management Practices	4R nutrient management	PO_4^{3-}	-80%	[36]
		N_2O	-23%	[37]
		NO_3^-	-40%	[38]

*DAP: Di Ammonium Phosphate; MAP: Mono Ammonium Phosphate; AS: Ammonium Sulphate; AN: Ammonium Nitrate; CAN: Calcium Ammonium Nitrate; NBPT: N-(n-butyl) thiophosphoric triamide; DCD: Dicyandiamide

to the market and farmers as a slow-releasing fertilizer as its percentage emission reduction is higher compared to AN. However, changing fertilizer type could affect the fertilizer import market, and these alternative fertilizers might not be appropriate for all the crop cultivations. Moreover, based on current data, this approach can be used to reduce NH_3 emission only. Even though fertilizer spreading techniques show significant emission reduction, these techniques were claimed as expensive [30]. Thus, as a developing country, quite challenging to implement such expensive techniques in Thailand. Although inhibitors can reduce N-related emissions and facilitate fertilizer use efficiency by decreasing the nitrification and denitrification processes; the studies on inhibitors claimed that there are problems with the commercial use of these inhibitors as they are expensive, only effective in certain soils. Undesirable residues might remain in the soil [33]. The common drawback of the above techniques is that it reduces only one or two types of emission. Thus, all the above three approaches might not be effective in the context of Thailand. The 4R nutrient management technique is introduced by 4R nutrient stewardship [41] for farmers to keep the nutrients on and in the field and minimize the emissions from fertilizers.

The 4R stands for right source, right rate, right time and right place. Implementation of the 4R concept aids to align the economic, environmental, and social aspects of nutrient management. Selection of fertilizers that crop needs, identifying the fertilizers required to match the plant requirement, deciding the fertilizer application time based on the nutrient availability for crop requirement, and applying fertilizers where the crop can use them are the main tasks to follow under the four steps. However, expert consultation may require to identify the effective 4R for your case since the 4R can be varied with the crop type, geographical and climatic conditions of the cultivation area. The field studies [36-38] have shown that the 4R nutrient management technique can significantly reduce NO_3, N_2O and PO_4^{3-} emissions (see Table 4). Due to the fact that the changing fertilizer type and using inhibitors/coated fertilizer approaches are considered when selecting the right source, NH_3 and NO_x emissions too can be reduced under this concept [42]. In addition, this concept can be practiced with low or zero cost based on the changes in selected 4R. Optimizing nutrient management, higher crop yield, improving fertilizer efficiency, and minimizing environmental impacts by retaining nutrients within the field are the key benefits of practicing the 4R nutrient management concept [38]. Therefore, 4R nutrient management practice would be the best and effective way to minimize the eutrophication impacts in developing countries.

Conclusions

Fertilizer application has been increased over the past few decades. One of the significant consequences of the excess application of fertilizers is eutrophication. This study assessed the aquatic eutrophication potential of fertilizers application in maize cultivation. Based on the midpoint level analysis, the total MEP from fertilizers applied in maize cultivation in 2019 was 26,514,965 kg N N-lim equivalent, while the total FEP was 50,175 kg PO_4^{3-} P-lim equivalent. The highest MEP and FEP were from Phetchabun province, while the lowest MEP and FEP were from Surin province. The northern region has the highest contribution to the total MEP and FEP. Nitrate emission has the highest contribution to the total MEP at regional, provincial and country levels, followed by NH_3 and NO_x emissions. Phosphate is the only emission that contributed to the FEP. The regions and provinces with the highest MEP and FEP have the lowest productivity, while the regions/ provinces with the lowest MEP and FEP have the highest productivity. Based on the endpoint level analysis, the northern region has the highest potential to lose species richness in both inland and marine water. The lowest contributors for loss of species richness in freshwater and marine waters are northeastern and central regions, respectively. The estimated ecosystem damage from MEP and FEP for Thailand was 332,009,061 PDF. m^2. year. with the high contribution of MEP (99.5%). Phetchabun province was the highly contributed province to the ecosystem damage, while the lowest from Surin province. These results shall be presented to the policymakers and researchers to develop the regulations to initiate emission reduction plans. The analysis of different emission reduction pathways is recommended that the 4R nutrient management practice would be the best and effective way to reduce the eutrophication impacts as a developing country compared to the other three approaches; changing fertilizer types, fertilizer spreading techniques and the use of inhibitors/soluble salts.

Acknowledgements

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