BACKGROUND FACTS: ROLE OF PHOSPHORUS IN LAKE CHAMPLAIN POLLUTION

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Introduction

INTRODUCTION

Phosphorus is an important element that is necessary to sustain life. It is a critical component of deoxyribonucleic acid and ribonucleic acid—better known as DNA and RNA—biomolecules that control the form and nature of all living organisms.[1] It is the essential atom in adenosine tri- and di-phosphate (ATP and ADP), the molecules that store and transport energy in all living organisms, making it possible to breath, move, think, reproduce, and survive.[2] Phosphorus is also a major element in phospholipids, one of the critical components of the cell walls in plants and animals and in hormones that regulate physiological functions.[3] One form of phosphorus

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[1] ROBERT W. STERNER & JAMES J. ELSER, ECOLOGICAL STOICHIOMETRY: THE BIOLOGY OF ELEMENTS FROM MOLECULES TO THE BIOSPHERE 50 (2002).

[2] *Id.*

[3] Gabriel M. Filippelli, *The Global Phosphorus Cycle: Past, Present, and Future*, 4 ELEMENTS 89, 89 (2008).

when added to the flexible protein called collagen, makes it possible to create hard, stiff bones for skeletons, which were essential for the evolution of large organisms, like humans.[4] In a very real sense, life as we know it would not be possible without phosphorus.

But like many materials that we think of as essential for one reason or another, too much of a good thing can be bad. Phosphorus is regularly, but not always, implicated as a pollutant that is responsible for ugly, smelly, and potentially dangerous algal blooms.[5] Indeed, the entire Lake Champlain TMDL focuses on phosphorus and nothing else.[6] Why this one element? What are the special characteristics of phosphorus that explain why it behaves the way it does in the environment? And why is it that an element so essential to life could be so undesirable in some settings? Answers to these questions are crucial to understanding the central role of phosphorus in waterbodies like Lake Champlain and help inform what we can expect to happen as we begin to control the amount of phosphorus that is delivered to the lake each year.

I. A PRIMER ON PHOSPHORUS IN THE ENVIRONMENT

To begin with, phosphorus is an element; number fifteen in the periodic chart of elements.[7] Pure forms of phosphorus can be manufactured and are identified by their colors (white, red, violet, and black).[8] But these forms of phosphorus are either very unstable (even explosive) or non-existent in nature. Thus, we never find phosphorus as a free element in nature; it is always combined with other elements, notably oxygen, to form phosphate molecules.[9] Each phosphate molecule is composed of a single P atom surrounded by four oxygen atoms arranged in a tetrahedral pattern with phosphorus in the middle.[10] Arranged in this way the phosphate molecule carries an excess negative charge of -3.[11] To a chemist this means that the

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[4] Vaclav Smil, *Phosphorus in the Environment: Natural Flows and Human Interferences*, 25 ANN. REV. ENERGY ENV'T 53, 54 (2000).

[5] J. Heisler et al., *Eutrophication and Harmful Algal Blooms: A Scientific Consensus*, 8 HARMFUL ALGAE 3, 4–5 (2008).

[6] U.S. ENVTL. PROT. AGENCY, PHOSPHORUS TMDLS FOR VERMONT SEGMENTS OF LAKE CHAMPLAIN (2015).

[7] *See generally* C.R. Hammond, *The Elements*, *in* CRC HANDBOOK OF CHEMISTRY AND PHYSICS 4 (David R. Lide ed., 86th ed. 2005).

[8] *Id.*

[9] *Id.*

[10] *Phosphate*, PUBCHEM, https://pubchem.ncbi.nlm.nih.gov/compound/phosphate#section=Top [https://perma.cc/WZR9-5QH9] (last visited Apr. 15, 2016).

[11] *Id.*

phosphate is a trivalent anion (PO_4^{3-}).[12] The practical implications of this characteristic is that the negatively charged phosphate molecule is naturally attracted to positively charged atoms and molecules (cations) and has the capacity to make three connections to these cations. For example, one of the most common and commercially important forms of phosphate is phosphoric acid (H_3PO_4).[13]

The ultimate source of phosphorus in the environment is from phosphate bound with a variety of other atoms in common minerals and rocks. Over time, the slow action of water and wind erodes even solid rocks in a process that geologists refer to as "weathering." Over geologic time periods, weathering erodes rocks and releases the phosphate that they contain.[14] Once released in this way, the phosphate is available for use by biota in ecological systems.[15]

The slow release of phosphate from rock naturally limits the rate at which phosphorus is released to the environment.[16] There are episodes in the pre-human past in which phosphorus delivery to the oceans was greater than normal.[17] However, it also appears to be the case that humans have accelerated the delivery of phosphorus to the ocean, perhaps by a factor of two.[18]

Long ago, humankind realized that by adding a little phosphorus (along with a few other key elements), one could grow a lot more biomass (i.e., food and fiber).[19] We now know why that is the case. Given that phosphorus is essential to so many critical parts of living organisms and is needed in only small amounts to serve these needs, it is clear that, given no other constraints, the addition of phosphorus in the form of phosphate will stimulate plant growth. This explains why phosphorus is such an important fertilizer. And so, the rush was on to find new and concentrated sources of phosphate that could be used to support a burgeoning, global, agricultural industry.[20] The first easy source of phosphate was from deposits of guano created by bird colonies, largely on small islands off the coast of Peru.

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[12] *Id.*

[13] STEPHEN M. JASINSKI, U.S. GEOLOGICAL SURVEY, MINERAL COMMODITY SUMMARIES, PHOSPHATE ROCK (2015).

[14] Holm Tiessen, *Phosphorus in the Global Environment*, *in* THE ENCYCLOPEDIA OF PLANT-PHOSPHORUS INTERACTIONS 1, 5 (P.J. White & J.P. Hammond eds., 2008).

[15] *Id.*

[16] W.H. SCHLESINGER & E.S. BERNHARDT, BIOGEOCHEMISTRY: AN ANALYSIS OF GLOBAL CHANGE (Academic Press 3d ed. 2013).

[17] Filippelli, *supra* note 3, at 89.

[18] *Id.*

[19] Dana Cordell, *The Story of Phosphorus: Global Food Security and Food for Thought*, 19 GLOBAL ENVTL. CHANGE 292, 292–94 (2009).

[20] Smil, *supra* note 4, at 55.

Evidence suggests that the Andean peoples of Peru had collected guano as an agricultural soil amendment for perhaps thousands of years and guano remained an important source of phosphorus well into the 20th century.[21] Currently, the primary source of phosphate is the mineral form apatite, which is mined from operations in Florida and North Carolina, with smaller amounts mined in Idaho and Utah.[22] Large amounts of phosphate rock are also mined in China, Russia, and Morocco with smaller amounts in other countries.[23] The annual report on the phosphate mining industry produced by USGS notes tersely that there are "no substitutes for phosphorus in agriculture."[24] To meet our agricultural demand for phosphorus in the U.S. in 2014, we imported about 2.6 million metric tons of phosphate rock, largely from Morocco and Peru, representing about 15% of our total usage (28.1 million metric tons). This phosphate rock is wet-processed to create the basic feedstocks needed to support U.S. agriculture and industry.[25]

II. THE CHEMICAL BALANCE OF LIFE: THE LIMITS OF PHOSPHORUS BENEFITS

Of course, phosphorus is not the only element needed to create a healthy crop or to sustain a healthy animal. Most of the other elements in the periodic chart help to support healthy organisms in one way or another.[26] Notably, two other elements acting with phosphorus play particularly important roles. The other two elements are carbon and nitrogen.[27] Interestingly, these three elements are all close neighbors on the periodic chart of elements. But they serve very different purposes and have very different characteristics. Nitrogen is a central element in all amino acids, which are the essential building blocks of all proteins.[28] Proteins form a substantial portion of the total mass of plants and animals and serve critical functions as enzymes in living systems. Therefore, large amounts of nitrogen are also required for a healthy organism. Carbon is the essential backbone element of all living matter.[29] It is essentially the chemical

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[21] GREGORY T. CUSHMAN, GUANO AND THE OPENING OF THE PACIFIC WORLD: A GLOBAL ECOLOGICAL HISTORY 25–26 (2013).

[22] JASINSKI, *supra* note 13, at 118.

[23] *Id.* at 119.

[24] *Id.*

[25] *Id.*

[26] *See generally* K.O. Soetan et al., *The Importance of Mineral Elements for Humans, Domestic Animals and Plants: A Review*, 4 AFR. J. FOOD SCI. 200, 203–04 (2010) (reviewing the biochemical functions and importance of mineral elements in human and plant health).

[27] SCHLESINGER & BERNHARDT, *supra* note 16.

[28] STERNER & ELSER, *supra* note 1, at 59.

[29] SCHLESINGER & BERNHARDT, *supra* note 16.

framework to which all of the other elements, including phosphorus and nitrogen, are attached. Thus, living organisms need a lot of carbon.

A logical deduction from this discussion is that there is some form of priority or "recipe" for these three fundamentally important elements. Specifically, living organisms need a lot of carbon to create the necessary organic framework, a moderate amount of nitrogen to fill in the protein matrix around the carbon framework, and a pinch of phosphorus to run the genetic engine of DNA and RNA fueled by energy from ATP and ADP.[30] The realization that carbon, nitrogen, and phosphorus are ordered in this way has profoundly important implications.

The first inkling that this ordering might be important arose from the work of Carl Sprengel, an agricultural chemist working in Europe in the early 1800s.[31] Even at this early time it was realized that nutrients played a key role in crop production. Sprengel was the first to note that it was not just the total amount of nutrient that was important. Rather, the factor that would most limit plant production was the nutrient that was least available to the plant: the so-called "minimum" or "limiting" nutrient.[32] This idea did not gain much attention until it was adopted by Justus von Liebig, an agricultural chemist working at about the same time who is now recognized as the father of organic chemistry.[33] Sprengel's hypothesis eventually became known as Liebig's Law of the Minimum and was widely illustrated by a figure in Whitson and Walster's 1912 book entitled *Soils and Soil Fertility*.[34] The figure shows a barrel composed of staves of different lengths. If one tried to fill the barrel with water, it could only be filled to the level of shortest stave. The only way to keep more water in the barrel would be to lengthen the stave. This illustrated Sprengel and Liebig's point that a crop (the barrel) is composed of many elements (staves) and the element that is most limiting (the shortest stave) will limit the crop production (the water in the barrel).[35] Liebig's Law subsequently became one of the most important tenants in the newly evolving field of ecology.

The next major evolution in thinking about the interplay of elements in crop production and ecological systems came from the work of an oceanographer, Alfred C. Redfield, working at the Woods Hole

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[30] STERNER & ELSER, *supra* note 1, at 49–50.

[31] R. R. van der Ploeg et al., *History of Soil Science: On the Origin of the Theory of Mineral Nutrition of Plants and the Law of the Minimum*, 63 SOIL SCI. SOC'Y AM. J. 1055, 1057–58 (1999).

[32] *Id.*

[33] *Id.* at 1061 (accounting Sprengel and Liebig's dispute over which of them originated the concept of the Law of the Minimum, a classic story in the history of science).

[34] A.R. WHITSON & H.L. WALSTER, SOILS AND SOIL FERTILITY 72 (1912).

[35] *Id.*

Oceanographic Institute ("WHOI").[36] Redfield was trying to understand the controls on algal production in the Sargasso Sea—an area in the middle of the Atlantic Ocean—in which nutrient concentrations are particularly low.[37] Redfield would have been well aware of Liebig's Law. But at the time, the implications of Liebig's Law were simply that if you lacked a particular element, adding it would help stimulate production. What Redfield observed was that everywhere he looked, he found that the algae were composed of more or less the same ratio of carbon atoms to nitrogen atoms to phosphorus atoms.[38] The ratio was about 106:16:1 and it was remarkably invariant.[39] Redfield's work showed that this ratio of elements was an inherent, structural characteristic of the algae and furthermore, this inherent ratio provided an important refinement and quantitative context for Liebig's Law of the minimum.

The fundamental importance of Redfield's observations can be illustrated with a simple analogy. Imagine you run a bakery that makes cakes. You need several ingredients for each cake, but the key ingredients are flour, sugar, and eggs. You do not need these ingredients in equal proportions, but if you do not have the correct proportions the cake recipe will fail. Let us say you need two cups of flour, one cup of sugar, and a single egg for each cake. Thus, there is a relatively fixed ratio of the materials you need to bake a cake. Now imagine that you have an abundance of flour and sugar, but you have run short on eggs. In this case, the number of cakes you can bake is limited, specifically by the availability of the limiting resource: eggs. In our cake example, the flour is carbon, the sugar is nitrogen, and the egg is phosphorus. You do not need that many eggs to make a cake, but if you do not have enough, it will not matter if you have an abundance of sugar or flour; you cannot use them. But, if you have lots of eggs and a limitless supply of sugar and flour, you could bake as many cakes as you wish. The same is true for algae (biomass) in lakes. If you provide plenty of carbon, nitrogen, and phosphorus—in the correct ratios—you can grow a lot of biomass.

Redfield's Ratio spawned a generation of research that was fundamentally important to the water quality management principles we now use on a daily basis. One of the most important uses of Redfield's Ratio and Liebig's Law was a recommendation that arose from research on

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[36] ROGER REVELLE, ALFRED C. REDFIELD: 1890-1983 317 (1995).

[37] A.C. Redfield, *On the Proportions of Organic Derivatives in Sea Water and Their Relation to the Composition of Plankton*, *in* JAMES JOHNSTONE MEMORIAL VOLUME (R.J. Daniel ed., 1934).

[38] *Id.*

[39] A.C. Redfield, *The Biological Control of Chemical Factors in the Environment*, 46 AM. SCIENTIST 205, 206 (1958).

the best way to manage algal production in lakes. Over many years, researchers had begun to notice a strong correlation between algal growth and phosphorus concentrations in lakes.[40] High phosphorus concentrations were correlated with more algal biomass.[41] Redfield's Ratio provided an explanation. As one of the three "essential" elements and the one that was needed in the lowest amount, controlling phosphorus was viewed as the most effective way to control algal growth.[42] This is still the primary objective of lake and reservoir management around the world. It is worth noting, however, that most of the research upon which this management recommendation was based was done on lakes in Europe, the United States, and Canada. These are all areas that have a common geologic history and climate. In other areas—for example, areas where the soils have very high phosphorus concentrations derived from volcanic parent materials—it might be more effective to control nitrogen than phosphorus. Hawaii and New Zealand are good examples where this is the case.[43] But under these circumstances, the principles behind Redfield's Ratio still hold with nitrogen rather than phosphorus as the focal element.

The next major advance in our understanding of nutrient interactions in environmental systems built on Redfield's ratio and the well-known concept in general chemistry called "stoichiometry," which is used to describe the strict ratio of atoms in a molecule.[44] For example, we all know that the water molecule is H_2O: two hydrogen atoms paired with one oxygen atom. That is the stoichiometry of water. If the ratio was something different—say, H_2O_2—the molecule could not be water—the stoichiometry would be wrong. In fact, this would be hydrogen peroxide, which you would want to be careful *not* to drink! Sterner and Elser reasoned that Liebig's Law and Redfield's Ratio suggested that there was a sort of *weak* stoichiometry in living organisms: an ecological stoichiometry.[45] They

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[40] Steven C. Chapra & Stephen J. Tarapchak, *A Chlorophyll a Model and Its Relationship to Phosphorus Loading Plots for Lakes*, 12 WATER RESOURCES RES. 1260 (1976); G.F. Lee et al., *Eutrophication of Water Bodies: Insights for an Age-Old Problem*, 12 ENVTL SCI. & TECH. 900 (1978); R.A. VOLLENWEIDER & P.J. DILLON, THE APPLICATION OF THE PHOSPHORUS LOADING CONCEPT TO EUTROPHICATION RESEARCH 21–37 (1974).

[41] Lee et al., *supra* note 40, at 900.

[42] David W. Schindler, *The Dilemma of Controlling Cultural Eutrophication of Lakes*, 279 PROC. ROYAL SOC'Y B. 4,322, 4,322 (2012).

[43] E. White, *Lake Eutrophication in New Zealand—A Comparison with Other Countries of the Organisation for Economic Co- Operation And Development*, 17 N.Z. J. MARINE & FRESHWATER RES. 437, 437 (1983).

[44] *Stoichiometry*, OXFORD ENGLISH DICTIONARY (2016) (stating that the word stoichiometry came into use in the early 1800s and is derived directly from the Greek word "*stoikheion" which means "element").*

[45] STERNER & ELSER, Ecological stoichiometry: The biology of elements from molecules to the biosphere. 2002. 45. Sterner & Elser, *supra* note 1.

noted that this ecological stoichiometry is not as strict as chemical stoichiometry, but it exists nonetheless.[46] Furthermore, they were able to demonstrate that the essential framework of ecological stoichiometry could be derived from first principles of biology and chemistry and had unexpected consequences for biological systems at scales ranging from cells to individuals to communities and ecosystems.[47] They even suggested that there are implications for ecological stoichiometry at regional and global scales.[48] Our modern approach to large ecosystem management, including the Great Lakes and our oceans, recognizes that the principles of ecological stoichiometry are at work.[49]

III. LIEBIG, REDFIELD, AND LAKE CHAMPLAIN

With the foregoing principles in mind, we can now understand why phosphorus management is often effective in controlling algal production in lakes like Lake Champlain. Perhaps more importantly, phosphorus management is also thought to be an essential defense against the development of harmful algal blooms or "HABs."[50]

To understand why this is the case, it helps to return to the example of baking cakes. Let us say that your limiting resource is eggs (phosphorus). You have plenty of sugar (nitrogen) and flour (carbon). So your cake production (algal production) is limited by the supply rate of eggs. Let us say that you run across a new source of eggs and can now bake and sell cakes at a much faster rate. That works for a while. But then you find that your cake production is limited by a new factor: your supply rate of sugar.

This analogy can be applied to nutrient dynamics in lakes. Prior to extensive development in areas like the Lake Champlain Basin, the primary limitation on algal growth is thought to have been the rate at which phosphorus could be delivered. Carbon is widely available in the form of carbon dioxide (CO_2) in the atmosphere and this carbon can easily be converted into biomass through the simple process of photosynthesis.[51] All green plants, including algae, can engage in photosynthesis, so acquiring

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[46] *Id.*

[47] *Id.*

[48] *Id.*

[49] Robert Ptacnik et al., *Applications of Ecological Stoichiometry for Sustainable Acquisition of Ecosystem Services*, 109 OIKOS 52, 59 (2005); Philip G. Taylor & Alan R. Townsend, *Stoichiometric Control of Organic Carbon-Nitrate Relationships from Soils to the Sea*, 464 NATURE 1178, 1178 (2010); Jofre Carnicer et al., *Global Biodiversity, Stoichiometry and Ecosystem Function Responses to Human-Induced C-N-P Imbalances*, 172 J. PLANT PHYSIOLOGY 82 (2015).

[50] David W. Schindler, *Evolution of Phosphorus Limitation in Lakes*, 195 SCI. 260, 260 (1977); Schindler, *supra* note 42, at 4,322.

[51] EUGENE RABINOWITCH & GOVINDJEE, PHOTOSYNTHESIS 16 (1969).

carbon is not a great problem. Nitrogen arises naturally through a variety of processes, including natural fires, volcanic emissions, and lightning.[52] For example, lightning converts di-nitrogen gas (N_2), which is about seventy-eight percent of what we breathe in the air, into nitrogen oxides (NO_x) that can be turned into useful forms of nitrogen (e.g., nitrate) in water.[53] However, phosphorus is relatively harder to acquire. Before the industrial era, the primary source of new phosphorus was the weathering of rocks by the action of wind, water, and plant root growth.[54] Weathering is an extremely slow process that plays out over decades to millennia. The amount of new phosphorus released to the environment by this means is quite low. As a consequence, under pre-industrial conditions, phosphorus was likely to be the element that most limited production of algae in lakes like Lake Champlain.

But in the post-industrial world, phosphorus began to be mined and concentrated into forms that could be used on farms, in industry, and at home.[55] Eventually, this "new" phosphorus introduced into the ecosystem found its way to downstream receiving waters. To return to our cake analogy, there is now a new source of eggs that could accelerate production. According to the principles of ecological stoichiometry discussed above, we would expect the delivery rate of nitrogen to now limit new production by algae, enabled by the higher rate of phosphorus delivery. To be sure, algal growth might increase a little bit due to the new phosphorus, but eventually nitrogen limitation would prevail.

However, there is an additional piece to this story. It turns out that some microbial organisms have evolved an enzyme—nitrogenase—that can break apart N_2 molecules that are abundantly available in the air and easily soluble in water.[56] These organisms can convert N_2 to "reduced" forms of nitrogen in a process called nitrogen fixation and this reduced nitrogen can be used by algae for growth.[57] It is worth pausing to consider what a remarkable feat this is. Karl Haber, working with Carl Bosch in Germany in the early 1900s, discovered a way to create industrial quantities of ammonium (NH_4^+) from atmospheric N_2 by creating an environment pressurized to a level about 200 times higher than standard atmospheric

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[52] David Fowler et al., *The Global Nitrogen Cycle in the Twenty-First Century*, 368 PHIL. TRANSACTIONS ROYAL SOC'Y B. 1, 3–9 (2013).

[53] *Id.* at 3.

[54] *See* Filippelli, *supra* note 3, at 90–94 (explaining the natural pre-human phosphorus cycle).

[55] *Id.* at 94; SCHLESINGER & BERNHARDT, *supra* note 16.

[56] Brian M. Hoffman et al., *Mechanism of Nitrogen Fixation by Nitrogenase: The Next Stage*, 114 CHEMICAL REV. 4,041, 4,042 (2014).

[57] *Id.* at 4,041.

pressure, with a temperature elevated to between 400-500°C (752-932°F), and including one of several forms of an iron, aluminum, or silicate catalyst.[58] This is an extraordinarily harsh environment in which no living organism could survive. Yet the algae that have the nitrogenase enzyme (a type of biological catalyst) can do the same thing at typical atmospheric pressure and comfortable—even cool—temperatures![59] This is an amazing biological adaptation.

Not all algal species have the nitrogenase enzyme, but those that do have a competitive advantage over algal species that do not have this enzyme. All algae have a virtually unlimited supply of carbon as CO_2 in the air, which they access through the process of photosynthesis. Algal species that have the nitrogenase enzyme have access to an unlimited supply of nitrogen as N_2 in the air, which they can reduce by the process of nitrogen fixation. Thus, the growth of these species is limited only by the supply rate of phosphorus.[60] If the phosphorus supply rate goes up, these algae produce more biomass and may rapidly grow to bloom conditions.[61] These are the pea-soup thick, bright green, and often smelly scums of plant matter that we see in quiet bays of Lake Champlain on some August days.

Unfortunately, a large portion of these blooms are composed of a special group of organisms called cyanobacteria or "blue-green algae."[62] These organisms are classified as true bacteria but have characteristics of algae (chlorophyll and photosynthesis) and also characteristics of bacteria (no nucleus or internal cell membranes).[63] Nitrogen fixation is common among cyanobacterial species.[64] Furthermore, these organisms are capable of producing species-specific toxins that can have serious human health impacts, including skin rashes, nervous system disruption, and liver damage.[65] A variety of toxins are produced by different cyanobacterial

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[58] VACLAV SMIL, ENRICHING THE EARTH: FRITZ HABER, CARL BOSCH, AND THE TRANSFORMATION OF WORLD FOOD PRODUCTION (MIT Press 2004).

[59] Hoffman et al., *supra* note 56, at 4,042.

[60] *Evolution of Phosphorus Limitation in Lakes*, *supra* note 50, at 262.

[61] Factors that control harmful algal blooms are more complicated than indicated by this simple summary. However, this is the rationale most often presented for controlling phosphorus loading to lakes to control algal blooms. *See* Heisler et al., *supra* note 5, at 5 ("Physical, biological, and other chemical factors may modulate harmful algal species' responses to nutrient loadings.").

[62] *Cyanobacteria: Blue-Green Algae*, VT. DEP'T OF HEALTH http://www.healthvermont.gov/enviro/bg_algae/bgalgae.aspx [https://perma.cc/4G95-ZFAE] (last visited Apr. 18, 2016).

[63] Antonia Herrero et al., *Minireview: Nitrogen Control in Cyanobacteria*, 183 J. BACTERIOLOGY 411, 411 (2001).

[64] *Id.* at 412.

[65] JAMIE BARTRAM ET AL., TOXIC CYANOBACTERIA IN WATER: A GUIDE TO THEIR PUBLIC HEALTH CONSEQUENCES, MONITORING AND MANAGEMENT 7, 133, 146 (Ingrid Chorus & Jamie Bartram eds., 1999).

species, including microtoxin, cylindrospermopsin, anatoxins, and saxitoxins.[66] One of the perplexing riddles yet to be solved is to understand "why do these organisms produce these toxins" and, more importantly, "under what circumstances"? In some cases, large and very dense blooms of cyanobacteria have proven to be entirely non-toxic and in other cases, small and seemingly feeble blooms have proven to be very toxic.[67] The bottom line is that potentially-toxic cyanobacteria are particularly well adapted to thrive in the warm, relatively phosphorus-enriched conditions that prevail in some parts of Lake Champlain in the late summer.

IV. SOURCES AND CONTROLS OF PHOSPHORUS TO LAKE CHAMPLAIN

How did all of this new phosphorus end up in Lake Champlain? To start with, it is important to remember that phosphorus is a natural element in the environment and that it is required for life. In this sense, it is an essential nutrient and a common element in soils and the rocks from which soils are derived. The concentration of phosphorus in undeveloped soils in Vermont are not particularly unusual in this respect.[68] However, human activities have intensified the use of phosphorus and created local "hotspots" of high phosphorus concentrations that have led to regular and persistent water quality problems in lakes like Lake Champlain.[69]

It has clearly become necessary to significantly reduce the amount or "load" of phosphorus that reaches sensitive lakes like Lake Champlain. As a consequence, the State of Vermont, working with Region 1 of the U.S. Environmental Protection Agency ("EPA") has developed a recommendation for the total maximum daily load ("TMDL") that is allowable for the health of Lake Champlain.[70] The history, rationale, development, and implementation of the Lake Champlain Phosphorus TMDL is the subject of other articles in this issue. But in the context of this article, it is relevant to review briefly where this excess phosphorus is coming from and what happens to it.

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[66] *Id.* at 19.

[67] *Lake Conditions and Blue-Green Algae Bloom Updates*, VT. DEP'T OF HEALTH http://healthvermont.gov/enviro/bg_algae/weekly_status.aspx [https://perma.cc/845H-ZY73] (last visited Apr. 1, 2015).

[68] Eulaila R. Ishee et al., *Phosphorus Characterization and Contribution from Eroding Streambank Soils of Vermont's Lake Champlain Basin*, 44 J. ENVTL. QUALITY 1,745, 1,746 (2015).

[69] *See* Laura Arenschield, *Toledo Bearing Full Brunt of Lake Erie Algae Bloom*, COLUMBUS DISPATCH (Aug. 4, 2014), http://www.dispatch.com/content/stories/local/2014/08/04/this-bloom-is-in-bad-location.html [https://perma.cc/KY9N-SU9X] (explaining that in the summer of 2014 the City of Toledo had to shut down the water supply for a population of nearly 500,000 due to a large and toxic algal bloom that developed in Lake Erie).

[70] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 1–2.

EPA has estimated that more than three-quarters of the total phosphorus load to Lake Champlain (631 of 922 metric tons/year) comes from sources in the State of Vermont with the balance coming from sources in New York and the Province of Quebec.[71] This is not surprising because compared to New York and Quebec, Vermont has more shoreline, a larger population, and more intensive land use.[72]

The largest portion—about forty-one percent—of the total phosphorus loading to Lake Champlain comes from agricultural lands in Vermont, which represent about nineteen percent of the total land area in the basin.[73] In the particular case of agriculture, farmers import large quantities of phosphorus in the form of grains for feed and fertilizers for crops.[74] The total quantity of phosphorus that leaves the basin in the form of intermediate or finished farm products is far less. The difference has to accumulate somewhere. It has proven to be impossible to retain this excess phosphorus on the farms and so it eventually makes its way to the lake.[75] On-farm retention is doomed to fail until imports to farms can be reduced to match exports from farms or the ability to permanently retain or recycle phosphorus on farm.

Developed (urban, suburban, and "barren") areas make up a relatively small portion of the overall land use in the Lake Champlain Basin approximately six percent) but account for eighteen percent of the total phosphorus load to Lake Champlain.[76] On a per-acre basis, urban areas deliver two to three times more phosphorus than agricultural lands.[77] It is still not clear why this is case. Leaking sewer pipes and excessive lawn

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[71] *Id.* at 17.

[72] Nathalie Fortin et al., *Toxic Cyanobacterial Bloom Triggers in Missisquoi Bay, Lake Champlain, as Determined by Next-Generation Sequencing and Quantitative PCR*, 5 LIFE 1,368, 1,369 (2015).

[73] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 47; *see* AUSTIN TROY ET AL., LAKE CHAMPLAIN BASIN PROGRAM, UPDATING THE LAKE CHAMPLAIN BASIN LAND USE DATA TO IMPROVE PREDICTION OF PHOSPHORUS LOADING 87 (2007) (calculated using data from Appendix I).

[74] *Where Does the Phosphorus in Lake Champlain Come From?*, LAKE CHAMPLAIN BASIN PROGRAM, http://sol.lcbp.org/Phosphorus_where-does-p-come-from.html [https://perma.cc/HQV9-WVAV] (last visited Apr. 19, 2016).

[75] Erica Joy Brown Gaddis, *Landscape Modeling and Spatial Optimization of Watershed Interventions To Reduce Phosphorus Load to Surface Waters Using a Process-Oriented and Participatory Research Approach: A Case Study in the St. Albans Bay Watershed, Vermont*, RESEARCHGATE (2007), https://www.researchgate.net/publication/33692301_Landscape_modeling_and_spatial_optimization_of_watershed_interventions_to_reduce_phosphorus_load_to_surface_waters_using_a_process-oriented_and_participatory_research_approach_a_case_study_in_the_St_A [https://perma.cc/H69R-KVEZ].

[76] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 47; TROY ET AL., *supra* note 73, at 87.

[77] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 47 (indicating the amount of phosphors delivered from urban and agricultural areas); *see also* TROY ET AL., *supra* note 73, at 87 (indicating land use trends in the Vermont portion of the basin).

fertilization are potential sources of excess nutrients in ground and surface waters.[78]

Sewage treatment plants or wastewater treatment plants ("WWTWs") are a part of the developed landscape. However, largely because they are easy to measure and easy to regulate, we have separate estimates of their total contribution to the phosphorus load to Lake Champlain. The Vermont contribution from WWTWs is about four percent of the total.[79] This is a small percentage, but some have argued that the form of the phosphorus released from WWTWs is more readily available to microorganisms and algae for growth.[80]

Forest lands make up the majority of the land cover in Vermont (approximately sixty-six percent).[81] Although the amount of phosphorus delivered from each acre of forestland tends to be low compared to agricultural and developed lands, the comparatively large number of forestland acres means that the cumulative contribution is substantial, about sixteen percent of the total.[82]

One of the more surprising findings in the most recent research supporting the new TMDL is that streambank erosion provides approximately twenty-one percent of the total phosphorus load to the lake.[83] It should be noted that this phosphorus load comes from some combination of eroding agricultural and developed land streams and erosion from backroads in forested areas.[84]

Before leaving this topic it is important to recognize that it is an oversimplification to say that agriculture is the largest source of phosphorus and so phosphorus reduction by farmers is the most important priority. Nor is it entirely accurate to say that developed lands have the largest per-acre loading rate of phosphorus and so developers need to reduce their phosphorus loads first. Both statements are true to a point. But we all use the products from farms, many of us live in homes or rely on businesses that operate in developed lands and most of us recreate in the forestlands of Vermont. Thus, the solution to reducing phosphorus loading to Lake

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[78] Neely Law et al., *Nitrogen Input from Residential Lawn Care Practices in Suburban Watersheds in Baltimore County, MD*, 47 J. ENVTL. PLAN. & MGMT. 737, 738 (2004); Duy Khiem Ly & Ting Fong May Chui, *Modeling Sewage Leakage to Surrounding Groundwater and Stormwater Drains*, 66 WATER SCI. & TECH. 2659, 2661 (2012).

[79] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 47.

[80] *Id.* at 19.

[81] TROY ET AL., supra note 73, at 87.

[82] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 47.

[83] *Id.*

[84] *Id.* at 19.

Champlain is not just one group's responsibility. It will require substantial efforts by everyone.

V. PHOSPHORUS AND FUTURE FOR LAKE CHAMPLAIN

As detailed elsewhere in this issue, Vermont will have to substantially reduce the total loading of phosphorus to Lake Champlain if we hope to control the unsightly and potentially dangerous algal blooms that now occur during most summers.[85] But "Vermont" is not a single entity that can be neatly managed. Vermont is composed of economic sectors, municipalities, neighborhoods, and individual property owners, each of whom is responsible—directly or indirectly—for some portion of the phosphorus that enters Lake Champlain. It is understandable that many people assume that their actions cannot possibly be important because the portion of the total phosphorus load for which they are responsible is infinitesimally small. It is interesting to note that there are about 600,000 people who live in the Lake Champlain basin.[86] If each person contributes about three-quarters of a pound of phosphorus each year, the sum is about 231 metric tons/year, the amount by which EPA has concluded that we need to reduce phosphorus loading.[87] Thus, if everyone committed to using just twelve ounces less phosphorus per year, we could reduce phosphorus loading to the target amount.

But, assuming we could do this, it is important to realize that we will not see an immediate improvement in lake water quality. Phosphorus is different from carbon and nitrogen in several respects. One important difference is that carbon and nitrogen can be converted naturally by microbes into forms that are volatile gases, which dissipate into the atmosphere.[88] Indeed, this process of volatilization renews these gas stocks in the atmosphere and allows the carbon and nitrogen cycles to persist.[89]

Phosphorus is different in that it has no volatile phase.[90] As a consequence, any new phosphorus that we bring into the Lake Champlain Basin will stay in the basin unless it is exported. It is true that a small amount of phosphorus leaks out each year via the Richelieu River and

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[85] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 7.

[86] *Lake and Basin Facts*, LAKE CHAMPLAIN BASIN PROGRAM, http://www.lcbp.org/about-the-basin/facts/ [https://perma.cc/5VRY-VFL8] (last visited Mar. 30, 2015).

[87] U.S. ENVTL. PROT. AGENCY, *supra* note 6.

[88] Fowler et al., *supra* note 52, at 5–6.

[89] *Id.* It is worth noting that we have created imbalances in these cycles to, which is leading to global warming.

[90] Smil, *supra* note 4, at 56, 61.

discharges to the St. Lawrence River.[91] But the majority of the phosphorus stays in the basin.[92] If that phosphorus stayed where it was used, we would have fewer problems with Lake Champlain. However, Lake Champlain is the lowest point of the basin. It is the receptacle that is the final resting place of sediment and phosphorus that drains from our entire landscape and travels down our rivers. It may take decades, centuries, or millennia, but much of the phosphorus that we use on fields, lawns, parks, gardens, and in the food we eat will eventually end up in the lake. If the sources of that phosphorus were originally from outside the basin, the total burden of phosphorus to the Lake Champlain Basin and, eventually, Lake Champlain will increase.

Fortunately, most of the phosphorus that settles into the sediments of Lake Champlain is buried.[93] In fact, the majority of the annual phosphorus load to the lake is simply buried and never has a chance to affect algal production.[94] This sediment phosphorus eventually becomes a part of the geological cycle of rock formation and weathering.[95] However, there is a store of phosphorus in the near-surface—active sediments of Lake Champlain that could continue to fuel algal production for decades, even without additional phosphorus inputs from rivers.[96] This is certainly discouraging news, but it should also reinforce our commitment to clean up the lake. Specifically, armed with this knowledge, it is clear that we have to commit to this clean up over the long haul. It is a certainty that we will expend great effort and considerable resources to reduce the phosphorus loading to Lake Champlain. We should not be discouraged if we see little immediate benefit in terms of reduced algal blooms. In time, we should begin to see positive results. However, this lag may be longer than the current planning horizon for Vermont Act 64,[97] or for the EPA TMDL.[98] Understanding why phosphorus behaves the way it does will hopefully reinforce our commitment to implement the hard changes needed to return Lake Champlain to a condition that supports all of our economic, recreational, and spiritual needs.

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[91] Eric Smeltzer & Scott Quinn, *A Phosphorus Budget, Model, and Load Reduction Strategy for Lake Champlain*, 12 LAKE & RESERVOIR MGMT. 381, 383–84 (1996).

[92] *Id.* at 384.

[93] *Id.* at 389.

[94] Eric Smeltzer et al., *Environmental Change in Lake Champlain Revealed by Long-Term Monitoring*, 38 J. GREAT LAKES RES. 6, 14–16 (2012).

[95] Smil, *supra* note 4, at 80.

[96] Donald W. Meals et al., *Lag Time in Water Quality Response to Best Management Practices: A Review*, 39 J. ENVTL. QUALITY 85, 89 (2010).

[97] 2015 Vt. Acts & Resolves 309,710.

[98] U.S. ENVTL. PROT. AGENCY, *supra* note 6, at 55–56.