AgriSim:A User-Friendly Learning Tool for Farmers Seeking to Prevent Harmful Algae Blooms

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Abstract

Harmful Algae Blooms (HABs) are a massive and increasing problem worldwide as they harm human health, wreak havoc upon delicate aquatic ecosystems, and cause massive damages to coastal, water-reliant industries. HABs largely occur because of an unnatural increase of Nitrate and Phosphate in a body of water (also known as nutrient pollution). The major source of nutrient pollution is runoff from improperly fertilized agricultural settings such as farms and feedlots. In the long-term, this study seeks to develop an user-friendly learning tool for farmers to help them understand how their fertilization practices are leading to HABs. In this phase of the study, the goals were to devise the foundational mathematical model which will serve as the basis for the learning tool and to conduct a thorough analysis of the HAB problem in Lake Erie through the means of literature review and stakeholder interviews. The devised model asked farmers for input parameters about their practices/farm and outputted parameters that quantify the severity of an HAB that could occur as a result of their practices. Upon further development of this mathematical model and eventual incorporation into a mobile application, this tool has wide applications. Farmers nationwide could become more aware of their practices and perhaps work as a coalition with policymakers to come to terms on a mutually beneficial solution to the problem of Harmful Algae Blooms.

Summary

Harmful Algae Blooms (HABs) are a massive and increasing problem worldwide as they harm human health, wreak havoc upon delicate aquatic ecosystems, and cause massive damages to coastal, water-reliant industries. HABs largely occur because of an unnatural increase of two nutrients called Nitrate and Phosphate in a body of water (also known as Nutrient pollution). The major source of nutrient pollution is runoff from improperly fertilized agricultural settings such as farms and feedlots. This study sought to create a learning tool for farmers to help them understand how their fertilization practices are leading to HABs as well as what they could do to improve and limit nutrient discharge.

1 Introduction

Harmful Algae Blooms (HABs) occur when there is excessive growth of algae in a body of water. Algae is an informal, umbrella term for a wide-variety of aquatic organisms that contain chlorophyll and are capable of photosynthesis [1, 2]. Algal species can range from being single, microscopic organisms to large, thick seaweed like mats. Algae can be found worldwide in both fresh and salt water bodies and they are very resistant to temperature/pH changes [3]. Contrary to popular belief, algae are a very beneficial organism in controlled amounts as they are primary producers in aquatic ecosystems. Additionally, they are responsible for producing nearly half of the oxygen in our global ecosystem [2]. However, in excessive amounts, Algae do more harm than good as they harm human health, wreak havoc upon delicate aquatic ecosystems, and cause massive damages to coastal, water-reliant industries.

1.1 The Effect of HABs on Human Health

Certain species of Algae, such as Cyanobacteria, release toxins into the water that they inhabit which are deadly to both animals and humans. Domoic Acid and Microcystin are two toxins released by Cyanobacteria and these toxins have been found to be responsible for gastrointestinal illness, liver damage, Amnesiac shellfish poisoning, seizures, and short-term memory loss [4]. Consumption of fish from waters contaminated with HABs are primarily how humans ingest these toxins. However in certain cases, reservoirs and water bodies that have HABs and are used for drinking water often have above advisory levels of toxins [5]. Dogs and other pets post - ingestion of HAB contaminated water often deal with neurotoxin anatoxin-a poisoning which causes muscle tremors, respiratory diseases, and in severe cases, death [4]. Recently, it was also found that Cyanobacteria also produces BMAA, a neurotoxin responsible for ALS disease, Parkinson's disease, and Alzheimer's. These aforementioned diseases were even found to be prevalent in areas surrounding HABs [6, 7].

1.2 The Effect of HABs on Aquatic Ecosystems

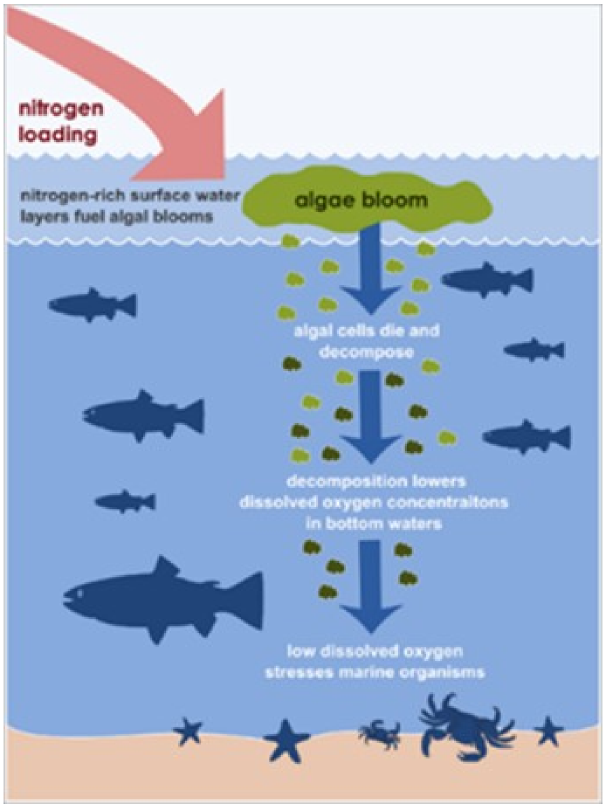

Figure 1: HABs cause Hypoxia. The death and sinking of algae during a harmful algae bloom leading to Hypoxic dead zones where no life can survive.

As algae dies and decomposes, it consumes dissolved oxygen that otherwise would have been used by aquatic wildlife. Most bodies of water can sustain this ecological process when there is a limited algae population but with excessive algae blooms, too much dissolved oxygen is consumed by the algae which results in the creation of hypoxic “dead zones”, where life cannot be sustained due to a lack of oxygen, as shown in figure 4 [8]. Immobile aquatic wildlife such as bottom plant life die from hypoxia, which has a ripple effect on the food web present in the body of water. Predators of algae ingest the aforementioned toxins when they consume the algae and as other fish and birds consume the algae-predators, the toxins “travel up the food chain”. Exposure of aquatic wildlife to toxins produced by HABs can disrupt their reproductive and behavioral processes [1]. Aside from toxins, the physical presence of algae also proves fatal to aquatic wildlife. Algae filament due to its microscopic size and large availability, can clog the gills of fish and smaller wildlife which ultimately leads to their death. Furthermore, algae presence on surface water prevents “sunlight” penetration which has a direct negative effect on bottom plant life [2] .

1.3 The Effect of HABs on Water-Reliant Industries

HABs also have negative impacts on coastal and water-reliant industries as they close beaches, worsen catches from fisheries, and ward away potential tourists. Ingestion of toxins by aquatic wildlife along with increased pressure from “heavy fishing” has drastically impacted desired-fish population. This alongside government bans on consumption of certain fish caught from HAB infested waters has put immense strains on the fishing industry. Due to the foul odors and murky waters near HABs, fewer tourists are visiting lakes and other water bodies. Potential threat to human health from HAB toxins has rendered numerous water bodies unsuitable for recreational use. From the years 1987 to 2000, it is estimated that HABs cost 82 million dollars in losses annually to US fishing and tourism industry [9]. This figure has not taken into account depreciation of property. Due to increasing frequency and severity of HABs, economic losses will continue to rise.

1.4 The Causes of HABs

HABs largely occur because of an unnatural increase of Nitrate and Phosphate in a body of water (also known as Nutrient pollution), warm water temperatures, and weak water currents. Nitrate and Phosphate are two essential nutrients that all living organisms need for growth and reproduction. They can be found in human/animal feces and are a large component of most fertilizers [10] .Population growth has placed greater demands on the agricultural industry which has caused for an increase in fertilizer use amongst farmers. In the past five decades, global use of Nitrate based fertilizer has increased 20 folds and the global use of Phosphate based fertilizer has increased 4 folds [**?**]. The "Industrialization of Agriculture" has also seen the development of Concentrated Animal Feed Operation (CAFOs) which cause for massive amounts of manure being produced in a relatively small area. Application of fertilizer on fields and animal waste from CAFOs results in nutrient discharge, which is the downhill flow of excess nutrients due to rainfall. Since major sources of nutrient pollution are non-point, such as farms, they are harder to regulate and control. The presence of these excess nutrients in a body of water "overfeeds" the algae in the body of water and causes for HABs [1].

In the long-term, this study seeks to develop a user-friendly learning tool for farmers to help them understand how their fertilization practices are leading to HABs. In this phase of the study, the objectives were to devise the foundational mathematical model which will serve as the basis for the learning tool and conduct a thorough analysis of the HAB problem in Lake Erie as a case study, through the means of literature review and stakeholder interviews. The tool will ask farmers for input parameters about their practices/farm and will output parameters that quantify the severity of an HAB that could occur as a result of their practices. Additionally, this tool will also mediate stakeholder negotiations as farmers could view the benefits and losses of implementing nutrient runoff limiting practices.

2 Development of Mathematical Model

This mathematical model was created to translate farmer input regarding farm and fertilizer application data into a simulated nutrient discharge and then further translate that into a quantitative measure of HAB severity and to present farmers with a cost/effective trade off about implementing buffer strips. The rationale behind the former objective is the assumption that farmers are good Samaritans and want to take measures to reduce their environmental impact. This assumption is supported by the findings of a 2013 survey of approximately 700 farmers in the Lake Erie watershed which state that most farmers recognize nutrient discharge as a serious problem and are willing to take at least one new action on their farm to reduce it. The latter objective is to present farmers with the possible solution of implementing buffer strips for reducing nutrient discharge and the costs/benefits associated with it. Buffer strips are patches of vegetation such as grasses and shrubs that grown downstream of agricultural land and serve the purpose of filtering nutrients from runoff. They are widely regarded as one of the best practices for reducing contaminant transportation from surface runoff [11].

Significant consideration with regards to user-friendliness and accuracy was put into the design of the model. Nutrient discharge from a farm is dependant on numerous factors like soil quality, percolation, rainfall, slope gradient, and fertilizer application. Even within a watershed or county, these factors largely vary from one farm to the next . Therefore, creating a model with lots of set constants for a large territory would diminish the utility of the model because its output would be largely inaccurate. However, given that the tool is meant for traditionally, non-tech savvy farmers, asking them to input a plethora of variables might be counter-intuitive and deter them from utilizing this tool. Thus to maintain accuracy of output as well as user-friendliness, this mathematical model combined various aspects of numerous, industry-wide accepted, and peer-reviewed models with the primary source being SWAT: Soil and Water Assessment Tool. This model is comprised of five stages: fertilizer application, rainfall event, nutrient polluted runoff, vegetative buffer strip filtration, and harmful algae bloom.

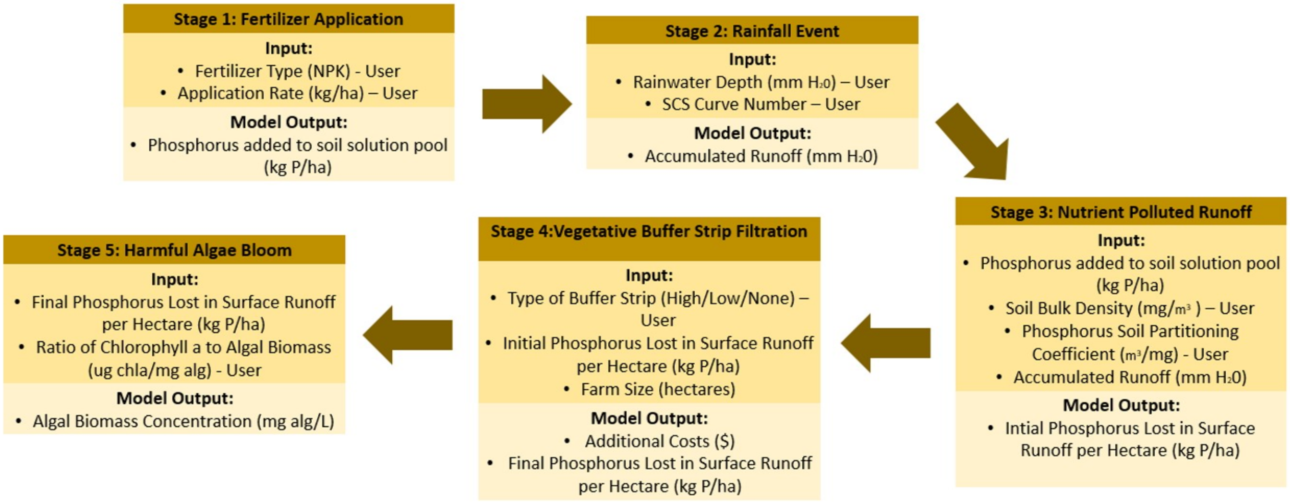

Figure 2: of the AgriSim Phase 1 Model. As shown in the figure, AgriSim Phase 1 Model is comprised of 5 sections with an end output of Algal Biomass Concentration.

2.1 Stage 1: Fertilizer Application

For the purposes of this model, it was assumed that Phosphorus is the limiting nutrient for algal growth in most bodies of water. It was also assumed that any nutrients introduced into the system are a result of fertilizer application, not pre-existing fertilizer. Therefore, only the movement of nutrients introduced via fertilization is tracked from soil to runoff to algae bloom. In this stage of the model, users input what fertilizer they wish to apply from SWAT's fertilizer database based on their desired NPK (Nitrogen/Phosphorus/Potassium) content. Additionally, users also have to enter the fraction of mineral P that corresponds to their selected fertilizer, which also can be found in the SWAT fertilizer database. Afterwards, users enter their fertilization application rate in kilograms per hectare (kg/ha). The default fertilizer is 15-15-15 (balanced NPK fertilizer) with an application rate of 155 kg/ha, the average rate in 20ll in the United States. Using the following equation:

$$\text{Phosphorus Added} = \text{Fraction of Mineral Phosphorus} \times \text{Application Rate}, [12]$$

the amount of phosphorus added to the solution pool of the soil is calculated. It is assumed that only Phosphorus from the solution pool can get carried away in runoff and that only soluble Phosphorus can be utilized by algae for growth.

2.2 Stage 2: Rainfall Event

Following fertilizer application, users simulate a rainfall event by entering the depth of rainfall for a day, in mm. Additionally, users also enter the SCS Curve Number, or CN, for their soil. The inclusion of the CN in the model takes into account land use, soil permeability, and other runoff related factors such as slope and vegetation grown. To certain extents, the CN can be considered a measure of runoff potential. Having soil quality and distinct farm geographical features being defined by a single input contributes to the user-friendliness of this model. The default values for rainfall depth is 10mm and for CN, it is 82, the value for a group D, row crop used, good hydrological land. Using the following equations:

$$\text{Retention Parameter} = 25.4\left(\frac{1000}{\text{CN}} - 10\right) [12]$$

and

$$\text{Accumulated Runoff} = \frac{(\text{Rain Depth} - 0.2 \times \text{Retention Parameter})^2}{(\text{Rain Depth} + 0.8 \times \text{Retention Parameter})}, [12]$$

the depth of the Accumulated Runoff was calculated.

2.3 Stage 3: Nutrient Polluted Runoff

Once the accumulated runoff has been calculated, the nutrient content of the runoff is calculated using the nutrients introduced to the system in stage 1 as well as other parameters input by the user. Again, it is assumed that Phosphorus is the limiting factor for algae growth thus, this model only computes the Phosphorus content of the runoff. The user inputs the Soil Bulk Density in mg/m^3 ,which can be considered a measure of how compact the top layer of the soil is, and the Phosphorus soil partitioning coefficient in m^3/mg. The default value for soil bulk density is 1.08 and was calculated by computing the mean of the soil density values reported in the SWAT database. The default value for the Phosphorus soil partitioning coefficient is 200, the default value used by the makers of SWAT. Using the following equation:

$$\text{Phosphorus Lost in Runoff}_{\text{initial}} = \frac{\text{Phosphorus Added} \times \text{Accumulated Runoff}}{\text{Bulk Density} \times \text{Phosphorus Soil Partitioning Coefficient} \times 10}, [12]$$

the Phosphorus lost in the runoff per hectare is calculated.

2.4 Stage 4: Vegetative Buffer Strip Filtration

This stage serves to demonstrate the benefits and losses of implementing vegetative buffer strips. There are three varying levels of buffer strip implementation and the following equations can be used to calculate the effectiveness and additional costs associated with each buffer strip once the user inputs the size of their farm, in hectares:

For no vegetative buffer strip:

$$\text{Additional Costs} = 0[13]$$

$$\text{Phosphorus Lost in Runoff}_{\text{final}} = \text{Phosphorus Lost in Runoff}_{\text{initial}}.[13]$$

For low vegetative buffer strip:

$$\text{Additional Costs} = 6.75 \times \text{Farm Size} \times 2.471 + 0.77 \times 0.3 \times \text{Phosphorus Lost in Runoff}_{\text{initial}} \times \text{Farm Size}[13]$$

$$\text{Phosphorus Lost in Runoff}_{\text{final}} = 0.7 \times \text{Phosphorus Lost in Runoff}_{\text{initial}}.[13]$$

For high vegetative buffer strip:

$$\text{Additional Costs} = 6.75 \times \text{Farm Size} \times 2.471 + 0.45 \times 0.5 \times \text{Phosphorus Lost in Runoff}_{\text{initial}} \times \text{Farm Size}[13]$$

$$\text{Phosphorus Lost in Runoff}_{\text{final}} = 0.5 \times \text{Phosphorus Lost in Runoff}_{\text{initial}}.[13]$$

2.5 Stage 5: Harmful Algae Bloom

Given the Phosphorus lost in the runoff per hectare as calculated in Stage 4, this model will calculate the algal biomass (in mg/L) that could result if this runoff were to enter a lake with 1 cubic kilometer of volume. First, the total kg of Phosphorus entering the lake was calculated in kg by multiplying the phosphorus lost in the runoff per hectare by the size of the farm in hectares. Afterwards, the total kg of phosphorus in the 1 cubic kilometer lake was converted to mg/L using the following equation.

$$\text{Phosphorus Concentration in Lake} = \text{Farm Size} \times \text{Phosphorus Lost in Runoff}_{\text{final}} \times 0.000001$$

Next, the Phosphorus concentration was correlated to concentrations of Chlorophyll a using the following equation:

$$\text{Chlorophyll A Concentration} = 0.551 * \text{Phosphorus Concentration in Lake}^{0.76}.$$

Lastly, the user will be asked to input the ratio of Chlorophyll a to Algal Biomass. The default value is 50, as recommended by the SWAT 2009 model. Using the following equation:

$$\text{Algal Biomass Concentration} = \frac{\text{Chlorophyll A Concentration}}{\text{Algal Ratio}},$$

the algal biomass concentration in a body of water (mg/L) receiving the runoff can be calculated.

3 Problem Analysis

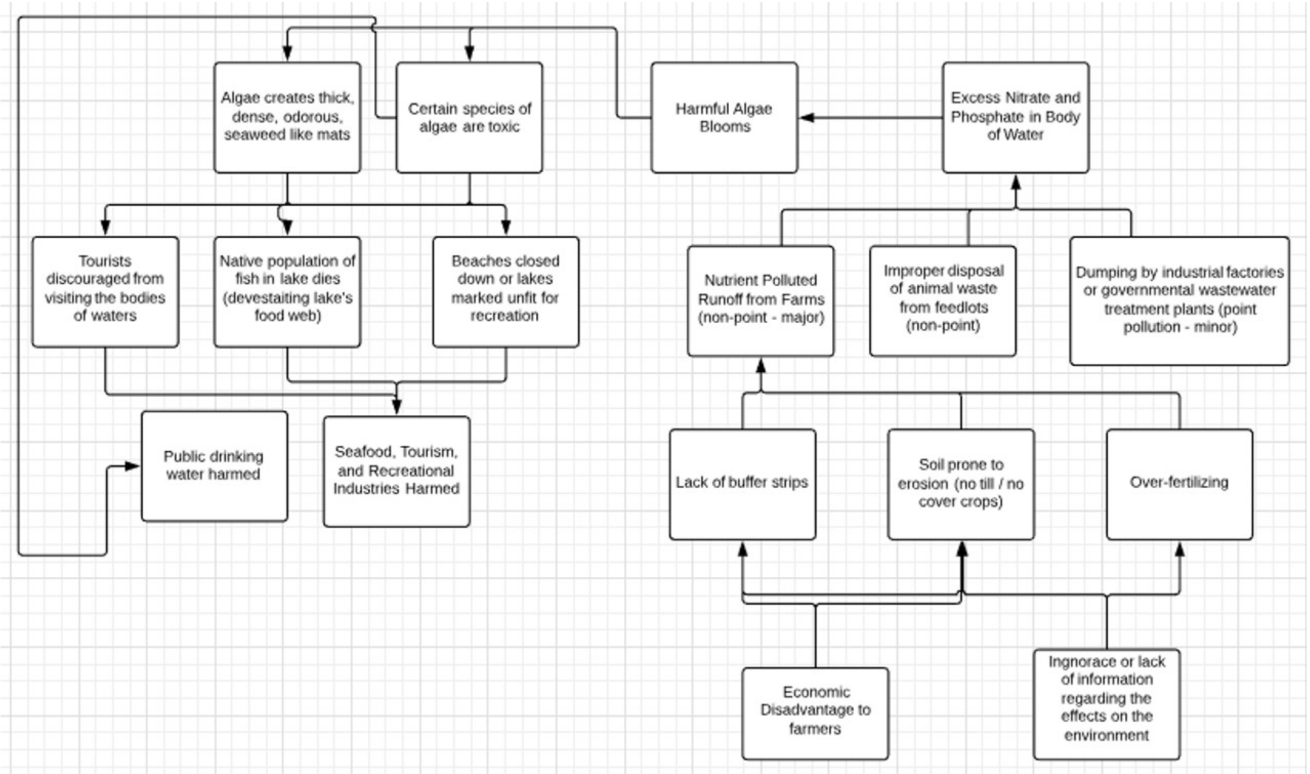

Figure 3: **Block Process Diagram of the HAB in Lake Erie.** This diagram demonstrates the causes and effects of the HAB in Lake Erie from the perspective of government officials and researchers in the Lake Erie region.

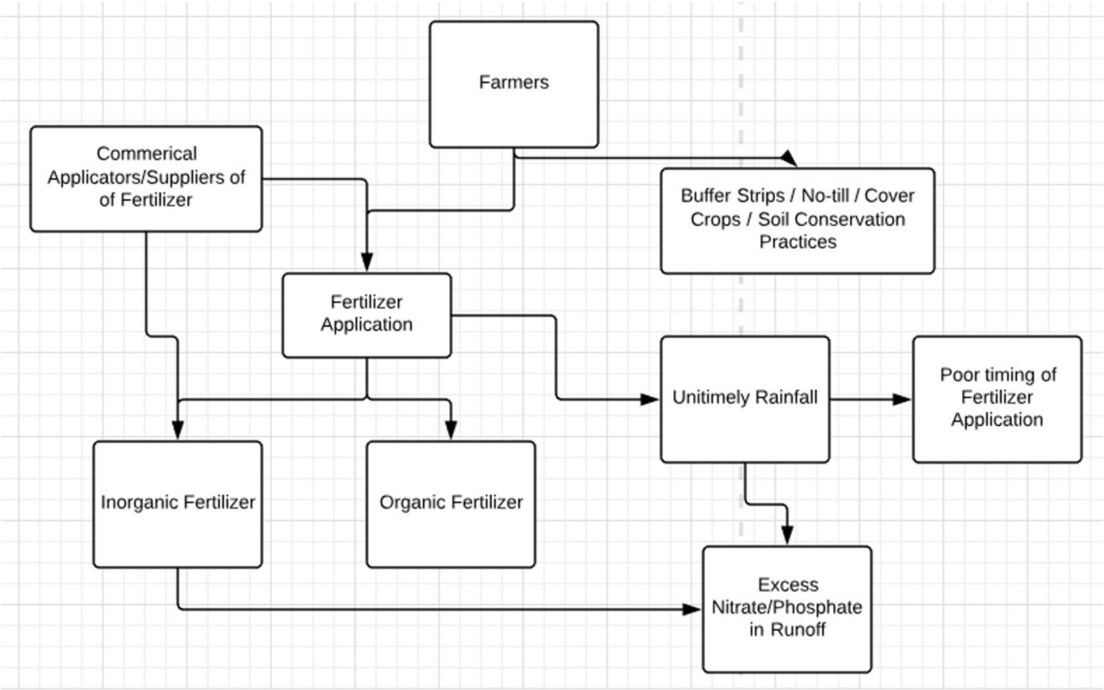

Figure 4: **Block Process Diagram of Excessive Nitrate/Phosphate in Agricultural Runoff** This diagram demonstrates the causes of excess Nitrate/Phosphate in agriculutral runoff from the perspective of farmers in the Lake Erie region. Note the differences in causes between Figure 3 and 4.

Results from an analysis of literature regarding the causes and effects of the Harmful Algae Bloom in Lake Erie are summarized in Figures 3 and 4. In addition to the review of literature, interviews were also conducted by the author with stakeholders in the Lake Erie region to develop a more comprehensive understanding of the problem. It is commonly believed that the Harmful Algae Bloom in Lake Erie can be attributed to fertilization practices by farmers in the Lake Erie - Maumee River Watershed. Given that farmers are key stakeholders in this problem, this study sought to obtain their perspective prior to modeling work was done. In an interview conducted by the author with Mr. Aaron Heileyrs, who is in-charge of Northwestern Ohio's demonstration farm program and a farmer himself, it was expressed by Mr. Heileyrs that the recent HABs in Lake Erie were not the fault of farmers, but rather the weather. Ohio has been experiencing heavier rainfalls in the past decade and most of the nutrient discharge from farms occurs during these periods of rainfall. In a second interview conducted by the author with Mark Badertscher, agriculture and natural resources educator at Ohio State University, it was expressed that the problem may not be the amount of fertilizer applied but rather when the fertilizer was applied. Most farmers apply fertilizer outside the main growing season in the fall for the next growing season because that is simply when they have the time to do so. Larger farming operations can afford to hire contractors to apply fertilizer simultaneously while the farmer does other work during the main growing season however most small farming operations do not have that luxury. Applying fertilizer in the fall creates more opportunity for fertilizers to runoff the land during rainfall events.

4 Policy Recommendations

Harmful Algae Blooms are caused by excessive Phosphorus in bodies of water and the largest source of Phosphorus is non-point sources such as farms and feedlots. After having spoken to both farmers and government officials, there seems to be a realization of a problem but debate over what is the best way to approach the problem. Government officials feel that farmers must alter their lifestyle whereas farmers feel that the weather is to blame. Possible solutions to this problem from a governmental perspective include investing funds towards educating farmers, requiring water-conservation practices such as filter strips, and subsidizing cover crops to encourage farmers to grow them.

Numerous states like Ohio have partnered with local universities to hold county wide educational sessions for farmers. Ohio has also made it required for its farmers to undergo a state training to get certified for fertilizer use on their farmer. Although they're not enforcing farmers to alter their fertilization practices, by educating farmers about the outcomes of their actions, they're making them more aware. This program has only been implemented for a couple of years and more time will be needed to determine its effective.

An alternative to reducing fertilizer application is to install vegetative buffer strips which act as natural Phosphate/Nitrate filters. The buffer strips are comprised of vegetation such as shrubs, grasses, and trees. They are ideally placed in downhill sections of farms and usually as water runs off the farms, it goes through the buffer strip and a lot of sediment, which often has attached Nitrogen or Phosphorus, gets trapped. Buffer strips are more effective as they get longer however as their length increases, so does their cost. Buffer strips when planted on farms take up farmland that otherwise could have been used to grow cost-positive crops. This loss of income opportunity discourages most farmers from effectively implementing them however. States could simply set a requirement for buffer strips across most farms and they would likely see significant decreases in the frequency of Harmful Algae Blooms. Minnesota for example has required for 50 feet long buffer strips around all of its lakes that are near an agricultural setting.

Cover crops are non main crops (i.e. corn, soy, etc.) that are grown in the off-season. The planting of these crops improves the nutrient retention of the soil and makes it less likely to lose nutrients during erosion. The planting of these crops also reduces the need for fertilizer application next year. Farmers don't like doing this because these cover crops are labor intensive and their cost per yield does not justify the effort. Certain states like Maryland have subsidized these cover crops and actually pay their farmers to grow. These incentives have caused for the Chesapeake bay, which has historically suffered with Harmful Algae Blooms, to experience significantly better water quality levels. Given that Maryland's agriculture economy does not bring in as many tax dollars as some the largest HAB causing states, it would definitely be a viable option for these states.

5 Future Study

Future models will take into account pre-existing sources of nutrients in soil such as past fertilizer applications and natural soil nutrient content. In order to remain accurate and useful over multiple uses, future models will have data storage capabilities to keep track of nutrient introduction via fertilization application with every use of the model. To be more user-friendly, future models could autonomously access a SWAT database and input the corresponding faction of mineral P for the user's selected fertilizer input. More and more farming counties nationwide are investing creating GIS maps of the farms in their counties and for further accuracy while not sacrificing user-friendliness, future models could harvest data directly from GIS maps and not just have to rely on CN numbers. To get more accurate results for the correlation of total phosphorus to algal biomass, future models could take into account more details about the body of water receiving the runoff such as its pre-existing phosphorus content and its volume. Additionally, further variables could be considered to determine the algal bloom size such as nitrate content, pH, and salinity.

Future versions of the model will also be representationally graphic. Visuals on the screen will change in response to input/output parameters. A higher output for algal biomass concentration will result in a lake with larger portions of it covered green. A higher input for fertilization application rate and type could result in a field with more greenery. A higher input for rainfall depth could result in a thicker blue film forming on the field on the screen. These graphics will be made using processing and ideally, the model could be developed into a website/mobile-application interface.

6 Conclusion

In the long-term, this study seeks to develop a user-friendly learning tool for farmers to help them understand how their fertilization practices are leading to HABs. In this phase of the study, the goals were to devise the foundational mathematical model which will serve as the basis for the learning tool and to conduct a thorough analysis of the HAB problem in Lake Erie as a case study, through the means of literature review and stakeholder interviews. The devised mathematical model combined various peer-reviewed models (primary reference was SWAT: Soil and Water Assessment Tool) and is comprised of five stages: fertilizer application, rainfall event, nutrient polluted runoff, vegetative buffer strip filtration, and harmful algae bloom. Users of the model can input data about their fertilizer application rate and fertilizer type in the first stage and the model will output the Phosphorus added to soil solution pool in kg/ha. In the second stage, users enter their SCS curve number thus, accounting for the geographical uniqueness of their farm, and simulate a rainfall event by entering a rainfall depth. The model outputs the depth of runoff that would accumulate given the farm's distinct geography. In the third stage, users input specific coefficients unique to their soil quality and using this along with the outputs from previous stages, the model outputs the initial phosphorus lost in surface runoff per hectare. In stage 4, users select between three types of buffer strips (high/low/none) and the model outputs the additional costs associated with selected buffer strip and reductions, if any, in the phosphorus lost in surface runoff per hectare. Lastly, in the fifth stage, users input the ratio of chlorophyll a to algal biomass and using previous outputs, the model outputs the algal biomass concentration that would occur in a lake with 1 cubic kilometer of volume if the output runoff were to enter it.

The devised model asked farmers for input parameters about their practices/farm and outputted parameters that quantify the severity of an HAB that could occur as a result of their practices. Upon further development of this mathematical model and eventual incorporation into a mobile application, this tool has wide applications and implications. Farmers nationwide could become aware of their practices and perhaps work as a coalition with policymakers to come to terms on a mutually beneficial solution to the problem of Harmful Algae Blooms.

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