

Review

How Effective Are Existing Phosphorus Management Strategies in Mitigating Surface Water Quality Problems in the U.S.?

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Abstract: Phosphorus is an essential component of modern agriculture. Long-term land application of phosphorous-enriched fertilizers and animal manure leads to phosphorus accumulation in soil that may become susceptible to mobilization via erosion, surface runoff and subsurface leaching. Globally, highly water-soluble phosphorus fertilizers used in agriculture have contributed to eutrophication and hypoxia in surface waters. This paper provides an overview of the literature relevant to the advances in phosphorous management strategies and surface water quality problems in the U.S. Over the past several decades, significant advances have been made to control phosphorus discharge into surface water bodies of the U.S. However, the current use of phosphorus remains inefficient at various stages of its life cycle, and phosphorus continues to remain a widespread problem in many water bodies, including the Gulf of Mexico and Lake Erie. In particular, the Midwestern Corn Belt region of the U.S. is a hotspot of phosphorous fertilization that has resulted in a net positive soil phosphorous balance. The runoff of phosphorous has resulted in dense blooms of toxic, odor-causing phytoplankton that deteriorate water quality. In the past, considerable attention was focused on improving the water quality of freshwater bodies and estuaries by reducing inputs of phosphorus alone. However, new research suggests that strategies controlling the two main nutrients, phosphorus and nitrogen, are more effective in the management of eutrophication. There is no specific solution to solving phosphorus pollution of water resources; however, sustainable management of phosphorus requires an integrated approach combining at least a reduction in consumption levels, source management, more specific regime-based nutrient criteria, routine soil fertility evaluation and recommendations, transport management, as well as the development of extensive phosphorus recovery and recycling programs.

Keywords: eutrophication; phosphorus; nutrient loading; algal bloom; runoff



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1. Introduction

Phosphorous (P) and/or nitrogen (N) are critical determinants of plant growth in most ecosystems. To increase crop yields, farmers apply nutrient-enriched fertilizer and manure on their lands that supply crops with nutrients needed for plant growth. Both N and P impact eutrophication, which refers to an increase in nutrient loading to water bodies to the extent of over-enrichment, leading to plentiful algal bloom [1]. Nutrient loading in aquatic systems is correlated to the levels of fertilizer applied in excess of nutrient demands by crops, vegetation, and soil biota. The nutrient status of a lake or river mirrors the different land-use types of the neighboring upstream drainage basin. Nutrient input into larger rivers or lakes may occur from smaller interconnecting streams within the drainage basin. Nutrients may also mobilize into downstream reaches from eutrophic lakes that feed into them. Erosion of river banks during flooding events may transport large quantities of P from the river banks and nearby areas into other water bodies. Numerous factors, such as water temperature, flow velocity, channel depth, catchment geology and riparian buffer, control the flow of nutrients from rivers into downstream waterbodies.

There are several kinds of nutrients necessary for plant growth, however, N and P are two of the most important and abundant ones. Nutrient loadings of N and P

to aquatic environments are of increasing concern worldwide due to an environmental epidemic of agriculture-related eutrophication, e.g., [1–3]. Even though N and P both affect eutrophication, P is less soluble than nitrate and can easily be transported in surface runoff [4]. The low concentrations of P in soil along with its low solubility make P a critical growth-limiting factor for plant growth in most freshwater bodies and, to a smaller extent, to some coastal waters. Phosphorus plays a vital role in several key plant functions, including structure, energy transfer, photosynthesis and reproduction [5]. Note that P cannot be substituted by any other element in these biological functions. Over the past several decades, there has been a dramatic increase in the use of P-enriched fertilizer due to P depletion in soils, which has resulted from an increase in global demand for agricultural products. Across the globe, large quantities of P (16.5 ± 3 million metric tons) in the form of chemical fertilizer are applied to agricultural lands annually to maintain soil P levels that are ideal for plant growth [6]. Applying highly concentrated P fertilizer or animal agriculture manure increases crop yield, however, P can also become a pollutant when applied in excess [7]. The amount of P soil accumulation depends on the soil's P adsorption capacity, which is directly related to soil pH, clay mineralogy, iron oxide, and organic matter content [8]. Soil P availability impacts plant uptake rates and the amount of P lost to the water resources via dissolution, erosion, surface runoff and subsurface leaching [9]. Phosphorus can mobilize into water bodies attached to particles (e.g., soil or organic matter particles carried in the runoff) or P can dissolve into surface runoff as it passes over agricultural fields [4,7,8].

Eutrophication is a natural process. Nonetheless, it can be enhanced by changes in land use and land cover pattern of a drainage basin. The hydrology, geology, soil type and topography of a drainage basin can exert major influences on its transport capacity, and subsequently, impact mobilization and transport of nutrients to a water body [1,10]. Numerous researchers connected the development and proliferation of algal blooms to nutrient loading resulting from activities related to agriculture, industry, and sewage disposal [11,12]. Subsequently, bacterial decomposition of the excess biomass results in oxygen consumption, which can lead to depletion of dissolved oxygen throughout the water body. Low or depleted oxygen in a water body can lead to hypoxic conditions, which is informally referred to as a "dead zone" because such an environment is unable to sustain life. Dead zones have been identified in many freshwater lakes, including the central Lake Erie region during the summer season [13]. Enhanced algal growth can also threaten biodiversity, lead to increased sedimentation and impairment in navigational and recreational use, and cause ancillary economic impacts to fisheries and the tourism industry along with property devaluation of waterfront homes. In America, the estimated annual value loss associated with human-induced eutrophication is around 2.2 billion USD [14]. Human-induced eutrophication of inland waters is of particular interest in lakes, reservoirs, and rivers that are sources of water for drinking purposes. Although eutrophication cannot be easily quantified, the overall impact of excessive nutrient input on lakes is reasonably well understood [15]. Our understanding of how eutrophication develops in rivers is still limited [16]. The effects of nutrient loading on rivers are complex due to their dynamic nature where plant communities respond to flow, sediment type and underlying geology surpassing any temporary changes in dissolved nutrient levels resulting from external inputs [16–18]. Additionally, dilution tends to restrict both the magnitude and extent of impacts of nutrient input in flowing bodies of water [15].

In the aquatic environment, increased growth of macrophytes, algae, and cyanobacterial blooms can result in dangerous toxins and taste-and-odor compounds, which can cause serious economic and public health concerns. For many years, farmers in the U.S. produced the majority of agricultural products through industrial agriculture, a system that promoted planting the same crop in the same field season after season, using large quantities of agrochemicals (e.g., fertilizers, plant-protection chemicals or pesticides) that threatened the surrounding environment. The American agricultural system is governed by taxpayer subsidies, private investment by agricultural business enterprises and relevant

policies and regulations, which have given rise to even larger farms and more industrialized practices [19]. This unsustainable system consumes and degrades the natural resources that it relies on. The subsequent spreading of agrochemicals along with nutrients in the country's water bodies (freshwater to marine continuum) over the past several decades is well documented, e.g., [19–21]. In particular, intensification of crops and expansion in livestock systems in many parts of the U.S. have led to areas of P surplus above local needs. The surplus P has, in turn, contributed to the impairment of water bodies across the country.

Human-induced eutrophication can occur in any aquatic system due to the availability of sunlight, carbon dioxide and nutrients - primarily nitrogen and phosphorus [22]. Phosphorus is a common ingredient in commercial fertilizers and its overabundance in water bodies from all sources leads to eutrophication. It is also noteworthy that human-induced eutrophication can occur well beyond where high P surface runoff initially entering the water body. By the time water quality degradation issues are apparent, remedial efforts become difficult and solution implementation becomes complex due to the interconnected nature of surface water bodies [21–24]. As such, a detailed understanding of the behavior of P in agricultural soils and watersheds can assist in maximizing crop productivity while minimizing adverse impact on water bodies. The United States Environmental Protection Agency (USEPA) has recognized the impact of agricultural chemicals in the country's surface waters for several decades and to meet water-quality standards and criteria, eutrophication management programs have focused on P control. There have been significant efforts to reduce P loads in streams and to improve agricultural P management practices. However, P continues to remain a problem in many waterbodies in the U.S. Some progress has been made towards improvements in water quality, however, improvement in water quality has been relatively slower and smaller than predicted by scientists and watershed managers [19,20,23,24]. These results have raised questions regarding the effectiveness of the applied P management strategies.

The global population is expected to be around 10 billion by the year 2050, and according to the Food and Agriculture Organization of the United Nations, food production is expected to increase by 50% to 70% [25]. In recent years, the world population growth along with changing food consumption patterns have amplified the demands for food, energy, water and sanitation. This in turn has accelerated environmental pollution along with unsustainable depletion of water and soil resources. Sustainable agriculture also focuses on maintaining economic prosperity and improving the living standards of farmers and human society [26]. Soil nutrient management is defined by the United States Department of Agriculture (USDA) as managing the rate, source, method of application and timing of commercial fertilizers, manure, amendments, and organic by-products to agricultural landscapes as a source of plant nutrients while protecting the environment. The increase in global population is expected to further increase agricultural raw materials along with generated wastes, which could cause serious environmental problems [27]. Projected climate change stresses are likely to magnify the environmental effects as agricultural systems heavily depend on reliable water sources, therefore any change in the weather pattern and magnitude of precipitation will create considerable uncertainty to agricultural yield. Additionally, water quality may also be compromised by increased sediment or nutrient inputs due to extreme storm events. In addition to nutrient losses, heavy precipitation events resulting from changing climate may result in changes in planted crop areas, P fertilizer application method and timing of P, cultivation practices, and growing season length [28].

Many U.S. regions, particularly the West, presently face water shortages and water quality degradation issues [29]. The increasing population will place further pressure on the already limited water supplies of the region. According to the USDA, as of 2017, across the U.S., 55% of assessed rivers and streams, 71% of lakes, and 84% of bays and estuaries have impaired water quality. Eutrophication has become the primary water quality issue and researchers suggest that with rising levels of atmospheric carbon dioxide, the occurrence of algal blooms will likely increase [30,31].

Sustainable P management is crucial for global food and water security. According to the World Food Summit of 1996, food security is “when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life” [32]. WaterAid defines water security as “reliable access to water of sufficient quantity and quality for basic human needs, small-scale livelihoods and local ecosystem services, coupled with a well-managed risk of water-related disaster” [33]. It is important to understand that the definition of agricultural sustainability is still evolving and is influenced by contemporary issues and perspectives around sustainable development. The 2030 Agenda for Sustainable Development acknowledges the importance of water quality and includes a specific water quality target in Sustainable Development Goal 6. This paper provides an overview of prior, relevant literature regarding the recent advances in the knowledge of sustainable phosphorus management strategies and surface water quality problems in the U.S.

2. Methodology

There is a massive abundance of published literature on eutrophication of lakes, rivers and estuaries. This present review provides a brief history of eutrophication in the U.S. and focuses on recent studies conducted on the concept of eutrophication as well as the associated surface water quality problems in freshwater bodies located within the continental U.S. along with the advances in P management strategies. As such, the sources of P, loss of agricultural P from terrestrial environment to aquatic systems along with impacts of eutrophication on U.S. freshwater systems have been thoroughly discussed based on recent progress on the topic. The review concludes by detailing available literature on P control measures that have been adopted to control eutrophication in the U.S., however, many of the strategies were found to be partially effective in governing the P input in water bodies.

3. Phosphate Sources in the United States

In nature, P is not encountered in a pure form, but it is commonly observed in the oxidized form of phosphate (PO_4). Phosphorus in commercial fertilizers applied to agricultural fields comes from naturally occurring PO_4 rock ore, a non-renewable resource formed over millions of years in the earth's crust. “Phosphate rocks” represents the general term used to describe naturally occurring mineral assemblages comprising of a high concentration of PO_4 minerals. The PO_4 content of the PO_4 rock $[\text{Ca}_{10}(\text{PO}_4)_6(\text{X})_2]$, where X is F^- , OH^- or Cl^- , in the form of the calcium (Ca)- PO_4 mineral apatite, is not readily plant-available [34]. Phosphate itself is rarely used directly as a fertilizer due to its low availability of P [35]. Phosphate rocks are usually treated to convert the PO_4 to water-soluble or plant-available forms. Globally, the majority of the P is consumed as a main component of N-P-potassium (K) fertilizers used on food crops. Of the mined P, roughly 80% is used for agricultural fertilizer and the remainder is used for animal feed additions (5%), whereas 15% is used for industrial purposes such as the production of detergent, metal treatment and other applications [36].

Phosphate rock deposits are widely distributed throughout the world and the major deposits of P are found in the U.S., Morocco, China and Russia [34]. Phosphate rock deposits can be sedimentary or igneous, and large sedimentary deposits are located in the United States. Globally, the U.S. is both the top producer and consumer of PO_4 rock, which is utilized to manufacture a variety of fertilizer and industrial products. According to the United States Geological Survey, the country's estimated apparent PO_4 rock consumption, based on annualized data, for 2020, was 25.5 million metric tons [37].

The total global PO_4 resources are projected to be over 300 billion tonnes, and a major portion of this PO_4 is unavailable for extraction under existing economic and technological settings [38,39]. Globally, wastewater treatment facilities are trying to remove P from effluents efficiently and cost-effectively while it is predicted that the more available global P reserves will likely be exhausted by about 2300 [39]. Researchers have investigated the prospect of recycling main P sources within the U.S. to supply the required P for local corn

production [40]. The findings indicate that domestic recyclable P sources, primarily from animal manure, could meet national corn P demand with no extra fertilizer inputs [40].

4. Mobilization of Agricultural Phosphorus

Soil fertility maintenance is essential at the base of the food web for sustainable agricultural production. However, the over-enrichment of chemical nutrients has accelerated eutrophication in many parts of the world. In North America, eutrophication problems grew during the twentieth century due to population growth along with farm mechanization and crop production intensification. Agriculture is a major industry in the U.S. and approximately 53% of its total land area (2.3 billion acres) is farmland that produces substantial quantities of agricultural products [41]. In the U.S., agrochemical usage exceeds 2 billion kg annually [42]. The top four crops produced in the U.S. are soybeans, corn, cotton and wheat, which comprise approximately 60% of the main crop acreage and receive more than 60% of N-P-K applied in the country [43]. Once applied, PO_4 from the fertilizer tends to remain attached to soil particles, however, P can subsequently be lost to the neighboring environment through various processes. Note that P from agricultural lands does not form gases, thus P loss is commonly linked to geology rather than to other processes. Table 1 presents model simulation results of P loss from cropland fields annually from data collected from the Natural Resources Conservation Service of USDA [44]. The findings indicate that a total of 360,000 tons of phosphorus was lost from cropland fields each year, which represents roughly 16% of the 2.2 million tons of P applied as commercial fertilizer and manure. The primary P loss pathway was P lost with waterborne sediment and windborne sediment.

Table 1. Model Simulation Results of Average Annual Values of P loss estimates by regions of the U.S. [44]. The data presented here is part of Table 54 of the report on Model Simulation of Soil Loss, Nutrient Loss, and Change in Soil Organic Carbon Associated with Crop Production by USDA-NRCS.

	Acres (%)	P Dissolved in Runoff		P Dissolved in Leachate		P Lost with Waterborne Sediments		P Lost with Windborne Sediments		All Loss Pathways (Total)	
		Tons	%	Tons	%	Tons	%	Tons	%	Tons	%
Regions of the U.S.											
Northeast	4.6	4811	6.9	684	9.5	23,387	10.3	282	0.5	29,163	8.1
Northern Great Plains	24.3	5628	8.0	145	2.0	24,441	10.7	21,294	38.5	51,506	14.3
South Central	15.2	18,271	26.1	2573	35.6	42,014	18.4	1543	2.8	64,401	17.9
Southeast	4.5	5850	8.4	984	13.6	10,814	4.7	19	0	17,667	4.90
Southern Great Plains	10.8	1976	2.8	177	2.5	8356	3.7	28,372	51.3	38,881	10.8
Upper Midwest	37.7	31,742	45.4	2550	35.3	116,841	51.3	3553	6.4	154,686	42.9
West	3.0	1689	2.4	109	1.5	2012	0.9	247	0.4	4057	1.1
All regions	100	69,967	100	7222	100	227,865	100	55,310	100	360,361	100

Natural Resources Conservation Service of USDA indicate that transport of PO_4 from soil to the surrounding environment is governed primarily by agricultural practices, such as tillage and drainage methods, and the timing of fertilizer application, erosion and runoff events. The use of agronomic conservation practices that slow down surface runoff, prevent erosion, and increase infiltration can also reduce the loss of nitrates or soluble P [32,44]. For example, contour farming activities minimize both erosion and nutrient runoff by storing rainfall behind ridges [45]. In filter strip farming, an area of grass or other permanent vegetation is used to capture contaminants and nutrients from runoff before they enter a body of water. In contour buffer strips, relatively narrow strips of permanent and herbaceous vegetation run along the contour of a farmed field. Contour buffer strips can retain nutrients and significantly reduce erosion [45].

Agricultural activities and the environment are closely connected, and each farming practice has its particular impact on the surrounding environment. Agricultural lands are a major nonpoint source of sediment, nutrients, and agricultural chemicals, which have been identified as a major contributor to water quality degradation in America's Midwestern region [46]. In particular, 65% of America's cropland is concentrated in the fourteen states

within the Mississippi River Basin [47]. Distribution, transport, and persistence of various agrochemicals in major rivers, such as the Missouri, Ohio and Mississippi Rivers and their tributaries have been a serious concern as millions of residents in the Midwest rely on the river water for drinking purposes [47,48]. Unlike point source of P (e.g., sewage treatment plants, industrial discharges), nonpoint sources of P (e.g., agricultural sources) are more challenging to contain, even harder to eliminate, and more expensive to mitigate due to highly variable hydrological controls of P transfer from soil to water bodies. Regardless of origin, dissolved loads of P can accumulate at numerous locations along transport pathways in watershed landscapes [23].

5. Phosphorus Eutrophication of U.S. Freshwaters

Concern over human-induced eutrophication is a fairly recent development in the U.S.'s major advances in scientific understanding, and the management of eutrophication has advanced since the 1960s [49–51]. During the 1950s and 1960s, Dr. Thomas Edmondson and his laboratory colleagues made strong efforts to understand the eutrophication process and associated problems. These researchers realized that increasing amounts of sewage from the City of Seattle were causing cyanobacterial blooms in Lake Washington [51,52]. Subsequently, in the 1960s and 1970s, Lake Erie experienced extensive eutrophication due to P loading from point and nonpoint sources [53,54]. Around this time, the eutrophication problems were temporarily alleviated through chemical treatment using copper sulphate and sodium arsenite, and light exclusion [55]. During the next few decades, water quality problems along with accelerated eutrophication drove the U.S. to further develop P eutrophication mitigation strategies that focused on methods to reduce the inputs of P in agricultural soils. In the late 1970s, in an effort to protect the Great Lakes along with inland lakes, policies to reduce the amount of P from detergents were implemented with some success. Even though many States banned P-containing detergents, P-containing dishwashing detergent remained in the market. It is noteworthy that compared with the P loads in municipal sewage water, the relative contribution of PO₄-based detergents is relatively low. For that reason, the limitations of the detergent P ban strategy continued to be debated for many years [56].

Over the past several decades, many freshwater lakes and estuaries, particularly in the northeastern U.S., have suffered from excessive algal blooms. For example, the Vermont segment of Lake Champlain located in the New England region of the northeastern U.S. suffered from severe eutrophication for many years. Numerous researchers investigated and identified that excessive levels of dissolved P played a key role in water quality degradation of Lake Champlain, one of the largest freshwater lakes in the U.S. [57–60]. Between 1979 and 1999, the LaPlatte River Watershed along with the St Albans Bay Watershed Rural Clean Water Program Projects in Vermont set out to minimize nutrient, sediment and microbial loads to parts of the lake [58]. Over the years, Agricultural Best Management Practices (ABMPs) were extensively employed in the region to control diffuse sources of pollution from dairy agriculture. However, water quality data revealed that even with extensive efforts to reduce P pollution in Lake Champlain, P concentrations showed minimal changes in most areas and exhibited more upward than downward trends in many parts of the lake [58,60]. In this area, farming has long been a way of life and many farmers voluntarily instituted various ABMPs along with nutrient and soil fertility management techniques specifically targeted to existing soil fertility levels and crop needs. According to USEPA, P Total Maximum Daily Load data for twelve segments of Lake Champlain indicate that along with agriculture, streambank erosion and runoff from developed land sources continue to remain the culprits for excessive P contribution to the lake [60].

Any successful ecosystem restoration program in the U.S. will require accuracy and precision in quantifying storm loads of sediments and nutrients. Additionally, across the nation, P flows are strongly related to historical, sociocultural, and geographical issues along with financial and political interests, and a successful nutrient management plan will require a detailed understanding of these contextual constraints [58–60].

6. Phosphorus Mitigation Strategies in the U.S.

In 1972, under the Clean Water Act (CWA), the USEPA implemented pollution control programs for effective management and protection of the country's water resources. The CWA aims to regulate discharges of pollutants into American waters and to regulate the quality standards for surface waters. The U.S. government made large financial investments to reduce pollution in the nation's rivers and streams [60]. In addition to controlling eutrophication and protecting favorable ecological uses, USEPA also established nutrient criteria for P in lakes, streams and rivers for different geographical areas of the U.S. The EPA considered 0.05 parts per million (ppm) to be the critical P level in lakes and 0.10 ppm to be critical in flowing waters [61]. The impact of land use, land cover and agricultural activities on surface water quality across the country can be seen by evaluating the variability of the quality of amongst drainage basins, e.g., [62–65]. The established pollution control measures improved water quality in certain areas, however, in spite of all the available strategies, surface runoff from agricultural fields often remained significantly higher than critical levels [66,67]. Numerous investigators suggest that the residual P stored in soils from past fertilizer and manure inputs contribute to direct and long-lasting impact on water quality, e.g., [12,19,20,22]. Repeated applications of P fertilizers result in accumulation and retention of P in soil, surface water sediments, biomass riparian groundwater through adsorption and reactions [68–70]. This P stored in soil in the form of inorganic and organic P from past inputs of fertilizers and manures is referred to as “residual” or “legacy” P. The releases and mobilization of legacy P act as a continuous source of soluble and particulate P to downstream water bodies that sustain algal blooms and tainted waters for many years both local and across multi-state drainage basins in the U.S. [71–73]. In recent years, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) application to field soils has been identified as a method to bind P and prevent off-site losses of both dissolved and particulate phosphorus to the environment, thus less P is available to algae as a source of nutrient [74–76]. However, the economic feasibility of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ application as an amendment is dependent on field erosion susceptibility and soil test P concentration [77]. Gypsum amendments appear to be a suitable technique for soil erosion control and P retention in annually tilled clay soils. The cost of the treatment likely limits the usage of gypsum for small areas, which has a substantial influence on surface water quality [75].

Over the years, the U.S. Department of Agriculture's Natural Resource Conservation Service (USDA-NRCS) has focused attention on nutrient losses and provided national guidelines for nutrient management. In particular, NRC Practice Standard Code 590 for Nutrient Management provides national guidance for state regulations and is implemented on farms receiving federal support for conservation and nutrient management. Code 590 recommends no nutrient application under winter conditions and requires the existence of conservation practices when manure is applied to frozen soils with slopes over 5% [78]. However, note that even before the USDA-NRCS national policy was implemented, many states in the U.S. began to develop guidelines and regulations for P-based nutrient management affecting crops and livestock [79–81]. In 2008, USEPA finalized a rule in order to protect the country's water quality by requiring Concentrated Animal Feeding Operations (CAFOs) for safe manure management. The USEPA's predictions are that CAFO regulations will stop roughly 56 million pounds of P from entering streams, lakes, and other water bodies annually. Even with all the regulations and policies in place, the contribution of the residual P stored in soils from past fertilizer and manure inputs has been identified as the principal source of failure to attain water quality goals two to three decades after implementing nutrient and manure management plans in many areas across the country [20]. The failure to achieve a reduction in P losses coupled with P-induced harmful algal blooms in marine, brackish, and freshwater environments has become a major concern in the U.S. [80,81]. The long-term assessment trends in P concentrations have led to an increasing realization that nutrient control strategies have been inadequate at both statewide and national levels within the projected timespan [19–21,76,81,82]. For example, P loading has severely impacted the water resources of the Chesapeake Bay

region, Mississippi River basin, Floridan inland and coastal waters, and Lake Erie drainage basin [11,12,19–21,76,80–82].

A study reviewed the efficacy of recent Conservation Practices (CPs) in the U.S. in light of the evolving challenges of reducing P loss to surface waters through agricultural management [14]. These researchers found that the recently recommended USDA-NCRS CPs and nutrient management practices are the only strategies that consistently reduce dissolved P losses. Although these strategies are included in most catchment scale conservation schemes, it is challenging to implement nutrient management plans as they are met with resistance by farmers. The researchers found that many farmers are unwilling to acknowledge the loss of dissolved nutrients to the environment compared to the easily visible loss of particulate matter [82,83]. Needless to say, the success of any agricultural nutrient plan management requires cooperation from farmers and ranchers. As such, higher levels of agricultural education along with appropriate outreach programs, which incorporate up-to-date scientific advances into their daily operation, are essential for effective nutrient management practices [83–85].

Given the implications of climate change on soil nutrient availability and plant nutrient uptake, advances in sustainable agricultural intensification along with nutrient use efficiency will be a critical solution to meet the future demand for food for the growing population in America. Sustainable intensification of agriculture refers to an effort to increase crop yields with fewer inputs (land, plant nutrients, labor and water) and without potential adverse impacts on the environment and without further expanding land usage [85,86]. Crop nutrient efficiency is an essential part of sustainable agriculture, which focuses on strategies to maximizing water use while optimizing soil nutrient management practices. A suggested approach to determine PO_4 fertilizer usage efficiency in cultivable land is based on the actual amount of P in the applied PO_4 fertilizer taken up by plants [87]. If the uptake of P is denoted as u , the uptake by plants that received P fertilizer is denoted as u_P , plants which did not receive PO_4 fertilizer is denoted as u_0 and the P input is denoted as P , then and the uptake efficiency, $eff_u = (u_P - u_0)/P$. However, in the U.S., it has been difficult to achieve sustainable intensification due to the impacts of climate change, established social norms, market structures along with the necessity for new services, information and infrastructure [87,88]. It is also noteworthy that experts on the topic have differing views regarding the definition of sustainable intensification and do not see sustainable intensification as a significant departure from existing agricultural practices due to a lack of established guidelines [88,89].

A recent study investigated the inputs of both N and P throughout the Mississippi/Atchafalaya River Basin (MARB) that have been connected to hypoxic zone in the Gulf of Mexico and water quality issues across the Midwestern Corn Belt [90]. In this study, refined SPATIALLY Referenced Regression On Watershed (SPARROW) attribute models were developed with higher resolution basin delineation, updated source inputs, improved calibration targets, and added statistical techniques (more so than those employed in the previous SPARROW models). The results showed that nutrient loads/yields were the highest from the central region of MARB and along the Mississippi River. Agronomic activities continued to be the dominant source of nutrients in the region. In addition, naturally occurring losses of P from earth materials across the river basin contribute to roughly 23% of the total P from the MARB. The findings of the study are expected to assist watershed managers to identify sources of nutrient losses and to adopt appropriate measures to make more significant impacts on nutrient reduction at the watershed.

In the past several decades, scientists and watershed managers have sought to improve the water quality of freshwater bodies and estuaries by focusing on reducing inputs of P alone (e.g., [4,91–93]). However, new research suggests that strategies that control both N and P are likely more effective in managing eutrophic processes in many environments [81,91–94]. For example, eutrophication management plans that focus only on P input-reduction strategies are unlikely to succeed in lacustrine environments where the dominance of non- N_2 -fixing cyanobacteria controls the rapid recycling of P between sedi-

ments and water. Non-N₂-fixing *Microcystis* can migrate vertically, consume excess P at the sediment–water interface, and subsequently move up to the water’s surface to develop blooms [95]. Research also suggests that the reduction of only one nutrient up-gradient to control eutrophication can result in the export of other nutrients downgradient, which may promote further algal bloom [80]. By limiting only P inputs to freshwater bodies and neglecting the considerable input of N introduced through sewage and fertilizers, a substantial amount of N can be transported downgradient where it can aggravate eutrophication in estuarine and coastal environments [96]. When planning eutrophication management, it is important to understand that watershed hydrological processes are complex and different watersheds are governed by a wide array of management activities related to various regulations and programs. Increasingly, the U.S. has been implementing watershed-based permitting and stringent effluent discharge regulations both for N and P [91,92,97].

There is no specific solution to solving P pollution of water resources [3]. Proper management of P for food security can be achieved through a holistic approach comprising of at least a reduction in consumption levels, source management, more specific regime-based nutrient criteria, routine soil fertility evaluation and recommendations, transport management, development of extensive water recycling programs and removal of P from wastewater using economical and environmentally friendly sorbing materials [12,15,98,99]. For example, the P recovery rate from the liquid phase can reach up to 40 to 50% and the costs for recovered PO₄ exceed the market price of rock PO₄ by several times [98]. Successful P recycling initiatives will give both economic and environmental gain with no detriment to agricultural production [98]. Additionally, strict upstream nutrient-control actions will result in downstream water-quality improvements. Without employing a combined approach, the traditionally applied surface runoff and erosion control measures may prove to be an inefficient and expensive solution to the problem. The USEPA is currently combating P pollution in the nation’s water bodies by taking concerted and collaborative approaches with stakeholders by providing guidance regarding water quality trading and market-based approaches, supervising regulatory programs, working with states to restore waterbodies impacted by P, conducting outreach programs to create public awareness of potential solutions to P pollution, developing partnerships with state, federal and national organizations to decrease influences of P pollution, providing direct technical support and resources to states to develop water quality criteria for nutrients, financing nutrient control activities, and conducting national research and development activities to understand the transport and behavior of P and eutrophication, and to develop nutrient monitoring sensors in an affordable platform [100].

The main challenge in the forthcoming few years lies in carefully considering soil nutrient management at all levels in order to provide farmers and ranchers with economic benefits while reducing the threat of nutrient pollution in the U.S. At the farm level, nutrient management practices can be improved by applying fertilizer and manure in the correct amount, at the right season, with the appropriate method and with the precise placement. With site-specific nutrient management, P-enriched fertilizer can be applied in enough amounts to overcome soil P deficiencies and ensure profitable crop farming. Freshwater bodies are valuable natural resources for irrigation of cropland and drinking water across the U.S. and sustainable nutrient management strategies should focus on the land–ocean aquatic continuum and control both nitrogen and phosphorus appropriately.

7. Conclusions

In recent decades, P use has become progressively widespread due to its depletion in soils used for agricultural and livestock production. In many areas of the U.S., a portion of the unused P-enriched fertilizer has accumulated in soil, which has subsequently led to severe environmental problems long after its application. In many areas, excessive use of P has also resulted in deterioration of water quality in aquatic systems by accelerating eutrophication. Although many advances have been made over the last several decades to manage eutrophication, it still remains one of the leading problems in protecting America’s water.

Case studies of individual ecosystems provide valuable insights into the extent of the impact of nutrient input in aquatic systems and also helps identify the weaknesses of current nutrient control measures. The review identified that sustainable P control strategies will require a multi-faceted approach integrating the economic, technical, environmental, and social aspects of P management. Additionally, it is clear that in the future, there should be systematic research on sustainable P control measures that should focus on the land–ocean aquatic continuum and control both nitrogen and phosphorus appropriately.

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