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Water Quality

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Past Challenges

About 60% of an adult human's body weight is comprised of water, highlighting the critical importance of access to drinking water to survival. Across human history, civilizations have developed and flourished around water resources. Water has also been a source of conflict, both between countries and even within a given country where water disputes have occurred. Water is needed to grow the crops and forages that feed humans and livestock, and to sustain forests used for housing and other products. Water is also used as a transport mechanism for commerce and in aquaculture, which contributes to the overall food supply of the population. Water resources in the United States have been protected with policies to conserve water quality, a natural resource vital to national security.

In the 1930s and 1940s water quality policies, resources, and practices largely focused on erosion and flooding, but there was not a national policy on water quality. Not until the Federal Water Pollution Control Act (FWPCA) was enacted in 1948 was the concept of water quality brought to the forefront. The original, unamended FWPCA addressed water quality issues that were related to soil erosion, sedimentation, and flooding control. As new challenges and research emerged, there were changes in the FWPCA to address challenges that were due to chemical and agrochemical pollution. In the decades that followed, legislative amendments were implemented to address these challenges, namely the Federal Water Pollution Control Act Amendments of 1972, the Clean Water Act of 1977, and the Water Quality Act of 1987.

Although it was not until the 1970s that changes in policy were implemented to specifically address the nutrient issues related to water quality, the issue of

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water quality was addressed when Congress acted in 1935 to authorize and direct the Secretary of Agriculture to establish the USDA Soil Conservation Service (SCS), which was later renamed with an amendment in 1994 as the Natural Resources Conservation Service (NRCS). The establishment of SCS (later NRCS) contributed to the improvement of water quality by creating an agency that led the effort to mitigate erosion, an action that also contributed to reducing the transport of agrochemicals to water bodies. This action, along with the FWPCA and later amendments, were key components of the 20th century efforts to protect water quality in the United States. Farm bills passed by Congress over the last 75 years have included water quality funding provisions that have contributed to programs and initiatives that have helped conserve water quality.

The challenges that the United States faced 75 years ago with soil erosion threatening the sustainability of agricultural systems, including the Dust Bowl era of the 1930s, were significantly mitigated as understanding of the soil erosion process improved and management practices reduced off-site transport of sediment, which was a major success for sustainability and food security in the United States. The SCS/NRCS addressed challenges related to sedimentation, which were impacting water quality and contributing to flooding problems, with the development and implementation of management practices to reduce erosion. Additionally, universities, extension services, private consultants, conservation practitioners, farmers, ranchers, and natural resource conservation organizations have been working with SCS/NRCS to implement conservation practices on the ground to reduce erosion and protect water quality. Professional societies have played an important role in bringing together experts in water quality. For example, the Soil and Water Conservation Society serves as a forum for soil and water conservation professionals to come together for discussion of water quality issues as well as policies related to water quality.

Current and Future Challenges

There is no doubt that there have been success stories that have contributed to significant advances in water quality protection through reduction of erosion, and conservation practices implemented during the last 75 years to reduce erosion have also reduced transport of agrochemicals and nutrients to the environment. NRCS reported significant reduction of erosion rates in the 20th century (USDA NRCS 2010; Argabright et al. 1995). Erosion rates declined about 58% from the 1930s to 1992 in the northern Mississippi Valley Loess Hills (Argabright et al. 1995). The reduction of erosion rates during the golden era of soil and water conservation (1930s to 1980s) is one of the great conservation success stories of the 20th century, yet it often goes untold. If we extrapolate the data from USDA NRCS (2010) and Argabright et al. (1995), we can infer that the erosion rate was reduced across the entire United States by over 50%, with roughly 80% of this reduction occurring during the golden era of soil and water conservation and 20% of the reduction occurring from the 1980s to 1990s, contributing to conservation of water quality (year and erosion rates in mm y^{-1} [in yr^{-1}]: 1930, 2.9 [0.11]; 1982, 0.77 [0.03]; 1992, 0.67 [0.03]; 2007, 0.51 [0.02]; 2020, 0.51 [0.02]). Yet significant water quality challenges remain, and there are biological, agrochemical, and other factors that are difficult to control. Excess nutrients can escape to the environment through different pathways, complicating efforts to control these losses. Losses of reactive nitrogen (N) and phosphorus (P) to the environment are a wicked problem, and this becomes particularly apparent when legacy P is considered. The water quality challenges of the 20th century were not completely resolved and indeed persisted, and may have even worsened by the end of the millennium.

The 21st century presents both familiar and new water quality challenges. Among the new challenges for water quality is the impact of rapid population growth that has occurred since 1946 in the United States and globally and the need to increase agricultural production to feed an additional 2.5 billion people by 2050. This has put pressure on agricultural systems to intensify production, including production of beef, poultry, pork, dairy products, and other agricultural products, which has contributed to some agricultural areas shifting from nutrient sinks to nutrient sources (Sharpley et al. 1999). Ribaudo et al. (2011) reported that over 90% of acres treated with manure in the United States were not using best N rate, best method of application, and/or best time of application. A changing climate with more frequent extreme weather events also threatens to increase erosion rates and the off-site transport of agrochemicals and nutrients to water bodies via surface runoff or leaching. Greater precipitation events can increase nitrate (NO_3^-) leaching through tiles and through the soil profile, potentially impacting groundwater. With legacy effects that continue to affect nutrient transport, these water quality challenges persist in the United States and other regions.

A new challenge is highlighted by recent reports of N contributing to increased microcystin concentrations via impacts to the cyanobacterial community. Guidelines established by the World Health Organization recommend that microcystin levels in drinking water not exceed 1.0 μg L^{-1} (WHO 2011). In the United States, the US Environmental Protection Agency (EPA) has established a safe limit for children under six years old of only 0.3 μg L^{-1} (USEPA 2015a). Microcystin contamination could compromise human health by contributing to gastroenteritis and liver and kidney damage.

It has been recently reported that nutrient losses could contribute to or exacerbate hypoxic zones and algae blooms that could increase microcystin levels

(Monchamp et al. 2014; Smith et al. 2018). Phosphorus losses can also contribute to hypoxic zones that impact water quality (e.g., Lake Erie) (International Joint Commission 2013). Besides negative environmental impacts caused by lower water quality, hypoxic zones and algae blooms negatively impact tourism and fishery industries as fish populations decrease and local communities are impacted by temporary closures of beaches, lakes, and other water bodies that serve as recreational areas.

Water quality affects water bodies across the United States, with economic impacts in the billions of dollars per year. For example, it is well established that soil erosion negatively impacts water quality. At the individual farm level, it is estimated that for every 10 cm (4 in) of soil lost via erosion there is approximately a 4.3% loss of productivity, and this loss of productivity will be greater for the next 10 cm of soils that get eroded (Bakker et al. 2004). Additionally, the value of the nutrients lost from a given field has a dollar value. The off-site impacts on water quality may be higher, especially the potential impacts to human health. Ribaudo et al. (2011) reported that the cost in the United States to remove NO_3^- from drinking water supplies is $1.7 billion annually. Nitrates can significantly impact human health (Follett et al. 2010; Temkin et al. 2019). The EPA has reported that the safe limit of NO_3^- in drinking water is 10 mg NO_3-N L^{-1} (USEPA 2015a). Temkin et al. (2019) has recently suggested that lower concentrations of NO_3-N could have negative impacts on human health. Temkin et al. (2019) reported that a colorectal cancer risk of one in a million was associated with concentrations as low as 0.14 mg NO_3-N L^{-1}, with higher risk at higher concentrations. They also reported that close to 3,000 cases of low birth weight and about 2,300 to 12,500 cancer cases annually in the United States could be linked to NO_3^- exposure. The economic cost of NO_3-N impacts on human health was reported by Temkin et al. (2019) to range from $250 million to $1.5 billion, with an additional cost of $1.3 to $6.5 billion when lost productivity is accounted for.

Delgado (2020) noted that while the use of N fertilizer has led to an abundant food supply, it has also resulted in increased N losses from agricultural systems to the environment. He also reported that although there are benefits to nutrient management, there will continue to be environmental damage unless the errors of the 20th century are avoided. The challenge of 21st century management is thus to avoid these errors to produce food for a population of 9.5. billion by 2050, while also adapting to the challenges of a changing climate, dwindling water resources, and the increased occurrence of extreme weather. Sustainable Precision Agriculture and Environment (SPAE, similar to the 7 Rs [Delgado et al. 2019]) can be used to help us adapt to a changing climate and reduce the off-site transport of nutrients to the environment.

Current Status of Water Quality

Although there have been significant advances in water quality efforts, recent analyses of trends in water quality across the United States indicate that water bodies remain significantly impacted. For example, a recent EPA study reported that more than half of the nation's stream miles are negatively impacted (USEPA 2016). The EPA reported that the water quality of the nation's streams is significantly impacted by chemical stressors, overwhelmingly N and P with 41% and 46% content, respectively. Additionally, the US Geological Survey (USGS) has a website that tracks current levels of pollution for water quality, including levels of total P, total N, orthophosphate (PO_4^{3-}), and NO_3^-. Visitors to the site may graph the trends across the nation for these and many other parameters from 1972 to 2012; 1982 to 2012; 1992 to 2012; and 2002 to 2012 (USGS 2020b).

Across about 100 sites in the United States, total P exhibited an increasing trend from 2002 to 2012, while at about 120 sites, the P concentrations decreased, and for about 80 sites, the concentrations of P remained the same, suggesting an average of about 30% of sites with increasing total P concentrations (figure 1). For NO_3^-, about 100 sites exhibited increasing NO_3^- concentrations from 2002 to 2012, and at about 70 sites, the concentrations of NO_3^- remained the same, while about 150 sites experienced decreasing NO_3^-concentrations, suggesting an average of about 30% of sites with increasing total NO_3^- concentrations (figure 2).

The trends in annual water quality load to the Gulf of Mexico may also be monitored through a USGS website (USGS 2020a). The five-year moving average of the yearly total P load increased from 1979 to 2019 (figure 3), and only in two years from 1997 to 2019 did the flows meet the goal of a 20% reduction from the 1980 to 1996 baseline in yearly total P load, with one of those years as low as 45% reduction (2006). The goal of a 20% reduction in total P has not been achieved during the last 13 years, and total normalized loads have not decreased since 1983. The year 2019 had the highest total annual P load of this 40-year period. The total dissolved NO_3^- plus nitrite (NO_2^-) flow-normalized loads have not been reduced since 1979, and if anything, have slightly increased (figure 4). The year 2019 had the highest total NO_3^- loads of the past four decades. The USGS data are in agreement with the EPA report that water quality in the United States is under stress, especially because of nutrient losses (mainly N and P). Other water quality measurements, such as trends in pesticides and algae (diatoms), are also available at the USGS website.

Current Advances in Nutrient Management

The growing use of N fertilizer recommendations for different crops and soil types across the United States and the world played a key part in the Green

Figure 1

Trends in nutrient content (total phosphorous) of water from 2002 to 2012 across the United States (USGS 2020b). Red triangles indicate areas where phosphorus is likely up, while upside-down black triangles indicate where it is likely down.

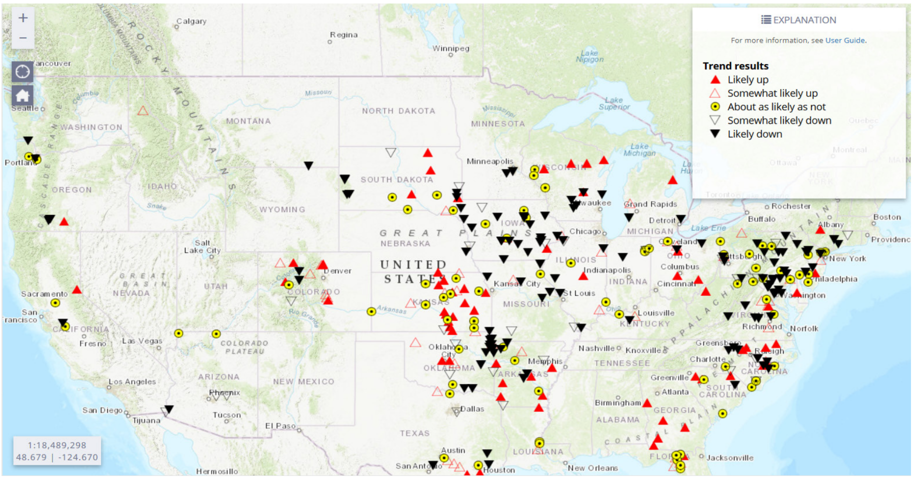


Figure 2

Trends in nutrient content (nitrate) of water from 2002 to 2012 across the United States (USGS 2020b). Red triangles indicate areas where nitrate is likely up, while upside-down black triangles indicate where it is likely down.

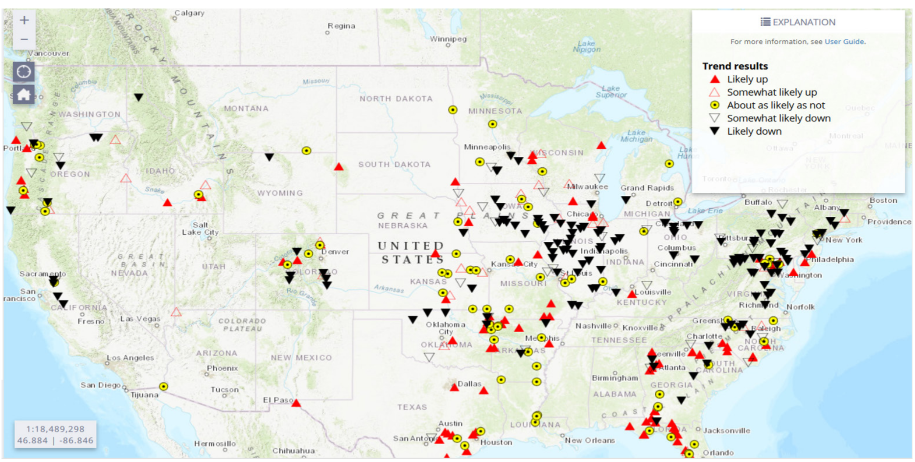
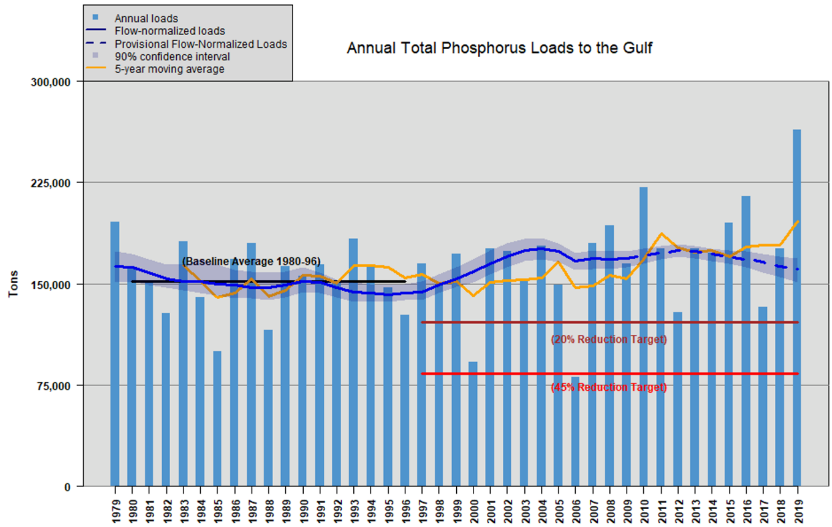


Figure 3

Trends in yearly phosphorus loads to the Gulf of Mexico from 1979 to 2019 (USGS 2020a). Graph shows annual loads (bars) and reduction targets (red lines), as well as flow-normalized loads (solid blue line), 90% confidential interval (shaded area), and the five-year moving average (yellow line).

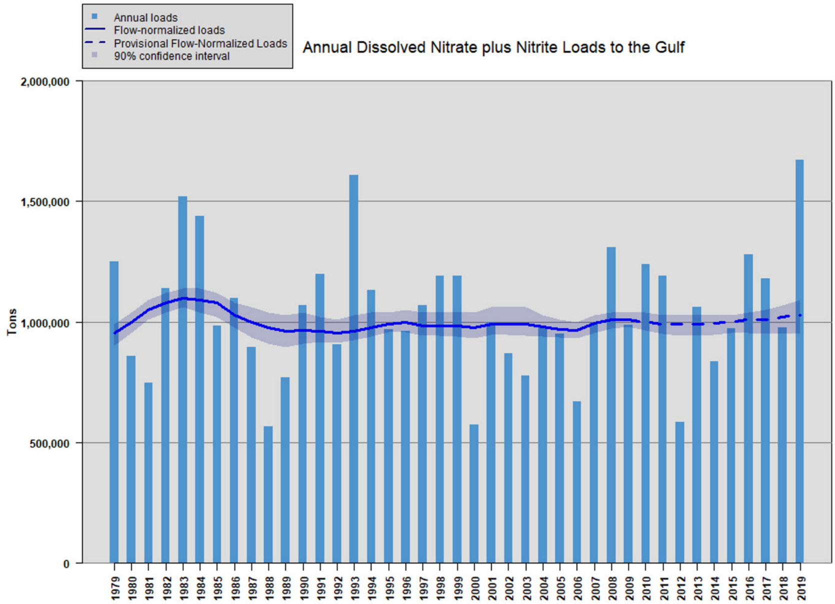


Trend start period	Trend end year	Trend, in percent change	Lower 90% confidence interval	Upper 90% confidence interval	Trend attributed to changes in streamflow	Trend attributed to other changes in the watershed
1980-1996	2019	7%	-5%	17%	1%	6%

Revolution in the 1950s and 1960s. The use of N fertilizer and other fertilizers increased greatly during this time (Cao et al. 2018). Although research about denitrification, ammonia (NH_3) volatilization, and leaching was being conducted by the 1960s, it was not until the implementation of amendments to the FWPCA in 1972 and the Clean Water Act amendments of 1977 that development of research and management practices that can be applied to reduce nutrient losses to the environment by these pathways was expanded. The goals of water protection and conservation of the Clean Water Act amendments stimulated this research and the transfer of these technologies and practices to address the increased losses of nutrients that were being observed at the time. Research during the second half of the past century improved our understanding of pathways for nutrient losses, and how to implement and apply best management practices and conservation practices on the ground to reduce the losses of nutrients from agricultural systems. Nutrient management was defined by Delgado and Lemunyon (2006) as "the science and art directed to link soil, crop,

Figure 4

Trends in yearly dissolved nitrate plus nitrite loads to the Gulf of Mexico. Annual total loads to the Gulf from 1979 to 2019 (USGS 2020a). Graph shows annual loads (bars), as well as flow-normalized loads (solid blue line) and 90% confidential interval



weather, and hydrologic factors with cultural, irrigation, and soil and water conservation practices to achieve the goals of optimizing nutrient use efficiency, yields, crop quality, and economic returns, while reducing off-site transport of nutrients that may impact the environment."

New technological trends at the end of the 20th century such as the proliferation of standalone personal computers in the 1980s facilitated the development and use of computer tools and simulation models to evaluate nutrient management practices. The development and expansion of geographic information systems (GIS) in the 1990s facilitated the assessment of nutrient management spatially across the landscape. Field applications of remote sensing for nutrient management, such as various indices (e.g., normalized difference vegetation index [NDVI], nitrogen reflectance index [NRI]) and global positioning systems (GPS), came to be used more extensively in agriculture during this time and were becoming nutrient management assessment tools during the 1990s, paving the way for the development of the concept and application of precision agriculture, which made it possible to better assess the temporal and spatial distribution of sources, sinks, and pathways for nutrients. New developments in agricultural engineering and computer systems allowed users to apply variable rates of nutrients across the landscape in a given field to match maps of nutrient rate recommendations that were designed to match the observed yield variability at the same field with new yield monitoring equipment that had GPS and computer software mounted on harvesting equipment.

These new developments enable users to apply site-specific approaches to nutrient management on the ground. Precision conservation, conceived and developed in the early 2000s, considered nutrient sources and sinks and pathways for losses and transport from fields to natural areas surrounding the fields. By the 2010s, the rise of open access databases and cloud technologies started enabling the potential application of machine learning and artificial intelligence for assessment of nutrient management. Applications of robotics and drones in agriculture were emerging. Universities, the private industry, government organizations, professional organizations, consultants, farmers, and ranchers began implementing these technologies to maximize yields and increase the use efficiency of inputs while reducing the losses of nutrients to the environment. A new generation of nutrient managers and conservation practitioners were being trained at the time to apply these new technologies that differed from the traditional nutrient management approaches of five or six decades ago.

Machine learning and artificial intelligence, big data, cloud storage technologies, and handheld field devices such as smartphones and tablets have provided crucial support to nutrient management research in the application of new technologies (e.g., the rise of personal computers, the Internet, simulation models, GIS, GPS, remote sensing, precision farming, precision conservation, the cloud, drones, robotics, new agricultural equipment) at a field level. The rapid advances of the past 30 to 40 years have meant that nutrient managers and conservation practitioners have had to adapt to keep pace.

Similarly, the traditional development of best management practices that was integrating these new management technologies also was expanded during the last three to four decades to integrate some of the new findings from research. Some of the principles of nutrient management for reduction in NO_3^- leaching were published by Meisinger and Delgado in the *Journal of Soil and Water Conservation* in 2002. They reported that NO_3^- leaching losses from N fertilizer applied to common grain-production systems typically could range from 10% to 30%. Meisinger and Delgado reported that management can be a viable approach to reducing NO_3^- leaching losses and that it is important to know the soil-crop-hydrologic cycle and apply the proper N rate and in sync with the crop demand by splitting N applications at planting and during the growing season. They reported that cropping systems could be used as management tools by rotating shallow-rooted crops with deeper-rooted crops that increase the use of soil resources. They also reported that rotations with deeper-rooted crops could be used as scavenger crops and recover residual soil NO_3^- from the soil profile. Additionally, they reported adding cover crops to the rotations could also help scavenge residual soil NO_3^- from the soil profile.

Meisinger and Delgado (2002) additionally recommended that adding a legume to the rotation of grain cropping systems will reduce the need for N fertilizers and increase N cycling. There is a need to manage ecosystems, and tillage equipment and improved management practices, such as use of nitrification inhibitors, controlled release fertilizers, and enhanced efficiency fertilizers, could potentially be used to manage/reduce NO_3^- leaching. They reported that controlled drainage also could be used to reduce NO_3^- leaching. For irrigated systems, use of water management tools such as irrigation scheduling, improved irrigation systems, and other water management tools is important. Monitoring on-site N management with in-situ tools and using real-time monitoring techniques and tools such as petiole analysis, pre-sidedress soil NO_3^- tests, chlorophyll meters, and remote sensing could contribute to better N management and potentially to reduced leaching. Simulation models and N index tools could be used to assess the risk potential for each crop-landscape scenario. Precision agriculture approaches could also potentially improve N management.

It has been well-established that by using the right rate, right time, right method, and right source of N (Roberts 2007) and management zones (Delgado and Bausch 2005; Khosla et al. 2002), NO_3^- leaching losses and losses of reactive N via other pathways could be reduced. Improving nutrient management with the 7Rs for nutrient management and conservation (often called 4R+) could contribute to lower nutrient losses across the environment than the use of the 4Rs alone (Delgado 2016). Precision conservation contributes to the use of the right conservation practice at the right place (e.g., placement of grass waterways), but also connects field management with off-site management practices such as buffers, riparian buffers, denitrification traps, and other soil and water conservation practices (Berry et al. 2003; Delgado et al. 2018). It has been shown that these practices can be used to minimize nutrient losses to the environment. Precision conservation increases the effectiveness of conservation practices.

Development of Tools for Nutrient Management. With the development of standalone computer tools during the 1980s, the development of software tools for nutrient management exploded. A large number of computer tools were developed to assess nutrient management and assess the effects of management practices on the risk for potential nutrient losses. A tremendous success was the development of a P index, which was initially proposed by Lemunyon and Gilbert in 1993. Sharpley et al. (2003) described the use of different N indices across the United States in the early 2000s. The P Index was significantly expanded to be used across all states. An N index was developed by Delgado et al. (2006, 2008a) that could quickly quantify the potential for NO_3^- leaching losses. Delgado et al. (2006, 2008b) discussed the advantages and disadvantages of previous indices used to assess NO_3^- leaching. A large number of more complex models have been developed since then to assess the losses of N to the environment, such as the Nitrogen Loss and Environmental Assessment Package with GIS capabilities (NLEAP GIS) (Delgado et al. 2020; Shaffer et al. 2010), Environmental Policy Integrated Climate model (EPIC) (Williams 1983; Williams and Renard 1985), Leaching Estimation And CHemistry Model (LEACHM) (Wagenet and Hutson 1989); Root Zone Water Quality Model (RZWQM) (Ahuja et al. 2000), Adapt-N (Melkonian et al. 2008), DayCent (Parton et al. 2001), and Agricultural Policy/Environmental eXtender model (APEX) (Gassman et al. 2010), among others. Some models now can be used to assess the effects of management practices on losses of nutrients to the environment and trade the savings (reduction in nutrient losses) achieved with implementation of best management practices (e.g., Nitrogen Trading Tool [NTT] [Delgado et al. 2008b]; Nutrient Tracking Tool [Saleh et al. 2011; Saleh and Osei 2018]; CarbOn Management and Evaluation Tool—Voluntary Reporting [COMET VR] [Paustian et al. 2018]).

The Future: Precision Farming, Precision Conservation, Precision Regulation, and Ecosystem Markets for Sustainable Agricultural and Natural Systems

Conservation of water quality is a wicked challenge that has yet to be resolved in the United States. The issue of erosion impacting water quality was significantly addressed with the creation of the SCS/NRCS and the FWPCA enacted in 1948, which contributed to reduction of erosion across the nation. The mitigation of erosion's impact on water quality is one of the great conservation success stories of the 20th century. However, even with the amazing advances in applied and basic research, and technology transfer for water quality (e.g., Universal Soil Loss Equation [USLE] and other the models that started the quantification of how land management affects erosion), including the development of precision agriculture, precision conservation, and new best management practices during the last 40 years, the problem of nutrient losses to water bodies impacting water quality endures (USEPA 2008; USGAO 2013).

Nonetheless, there are nutrient management success stories to be found, such as the new crop varieties that have been increasing N use efficiencies for cropping systems. Fixen and West (2002) and Snyder and Bruulsema (2007) analyzed the yields across the United States during the last three decades; they found that they have increased significantly during this period since corn yields have been increasing, even as the average fertilizer application rate remained unchanged. In contrast, Ribaudo et al. (2011) reported the need to increase N use efficiencies in a national report finding that only about one-third of the farmland in the United States was implementing all three best management practices of applying the best N rate, with the best method of N application, at the best time of N application. Legacy nutrients, especially legacy P, which can remain in the system for a long time and moves more slowly in the environment, can also be a source of nutrients. Losses of reactive N are more dynamic since N could be lost via many pathways such as NO_3^- leaching, surface losses, NH_3 volatilization, denitrification, and emissions of nitrous oxide (N_2O), among others.

Recent in-depth reports by the EPA identify significant areas across the United States with impaired water quality. Additionally, hypoxic zones persist in some areas and are even expanding in some regions. The Gulf of Mexico continues to struggle with hypoxic zones exacerbated by N and P loads. A US Government Accountability Office publication reported that more than four decades after the enactment of the Clean Water Act, an EPA assessment had found that over 50% of the assessed waters in the United States did not meet the established water standards for fishing, swimming, or drinking, and that of the assessed lake acres and miles of rivers, 67% and 53% were impacted, respectively—a greater percentage than ever before. Recent data available from USGS about fluxes of N and P to the Gulf of Mexico reveal the stubborn persistence of water quality challenges related to nutrient loads. Delgado (2020) reported that the errors of the previous century cannot be repeated in the present one and that it is critical that we address the water quality issues related to nutrient contamination.

A modeling simulation of the effect of climate change across the Mississippi watershed should be conducted to test the hypothesis that there may be a correlation between weather and nutrient losses, with lower nutrient loads reaching the Gulf of Mexico in years with lower precipitation and higher precipitation increasing the loads, and to assess what management practices will be needed to minimize future impacts in tile and nontile systems. This evaluation should also consider the effects of extreme weather events since higher NO_3^- leaching rates might be driven by large precipitation events. As the climate changes and extreme weather events occur more frequently, this will pose additional challenges to nutrient management. Fortunately, we can use conservation practices as a tool for climate change adaptation, and we have the technology and knowledge to continue our efforts to minimize nutrient losses from agricultural fields (Delgado et al. 2011). Using the right conservation practice for the right site (precision conservation) will help us adapt to a changing climate and these extreme weather events.

Precision agriculture and the 4Rs are a great start to reduce the losses of nutrients (Roberts 2007). However, as described by Delgado (2016), the 4Rs are not enough—there is a need for a joint precision agriculture and precision conservation approach; such an approach was first described as 7Rs by Delgado (2016) but has also come to be known as 4R+, where the "plus" signifies the implementation of the precision conservation component. We need to connect the flows from the field to the natural areas and implement precision conservation to increase the effectiveness of conservation practices across the landscape. This will contribute to improved water quality in the 21st century. As we face new challenges of more intensive agriculture in a changing climate, we cannot miss the opportunity to apply the available technologies, and voluntary precision regulation could be applied via implementation of ecosystem markets where farmers and ranchers are compensated for implementing best management practices that reduce the losses of nutrients to the environment by trading these "savings" in water quality and air quality markets (Sassenrath and Delgado 2018). Management practices could be applied in an agricultural field or in natural areas using precision technologies to maximize the effectiveness of conservation practices. There is potential to use these new technologies for environmental conservation, climate change adaptation, and improving water quality in the United States.

This review has not addressed air quality, but there are atmospheric pathways for N losses that contribute to movement of N in the environment and impact ecosystems, and these pathways should also be addressed even when we are trying to improve N management for water quality and thus warrant a brief mention. Emission of greenhouse gases from cropland agriculture is 46% of the emissions from agriculture (USEPA 2015b). About 95.8% of the carbon dioxide (CO_2-C) equivalents greenhouse gases emissions from cropland agriculture in 2013 were from net N_2O (USDA 2016). The largest contributor in cropland agriculture to the emission of greenhouse gases is N fertilizer inputs. The first paper connecting emissions of N_2O to fertilizer sources in agricultural systems was published by Mosier et al. in 1991, and since then key methods have been identified to minimize N_2O emissions such as the use of nitrification inhibitors, controlled release fertilizers, and enhanced efficiency fertilizers in agricultural systems. Ammonia volatilization is also a problem and can contribute to significant amounts of N being deposited in natural areas, impacting the environment. The use of N fertilizer in the United States increased significantly from about 0.3 Tg N y^{-1} in 1940 to 11.4 Tg N y^{-1} by 2015 (Cao et al. 2018). Thus, when it comes to N inputs from fertilizer or manure sources, the atmospheric pathways for N losses also contribute to movement of N in the environment and impact ecosystems, and these pathways should also be addressed, even when trying to improve N management for water quality.

Precision farming, precision conservation, precision regulation, and ecosystem markets for sustainable agricultural and natural systems can potentially present some of the solutions that will be needed to address the formidable problem of water quality impacted by nutrients. The new agriculture that is being developed with machine learning and artificial intelligence, and increased use of cloud technologies, open-access databases, and robotics, presents great future opportunities to improve nutrient management and reduce nutrient losses. Additionally, the potential to develop new combinations of enhanced efficiency fertilizers and biostimulants also offers opportunities to increase nutrient use efficiencies in the decades to come. Research, education, and training of the upcoming generation that will use the technologies developed in the coming decades will also be an important part of technology transfer to address this wicked challenge.

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