Costs and Benefits of Nitrogen and Phosphate Fertilizer Use In the Lake Erie Basin

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Abstract

This paper explores both the positive and negative externalities associated with nitrogen and phosphate-based fertilizer use. Using 57 scholarly journal articles, government reports, manuscripts, and news articles; a comprehensive review was made on the effects fertilizer use and eutrophication has on ecological, environmental, human health, and economic systems in the western Lake Erie Basin. Negative externalities associated with fertilizer use included species population decline; environmental degradation; increased risks on public health; increased water treatment and maintenance spending; decreased tourism and recreation spending; decreased real estate value; and decreased aquaculture yields. Positive externalities associated with fertilizer use included increased crop yields; decreased food prices; and increased food security. The paper qualitatively examines total costs and benefits accrued on these systems, while making recommendations for further study and investigation in a quantitative manner.

Keywords: fertilizers, eutrophication, Lake Erie, externalities

1.0 Introduction

Over the course of the State of Ohio's history, entrepreneurs and farmers have developed a series of new techniques and tools in order to increase agricultural yields and overall food production. By building prosperous communities backed by the hard working ideals of resource extraction and industrial production, Ohio quickly became a haven for Americans and immigrants looking for opportunities westward. As agricultural production increased though, unintended consequences as a result of those new innovations became apparent.

Over the last few decades, algae growth in western Lake Erie has become a constant concern for various stakeholders invested in the environment, society, and economy. This paper will go through an analysis on the history, technology, and processes by which chemical fertilizers induce increased algal growth and therefore affect ecological, human health, and economic systems across western Lake Erie. In addition, the paper will review the benefits of using chemical fertilizers by farmers in Ohio's Lake Erie basin. By compiling research on the costs and benefits of chemical fertilizer use in the western Lake Erie basin, stakeholders will have access to a comprehensive review of externalities associated with agricultural production and eutrophication. In this paper, it was expected that costs incurred on species, the environment, human-health, and the economy are, on an aggregate basis, greater than the benefits gained out of using chemical fertilizers on Ohioan cropland.

The primary limit of this paper's approach and analysis is the qualitative nature of aggregating effects across the environmental, social, and economic spectrums. Additionally, surveys and other data capturing techniques were not used to produce the analysis. Instead, a literature review and compilation of 57 scholarly journal articles, government reports, manuscripts, and news articles were used to produce an overview of the costs and benefits associated with chemical fertilizer use. Recommendations for areas of future investigation were also made with respect to the surveyed research on this subject.

2.0 History

Shortly after the American Revolutionary War, Americans looking to expand their territory soon populated the area of what is today known as Ohio. As the 17th state in the union, Ohio, like many other Midwestern states, focused its economy on the production of raw materials and common-pool resources, which were both subtractable and non-excludable. These types of goods made it easy for Ohioans to establish local economies that were self-sustaining and efficient. A combination of abundant land, rich soil, and ample water resources made it possible for Ohio to become a hotbed of growth for the early American agricultural industry.

Farming provided the opportunity for Ohio's economy to develop rapidly over the course of the early-mid 19th century. By 1849, Ohio was the largest producer of corn and the second largest producer of wheat in the United States (Knepper, 2003). This also helped contribute towards the increase of Ohio's population, which increased from 42,159 in 1800 to 2,339,511 by 1860 (U.S. Department of Commerce, Census Bureau, 1970).

The diversification of Ohio's economy eventually began to occur after the end of the civil war. Early Ohioan factories were born out of the very agricultural industry that established the state's economy. Industrialized goods were produced in order to complement the existing agricultural economy. For example, iron-manufacturing plants along the shores of Lake Erie were able to create the steel needed for new farming equipment. Advances in agricultural technology also helped increase total crop yields, which helped incur greater profits for farmers. In addition to farmers, investors looking to expand their opportunities were provided with a wealth of both natural resources and human capital, which made newly industrializing cities, such as Toledo and Cleveland, attractive locations to settle in. The economic ecosystem of the region became a flourishing environment for a diverse set of players that had been backed by decades of a developing agricultural industry.

As Ohio became increasingly industrialized, however, the state relied on its agricultural industry less. While specific periods in the 20th century spurred growth for the industry, such as World War I and World War II, agriculture in Ohio had been declining. Despite this decline, farming in the state has remained an essential segment of Ohio's economy during the 20th and 21st centuries. Ohio's agricultural industries today represent over $90 billion USD of the state's total economic output and employ one in seven Ohioans either directly or indirectly (Myers, 2005).

In addition to being a core component of Ohio's economy, the state's geography is also significantly shaped by the agricultural industry. In 1997, approximately 13.6 million acres (52%) of Ohio's 26.4 million acres were agricultural, 7.1 million acres (27%) were forested, and 3.6 million acres (14%) were developed or urban areas (Ohio Legislative Service Commission, 1997). Today, approximately 30% of Lake Erie's surrounding land is cropland, which is significantly greater than any other Great Lake (Ohio Legislative Service Commission, 1997).

2.1 Technology & Innovation

America in the mid-1800s was a time of technological innovation and re-development for the agricultural industry. New farming equipment, such as the steel plough, were a major contributor to the economic success of the Midwest. However, it wasn't until the "Green Revolution", that occurred between 1930 and 1970, when agriculture started to become a truly technologically driven industry. During this period, farming technologies that had already existed in many industrialized countries were spread to developing countries, such as Mexico, India, Brazil, and the Philippines.

The one development that has possibly revolutionized the production of food and shifted its supply more than any other has been the continuous improvement of agricultural fertilizers and pesticides. While prioritization for the management of soil fertility had been in place for thousands of years before, the modern science of plant nutrition didn't develop until the 19th century. Malthusian theories of exponential global population growth concurrent with linear food production growth drove scientists to investigate the mechanics of agricultural production greatly, which included comprehensive study within the botanic sciences. Prominent scientists, such as the Dutch chemist, Justus von Liebig, were now performing research and development on an industry that had experienced little advancement since the Middle Ages.

Throughout the modern historic use of fertilizers and pesticides, there have been a series of discoveries that have made them more efficient to produce, less costly, and more effective. This has caused the use of agricultural supplements to increase greatly over time. Today they're commonly used throughout the majority of North American farms. According to the United States Department of Agriculture (USDA), 78% of corn acreage in the United States received phosphate fertilizer in 2010, compared to 90% in Ohio (National Agricultural Statistics Service, 2010). In the same survey, it was found that 97% of corn acreage in the United States received nitrogen fertilizer in 2010, compared to 100% in Ohio. The widespread use of new farming technologies in Ohio, such as chemical fertilizers, has a deep-rooted history and tradition that dates back over centuries.

3.0 Soils & Eutrophication

Northern Ohio's soil was formed largely by glaciers and weathering of sedimentary rock (Ohio Department of Natural Resources, 2007). Western Ohio soil also exhibits greater levels of lime, which increases soil pH. This allows soils in western Ohio to generally be more productive and fertile for crops, due to increasing natural acidity to soils over time. Soils along Ohio's northwestern corridor were formed in lake and beach sediments and in glacial till associated with glacial lakes. Because of this, soil horizons in the region typically exhibit high levels of silt and sand within the topsoil. Further west, agricultural land in northern Ohio is characterized by near-level crop fields that contain both drainage ditches and subsurface drains. To the east, soils contain greater clay materials, which provide both coarser textured and steeper soil horizons.

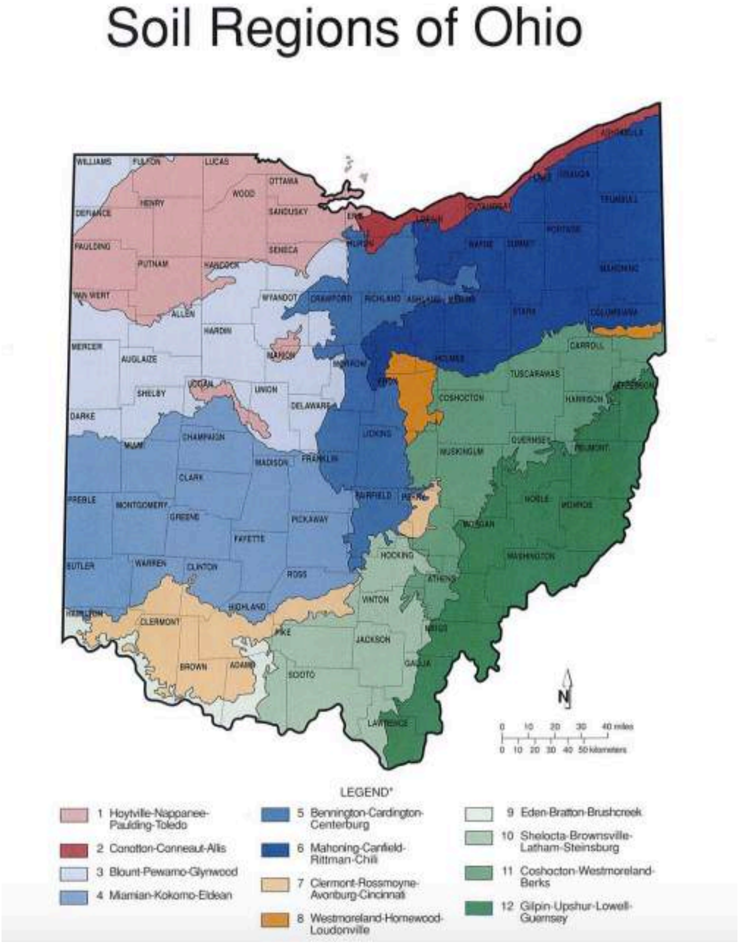


Figure 1 Soil Regions of Ohio (Ohio Department of Natural Resources, 2007)

Due to northern Ohio’s high level of sand and silt in its soil, the region is highly prone to experiencing drainage issues and eutrophication. The Natural Resources Conservation Service (NCRS) of the USDA defines eutrophication as, “(1) the degradation of water quality due to enrichment by nutrients, primarily Nitrogen (N) and Phosphorus (P), which results in excessive plant (principally algae) growth and decay. When levels of N:P are about 7:1, algae will thrive. Low Dissolved Oxygen (DO) in the water is a common consequence. (2) The process of enrichment of water bodies by nutrients.” (Natural Resources Conservation Service, 2011).

While the use of chemical fertilizers can provide immediate adequate nutrition to crops, they are also highly susceptible to leaching through sand and silt based soils, particularly those in northwestern Ohio. Furthermore, 63% of soils further west experience seasonally high water tables that are less than a foot below the surface (Ohio Department of Natural Resources, 2007). A high water table provides easy transportation for leached chemical fertilizers to flow through these water channels, and eventually into western Lake Erie.

Added chemical fertilizers from crop fields that are leached into local water systems eventually end up in the Lake Erie Basin, which consists of watersheds surrounding the lake. While 80% of Lake Erie's water is captured via the Detroit River, 9% is derived from these watersheds (New York State Department of Environmental Conservation, 2005).

4.0 Algal Blooms

Through rain and irrigation-caused leaching, agricultural fertilizers containing phosphorus and nitrogen provide water systems with an influx of nutrients. These nutrients help spur the rapid growth and multiplication of aquatic vegetation and algae. Western Lake Erie, in particular, experiences the rapid growth of cyanobacteria, which produce harmful toxins known as microcystins.

Microcystins are a class of toxins that are commonly produced by certain freshwater cyanobacteria. With over 60 microcystin toxins known, they pose major threats to ecosystems as well as drinking and irrigation water supplies (Ramsy et al., 2013). Previous research has validated the positive correlation between phosphorus loading and microcystin concentrations in western Lake Erie (Rinta-Kanto, 2009).

4.1 Microcystin Structures

As cyclic peptides, microcystin structures consist of a seven-membered peptide ring that is made up of five non-protein amino acids and two protein amino acids (Schneegurt, 2000). When cyanobacterial cells die, their cell walls burst, releasing the toxins into the water.

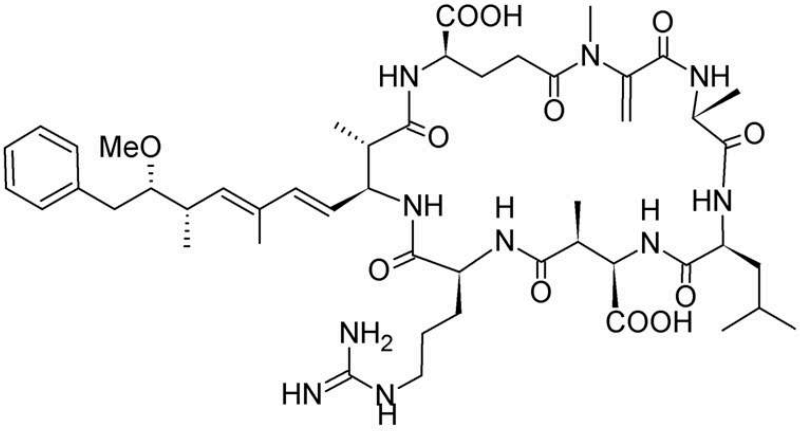


Figure 2 Microcystin Chemical Structure

4.2 Microcystin Remediation

Microcystin structures are exceedingly resistant to chemical breakdown, such as hydrolysis or oxidation. In addition, microcystin toxins are nonvolatile, hydrophilic, resistant to photodegradation, and are stable over a wide temperature and pH range. The structures are therefore extremely stable under most natural conditions. This makes remediation efforts to rid waters from contaminated microcystin toxins difficult and costly. Furthermore, due to the delicate nature of deceased algal cells that are prone to rupturing and contain microcystin, cleanups are usually extremely time intensive (International Organization for Standardization, 2005). The efficacy of drinking water filters to remove microcystin toxins varies significantly by filter type. A study in 2006 found that carbon filters allowed only 0.05-0.3% of the toxin load to pass through, while pleated paper and string based filters allowed more than 90% of the toxin load through (Pawlowicz et al., 2006).

Microcystin-producing cyanobacteria thrive in waters with warmer climate conditions. Because of this, harmful algal blooms (HABs) in western Lake Erie occur more commonly during hot summer months. With anthropogenic climate change, HAB occurrences are expected to increase along with rising temperatures in the northwestern Ohio region (Michalak et al., 2013).

5.0 Overview

With a combination of increased chemical fertilizer use and anthropogenic climate change, eutrophication will have an increasing impact on western Lake Erie's ecosystems, environment, and economies over the next few decades. In particular, algal blooms that produce microcystin toxins, as well as hypoxic water, degrade both ecosystem health and public health. These effects raise significant concerns for key stakeholders including citizens, policymakers, public health officials, and environmental advocates. The following sections of this paper will review those effects by analyzing the role HABs have on individual species; aquatic and terrestrial ecosystems; public health; as well as the economy and environment at-large. In addition to the effects eutrophication has on species, the environment, human health, and the economy; this paper will provide an overview of the benefits gained by using chemical fertilizers.

6.0 Ecological Effects

Large quantities of toxins produced by HABs affect the ecology of both marine and fresh water biomes. For example, 34 phytoplankton species are known causative agents in fish and shellfish mortality events along the U.S. west coast (Lewitus et al., 2012). This section will discuss the mechanisms by which organisms are directly and indirectly exposed to HAB toxins, as well as the impacts they incur as a result of increased algal growth.

6.1 Direct Exposure

Organisms are affected by HABs by way of either direct or indirect exposure. Direct exposure to microalgal cells and their toxins occurs through drinking or ingesting them through various consumption modes, such as filter feeding or predation. Smaller organisms such as zooplankton and shellfish often retain these toxins within their body cavities, and can present issues for bioaccumulation along the freshwater food chain. In calm, summer months, cyanobacteria forms a thick layer of surface scum that is dispersed over a significant portion of western Lake Erie. When wind and wave action is increased, however, this surface scum often concentrates closer towards shorelines. Wildlife and domestic animals that obtain their drinking water supplies from lake shorelines are therefore often directly exposed to large quantities of both algal cells and their toxins. Principal routes by which representative groups of organisms are directly exposed to harmful microalgal microcystin toxins includes the ingestion of cells by zooplankton, molluses, fish, birds, and terrestrial mammals (Landsberg, 2002).

In addition to obtaining direct exposure to microalgal microcystins through the ingestion of cells, organisms may also come into contact with extracellular microcystin toxins. These toxins have often been released from their cell membranes by way of either force or decomposition. If concentration levels are low with respect to water volume, then direct exposure to extracellular microcystin is unlikely. However, organisms that feed in the lake during the expiration of algal blooms are highly susceptible to coming into direct contact with extracellular microcystin. Furthermore, due to microcystin's highly stable amino acid structure, the toxins can persist in lake waters for months before being broken down by natural processes (Landsberg, 2002).

6.2 Indirect Exposure

Aside from direct exposure with HABs, organisms are also susceptible to indirect exposure with algae. When organisms consume other organisms that have previously been directly exposed to microcystin and other toxins, they transfer trophically through the food chain. Worse, toxicity concentration rates increase with each higher trophic level, due to bioaccumulation, bioconversion, and/or biomagnification. One of the most common cyanobacterium in western Lake Erie, *Microcystis aeruginosa*, is known to produce microcystin toxins that readily move through the food chain in this manner (Kotak et al., 1996).

6.3 Impacts from Toxins

Exposure of HAB toxins can lead to mass mortalities of aquatic organisms. Exposure to such toxins usually results in an immediate physiological, pathological, or behavioral change, depending on the species and concentration.

The following are examples of species that are affected by toxic cyanobacteria in freshwater lakes and reservoirs:

Molluscs:

- *Anabaena circinali*
    - Reduced overall feeding for *Alathyria condola*, species of mussel (Negri & Jones, 1995)

Zooplankton:

- *Anabaena affinis*
    - Reduced overall feeding for *Ceriodaphnia dubia*, species of water flea (Kirk & Gilbert, 1992)
    - Reduced fecundity for *Daphnia galeata*, species of planktonic crustacean (Gilbert, 1990)
    - Reduced fecundity for *Daphnia magna*, species of water flea (Gilbert, 1990)
    - Reduced fecundity and mortality for *Daphnia pulex*, species of water flea (Gilbert, 1990)
- *Anabaenan flos-aquae*
    - Feeding inhibition for *Daphnia hyalina*, species of planktonic crustacean (De Mott, et al., 1991)

  - Reduced feeding for *Daphnia parvula*, species of planktonic crustacaen (Fulton, 1988)
  - Reduced feeding for *Daphnia pulex*, species of planktonic crustacaen (Fulton, 1988)
  - Feeding inhibition for *Daphnia pulicaria*, species of planktonic crustacean (De Mott, et al., 1991)
  - Feeding avoidance for *Diaptomus reighardi*, species of copopod (Fulton, 1988)
  - Feeding avoidance for *Eurytemora affinis*, species of copopod (Fulton, 1988)
- *Anabaena minutissima* var. *attenuate*
  - Reduced feeding, survival, and inhibition of appendage beat rate for *Daphnia carinata*, species of planktonic crustacean (Peter & Lampert, 1989), (Forsyth et al., 1992)
- *Aphanizomenon flos-acquae*
  - Reduced feeding and fecundicity for *Acartia bifilosa*, species of copepod (Sellner et al., 1994)
  - Inhibition of appendage beat rate for *Daphnia carinata*, species of planktonic crustacean (Haney et al., 1995)
  - Feeding avoidance for *Diaptomus reighardi* (Fulton, 1988)
  - Reduced feeding, increased avoidance, and reduced fecundity (Fulton, 1988), (Sellner et al., 1994)
- *Microcystis aeruginosa*

  - Reduced feeding and fecundity for *Acartia bifilosa* (Sellner et al., 1994)
  - Reduced feeding for *Bosmina longirostris*, species of water flea (Fulton & Pearl, 1987), (Fulton & Paerl, 1989)
  - Reduced feeding for *Ceriodaphnia quadrangula*, species of planktonic crustacean (Fulton & Paerl, 1989)
  - Reduced feeding and mortality for *Daphnia ambigua*, species of planktonic crustacean (Fulton & Paerl, 1989)
  - Feeding inhibition for *Daphnia hyalina* (De Mott, et al., 1991)
  - Reduced growth and depressed clutch size for *Daphnia longispina*, species of planktonic crustacean (Stangenberg, 1968), (Reinikainan et al., 1994), (Hietala et al., 1995)
  - Feeding avoidance for *Daphnia magna* (Yasuno & Sugaya, 1991)
  - Mortality for *Daphnia parvula* (Fulton, 1988)
  - Reduced growth, depressed reproduction rate, and clutch size for *Daphnia pulex* (De Mott, et al., 1991), (Reinikainan et al., 1994) , (Hietala et al., 1995)
  - Feeding inhibition for *Daphnia pulicaria* (Lampert, 1981), (De Mott, et al., 1991)
  - Reduced feeding of *Diaptomus reighardi* (Fulton & Paerl, 1989)
  - Mortality for *Eucypris virens*, species of planktonic crustacean (Stangenberg, 1968)

    - Feeding avoidance and mortality for *Moina macrocopa*, species of water flea (Yasuno & Sugaya, 1991)
    - Mortality for *Moina micrura*, species of water flea (Fulton, 1988)
    - Reduced feeding for *Simocephalus serratulus*, species of crustacean (Fulton & Paerl, 1989)
- *Planktothrix agardhii*
    - Reduced growth and fecundity for *Daphnia pulicaria* (Infante & Abella, 1985)
    - Reduced growth and fecundity for *Daphnia thorata*, species of planktonic crustacean (Infante & Abella, 1985)

In addition to the aforementioned species harmed by algal toxins, fish, reptiles, and mammals such as birds, are often affected as well. However, animals that drink contaminated freshwater are by far the largest terrestrial group affected by HABs.

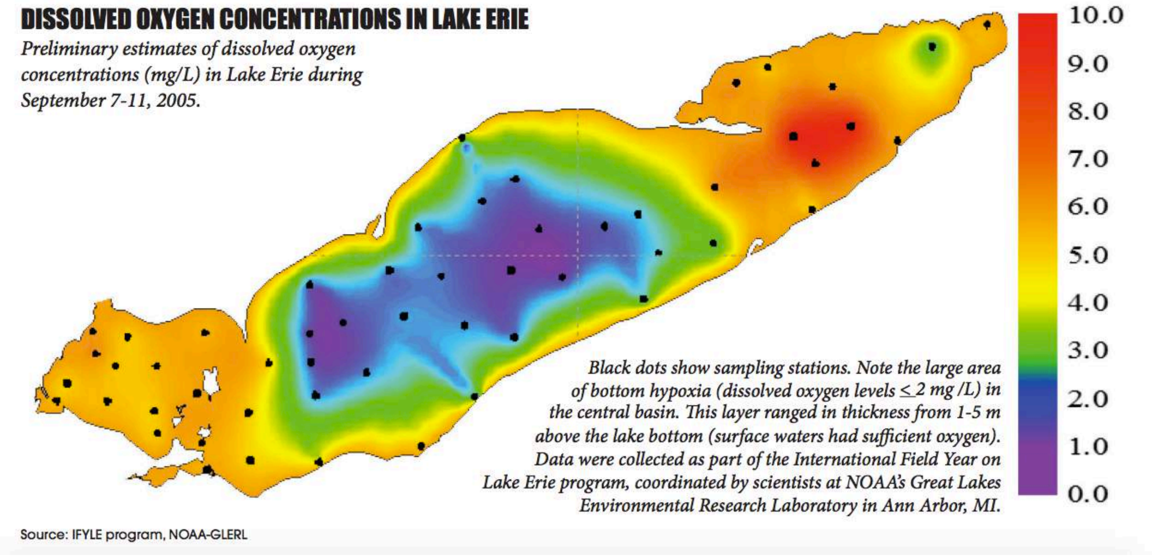
Overall effects of HABs on food webs and ecosystems are often difficult to study. This is particularly due to the complexity of such food chain systems. The set of long-term implications of released algal toxins currently requires further investigation.

6.4 Impacts from Hypoxia

In addition to HAB toxins, algal blooms also produce hypoxic (low-oxygen) water over time. This is due to bacterial decomposition of algae that has grown from added nutrients (phosphorus and nitrogen from chemical fertilizers). Due to bacterial respiration during this process, temperature differences between poorly oxygenated water and oxygenated-water helps stratify water columns to prevent mixing from occurring.

Hypoxic water zones typically do not kill fish populations by way of suffocation (Almeida, 2015). Instead, by decreasing the amount and quality of habitat available, fish become physically constrained to habitable zones that do provide adequate oxygen, light, and temperature levels. However, with other species inhabiting these environments already, fierce competition between species often occurs.

During mid-late summer, water stratification becomes more intense, which prevents fish from occupying the cooler, poorly oxygenated bottom waters, where benthic prey are abundant.



DISSOLVED OXYGEN CONCENTRATIONS IN LAKE ERIE

Preliminary estimates of dissolved oxygen concentrations (mg/L) in Lake Erie during September 7-11, 2005.

Black dots show sampling stations. Note the large area of bottom hypoxia (dissolved oxygen levels ≤ 2 mg /L) in the central basin. This layer ranged in thickness from 1-5 m above the lake bottom (surface waters had sufficient oxygen). Data were collected as part of the International Field Year on Lake Erie program, coordinated by scientists at NOAA's Great Lakes Environmental Research Laboratory in Ann Arbor, MI.

Source: IFYLE program, NOAA-GLERL

Figure 3 (Hawley et al., 2006)

Due to overall warmer temperatures year round, Lake Erie becomes more productive, and thereby allows the increase of amount of prey available and habitat suitability early in the year. However, these benefits don't cancel out the negative effects that occur during late summer.

Fish species that are most affected by hypoxic water zones in Lake Erie include the yellow perch (*Perca flavescens*), rainbow smelt (*Osmerus mordax*), emerald shiner (*Notropis atherinoides*), and the round goby (*Neogobius melanostomus*). These fish primarily feed on zooplankton and benthic organisms. Due to the decreased habitat availability during late summer months, zooplankton becomes the primary source of food for these fish during this time. However, the availability of zooplankton in warmer, upper waters becomes constrained over time. Furthermore, algal toxins directly affect many species of zooplankton, as cited previously. With decreased overall availability of zooplankton prey, significant populations of fish along the food chain become malnourished. These effects strongly increase the risk for mass death among aquatic species.

7.0 Human Health Effects

Huynh et al., 1998 notes that at the biochemical level, microalgal toxins are genotoxic and can affect DNA adducts (Huynh et al., 1998). At the cellular level, though, Huynh et al. also notes that toxins can be cytolytic, hemolytic, antieoplastic, or tumor inducing. At the organ level, toxins can be neurotoxic, dermatoxic, or hepatoxic. Neurotoxic paralytic shellfish toxins (PSTs) are also produced by the following cyanobacteria: *Anabaena circinalis*, *Aphanizomenon flos-aquae*, *Cylindrospermopsis raciborskii*, and *Lyngbya wollei*. PSTs present significant concerns for public health officials as well as drinking water treatment specialists. As extremely potent neurotoxins, PSTs are highly lethal. Symptoms of paralytic shellfish poisoning (PSP) include paresthesia and numbness, particularly around the face and neck.

Effects of microcystin on organisms can also be lethal when administered in high doses. In humans, symptoms of microcystin poisoning include diarrhea, vomiting, piloerection, weakness, and pallor (Bell & Codd, 1994). Microcystin toxins specifically target the liver and can cause significant cytoskeletal damage, necrosis, and pooling of blood, which can increase liver weight by up to 100% (Hooser et al., 1989). Microcystin disrupts the liver's cytoskeleton, which leads to loss of cell morphology, loss of adhesion from cell-to-cell, and cellular necrosis. At especially toxic doses, microcystin causes disorganization of tissue, which leads to massive hepatic hemorrhage, which can be lethal within a few hours after administering the dosage (Hoosner et al., 1989). In addition to liver damage, microcystins also promote tumor growth in humans by inhibiting the protein enzyme's phosphatase type 1 and 2A activities (Eriksson et al., 1990).

In February of 1996, a hemodialysis center in Caruaru, Brazil exposed 116 patients to acute levels of microcystin toxins via water supplied from a nearby-contaminated reservoir by cyanobacteria. Of the 100 patients who were affected, 52 died (Jochimsen et al., 1998). Although there have been reports of human deaths caused by inadvertent injection of microcystins, there have been no reports caused by the direct ingestion of such toxins (Butler et al., 2009).

7.1 Drinking Water Quality

Aside from the direct health risks cyanobacteria pose, toxins can also leave communities vulnerable to a variety of indirect consequences. One of the foremost concerns public officials have on HABs is in the area of drinking water quality and treatment. In August of 2014, approximately 500,000 residents of the Greater Toledo, Ohio region were advised not to drink water via tap and were recommended to use bottled water for showering, bathing, brushing teeth, and washing dishes. In addition to emergency warnings on drinking water supplies, microcystin toxins forced local restaurants, universities, and public libraries to close. The National Guard was also deployed in order to deliver cases of bottled water from Akron, Ohio, to residents who were especially vulnerable.

The EPA currently does not have standards and regulatory limits associated with cyanobacterial toxin concentrations provided for public water systems. However, many states have implemented guidelines that apply to cyanotoxins and cyanobacteria in drinking water. Many of these states utilize standards set forth by the World Health Organization (WHO) of the United Nations, which has a standard of 1 μg/L for microcystin-LR (Rao et al., 2002).

8.0 Economic Effects

HABs present biological systems with an array of challenges. Often, these stressors not only affect wild species, but also human society as well. Estimating the economic impacts HABs create is important for policymakers and environmental advocates to determine the level of effort that mitigation and remediation treatments should yield. However, it should be noted that estimating the social and environmental costs associated with HABs is difficult and values should be exercised with caution. Nevertheless, the provision of a comprehensive economic analysis can be highly valuable for agriculturally driven communities that are in the process of weighing the costs and benefits of using chemical fertilizers that contain phosphates and/or nitrogen.

8.1 Water Systems

In 2013, the city of Toledo, Ohio allocated $4 million USD for water treatment chemicals, which was doubled from what it spent in 2010 (Henry & Writer, 2015). In 2014, blooms around Maumee bay and areas of western Lake Erie were especially concentrated and thick, and prompted the city to deliver its drinking water emergency advisory. This resulted in total spending to increase to $4.7 million USD for water treatment chemicals (Henry, 2014). Monitoring tasks by municipal, state, and federal governments include the testing, treatment, and management of infrastructure and facilities that are designed to sustain large populations with a consistent supply of water. Monitoring programs that are designed to look for PSTs in particular, had an average annual monitoring and management cost that totaled $2.89 million USD in the United States in 2000 (adjusted for 2015) (Hoagland et al., 2002). However this figure only factored in 12 total states and did not account for HAB occurrences in any of the Great Lakes.

8.2 Tourism and Recreation

In addition to water treatment and monitoring costs, a number of industries along Ohio's Lake Erie coastline are directly affected by HABs. In 2013, *Tourism Economics* calculated that total sales from tourism were valued at $12.9 billion USD across the Ohio coastline (Winslow, 2015) [48]. The industry helps employ over 119,000 people and generates over $1.7 billion total in tax revenue for federal, state, and local governments. Increasing HAB occurrences primarily threaten the tourism industry by limiting land area recreational usage. However, the tourism industry in particular, may be the most significant industry affected by HABs. It was estimated in 1975 that economic damage to the tourist industry of a summer 1971 *Gymnodinium breve* red tide event amounted to over $93 million (Habas & Gilbert, 1975) (adjusted for 2015). Future research should estimate similar impacts to the tourism industry along Ohio's coastline.

8.3 Real Estate

HABs also can affect property values and the real estate industry along Ohio's shorelines. This is due to both decreased recreational and aesthetic values associated with algal bloom sights and smells. While several news reports reference property value losses as a result of algal blooms along western Lake Erie's shores, there is currently limited scholarly research in this area.

8.4 Fisheries

The commercial fishing industry is the most directly affected industry by HABs in western Lake Erie. The industry is especially important both socially and economically for both Ohio Buckeyes and Ontarians. Overall, the industry is worth approximately $50 million CDN and employs around 715 people (Hill, 2015). The fish processing industry in Lake Erie has an economic impact of approximately $194 million CDN and employs around 755 people. In total, the industry amasses over $244 million CDN and employs over 1,490 people either directly or indirectly.

Several news reports have suggested decreased earnings during algal blooms in western Lake Erie, although scholarly surveys are currently limited and should therefore be investigated. HAB events harbor the potential to shift the supply of fish inwards, which simultaneously increases cost and decreases quantity demanded. Both producer and consumer surpluses are therefore shrunk and total economic losses are incurred on society.

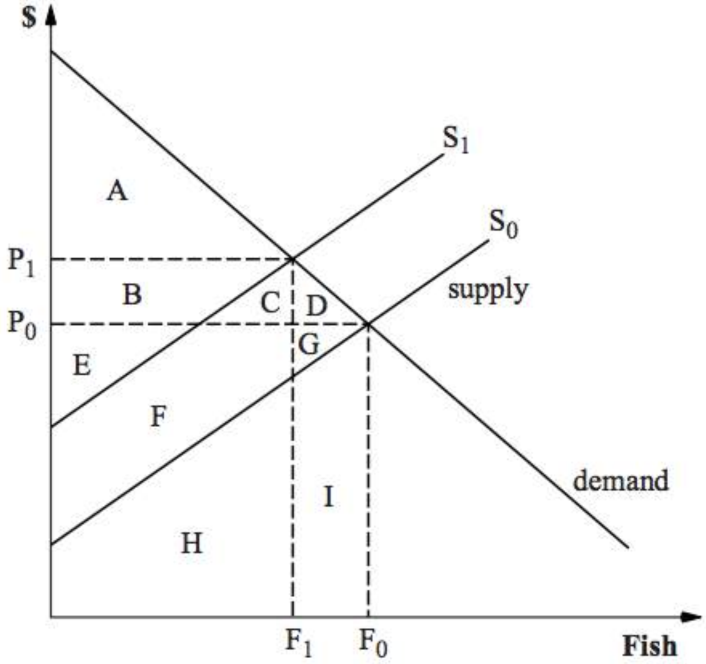


Figure 4 Economic Effects of Decreased Supply (Anderson et al., 2000)

8.5 Public Health

Lastly, human sickness and death from exposure to cyanotoxins in Lake Erie has the potential to significantly increase both the economic and social cost of HAB events. Costs of widespread medical treatment due to an algal outbreak in drinking water could pose significant economic concerns for communities. While relatively few cases have thus far been reported, the region's population of over one million residents raises the risk of such an outbreak to occur in the future. With expected increasing temperatures in the region due to anthropogenic climate change, these risks may be further elevated.

Overall, HABs pose a variety of costs and risks related to the health of Lake Erie's economy. Furthermore, due to the frequent recurrence of such events, annual costs are multiplied over the long run and threaten the existence of industries and communities reliant on the lake's resources. While few data are available to complete a comprehensive overview on the economic effects of eutrophication-induced HABs in Lake Erie, researchers have been able to build framework models that can quantitatively estimate overall impacts. A joint study commissioned by the Woods Hole Oceanographic Institution in September of 2000 estimated the average total annual economic impacts from HABs in the U.S. amounts to be over $67 million USD (adjusted for 2015), which included public health, commercial fishery, recreation/tourism, and monitoring/management costs (Anderson et al., 2000). Future research should develop a framework that estimates the total balance between both the benefits and costs incurred by using chemical fertilizers that contain phosphorus and nitrogen.

9.0 Benefits of Chemical Fertilizer Use

Fertilizers consist of a wide array of materials of either natural or synthetic origin that are used to supplement the growth of plants through their application to soils or plant tissues directly. In the context of this paper, fertilizers will reference only those materials that contain phosphates and nitrogen.

9.1 Nitrogen Fertilizers

Nitrogen fertilizers are most often derived from ammonia (NH_3). Ammonia itself is produced through the Haber-Bosch process ($N_2 + 3\ H_2 \rightarrow 2\ NH_3$), which is highly energy-intensive. In 2009, Sarah Simpson published in the sustainability section of *Scientific American*, “Nitrogen Fertilizer: Agricultural Breakthrough--And Environmental Bane” (Simpson, 2009). While the article gives a nod to Chemist Fritz Haber’s discovery of ammonia’s synthesis, which has enabled the widespread fertilization of croplands globally, Simpson notes that nitrogen-based “nutrients often spur harmful algal blooms as they flow into the ocean, and hundreds of estuaries around the world suffer from so-called seasonal dead zones as a result.” (Simpson, 2009). The article goes on to cite some of the more beneficial products nitrogen fertilizers have been able to yield, such as biofuels.

The total consumption of nitrogen fertilizers in the United States has increased significantly over the last 50 years. Increased consumption has largely been driven by scholarly research, which has shown a strongly significant and positive effect on total crop yields by increased inputs of nitrogen fertilizers (Lawlor et al., 2001), (Jagadamma et al., 2008). However, with the rise of environmental concerns with respect to nitrogen leaching and eutrophication, many scholars and practitioners have developed management techniques to maximize the use of nitrogen inputs, while limiting external effects on the environment.

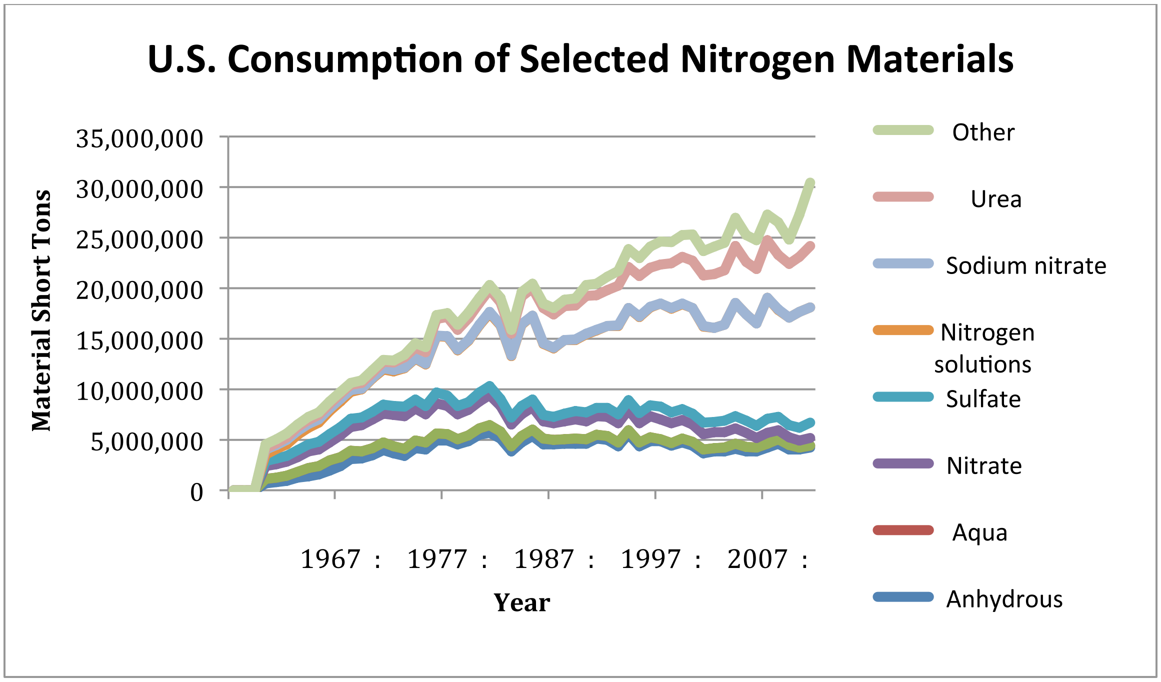


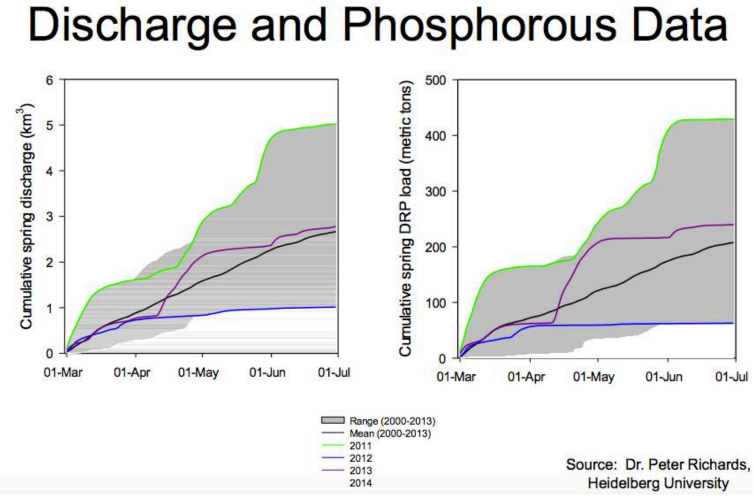
Figure 5 (Cordell, 2009)

A joint study by Texas A&M University and the Tennessee Valley Authority investigated the impact that chemical use reduction had on yields for eight major agricultural crops in the U.S (Smith et al., 1990). Overall, results showed that U.S. corn yields would decline by 41%, cotton by 37%, rice by 27%, barley by 19%, sorghum by 19%, and wheat by 16% when grown without any added nitrogen. Economically speaking, this would result in similar figures according to pricing of each respective crop. Lowered crop prices are important for the provision of local and regional food supplies, due to the variable elasticity of demand for food by food type.

In addition to decreasing prices associated with nitrogen use, there is also considerable evidence that nitrogen fertilizers have significantly helped support the supply for food globally, which is important for communities to support food security (Tilman et al., 2002). In total, evidence is clear that the benefits to society, by using nitrogen fertilizers for increased cropland yields, are high.

9.2 Phosphorus Fertilizers

The second main chemical that helps spur cyanobacterial growth through fertilizer eutrophication in western Lake Erie is phosphorus. Phosphate fertilizers are primarily extracted from minerals that contain the anion PO_4^{3-}. Like nitrogen fertilizers, phosphate fertilizers use has also increased over the last 50 years. Phosphorus is vital for plants to grow, as the chemical is used to transfer and store energy within their cells. An adequate supply of phosphate nutrients enables plants to grow rapidly and mature earlier than those plants without such a supply. Specifically, phosphorus is most abundant in plants in the early stages of tissue growth. Plants without an adequate supply of phosphorus become stunted and can turn shades of purple or brown.



Source: Dr. Peter Richards, Heidelberg University

Figure 6 Annual Phosphate Loading (Winslow, 2015)

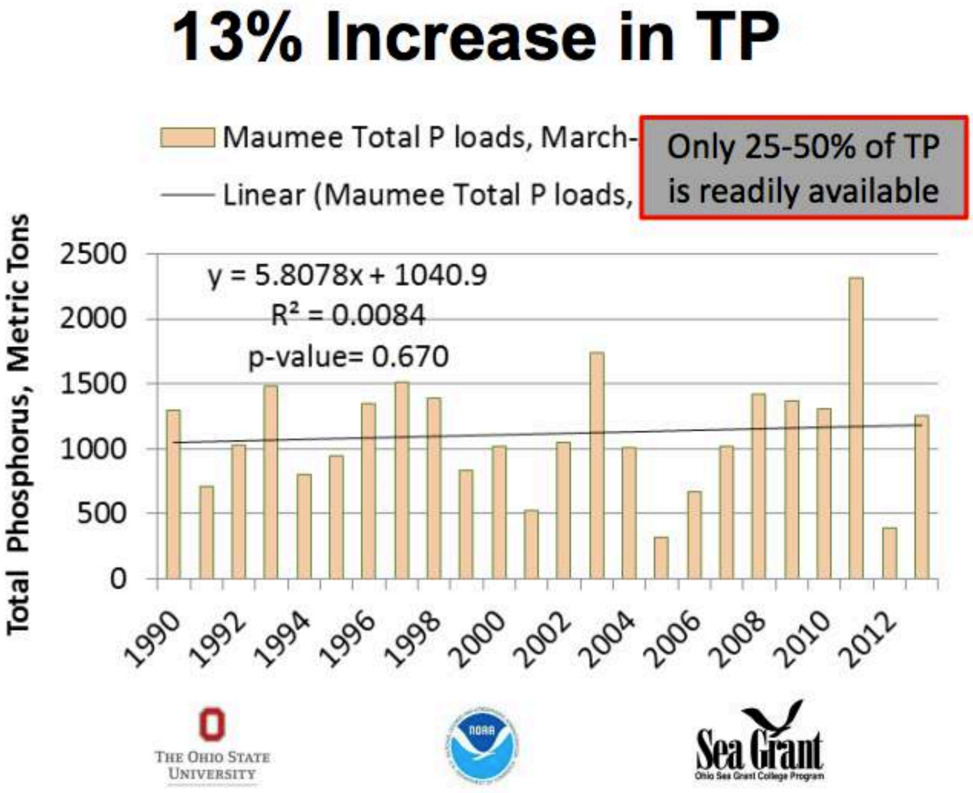


Figure 7 Total Phosphorus Usage Over Time (Winslow, 2015)

Agronomic experiments with phosphate fertilizers have provided evidence for increasing crop and plant yields with increasing phosphate application (Pasda et al., 2001). However, the agronomic effectiveness of phosphate fertilizers is largely attributed to the capacities of the soil to retain and release the chemical (Ozanne & Shaw, 1967). As the phosphorus retention capacity of the soil increases, however, a larger amount of phosphate fertilizers are needed in order to produce the same output yield.

Total benefits of phosphorus are significant when considering total agricultural output. Like nitrogen, phosphate fertilizers promote the opportunity to further food security by increasing crop yields and decreasing food prices.

9.0 Discussion

Completing a qualitative analysis on chemical fertilizer use in the Lake Erie basin required the development of a decomposition framework. By decomposing both direct and indirect effects, it's possible for practitioners and stakeholders to assign weighted values per each of the variables analyzed, and therefore make recommendations for remediation efforts and policies going forward.

Overall, effects of eutrophication via uses of chemical fertilizers on agricultural land surrounding Lake Erie are substantial. Additionally, the benefits Ohio communities gain out of using chemical fertilizers are sizable as well. It is generally reasonable to argue net costs outweigh net benefits. However, due to biased weighting, assigning greater value towards particular variables over others is discriminatory in nature.

When considering total costs and benefits of chemical fertilizer use in the Ohio Lake Erie basin, it is important to note the qualitative nature many variables exhibit. This is largely due to the difficulty in setting social prices according to many of the externalities that affect ecological, environmental, and human health outcomes. However, it is possible to set economic prices according to the effects chemical fertilizer use has on industrial, public health, governmental, and agronomic variables. Future research should therefore investigate total aggregate effects of chemical fertilizer use in the Lake Erie basin, with regards to a full quantitative analysis of its costs and benefits. Deciding whether the costs of chemical fertilizer use outweighs its benefits presents many issues underlying variable ambiguity.

10.0 Conclusion

Eutrophication-induced HABs present a diverse range of issues for ecosystems and communities in the western Lake Erie region. Microcystin and other toxins produced by cyanobacteria harm many organisms along the food chain, human health, and economic viability in core industries that are reliant on the lake's resources. Providing Lake Erie stakeholders with an overview of these effects, how they are caused, and the mechanisms by which they transpire is useful for creating pragmatic and enduring solutions for the future.

With a long history of agricultural innovation and entrepreneurship, Ohio has the capability to further develop and grow its communities and industry. While chemical fertilizers provide farmers with the opportunity to increase yields and reduce costs of agricultural products, they present unintended consequences to the environment, society, and the economy at-large. Cyanotoxins produced by eutrophication-induced algae growth directly harms numerous species, including various zooplankton, fish, reptiles, and birds. Additionally, microcystins harm human health by damaging liver processes and inducing tumor growth. By reviewing both these consequences and gains, stakeholders will have access to a comprehensive vantage point on the effects of chemical fertilizer use in Ohio.

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