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Perspective

Effective Nutrient Management of Surface Waters in the United States Requires Expanded Water Quality Monitoring in Agriculturally Intensive Areas

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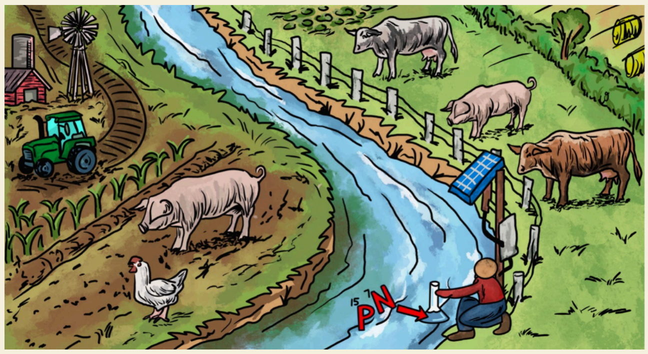
ABSTRACT: The U.S. Clean Water Act is believed to have driven widespread decreases in pollutants from point sources and developed areas, but has not substantially affected nutrient pollution from agriculture. Today, the highest nutrient concentrations in surface waters are often associated with agricultural production. In this Perspective, we explore whether challenges stemming from the Clean Water Act's inability to mitigate agricultural nutrient pollution are also exacerbated by coarse nutrient monitoring. We evaluate the current state of nutrient monitoring in surface waters of the contiguous U.S. relative to agricultural nutrient inputs to assess how monitoring effort varies across agriculturally intensive areas. The locations of nutrient monitoring stations with approximately seasonal sampling frequency (4 samples per year, on average) from 2012 to 2021 were compiled from the U.S. Water Quality Portal. Monitoring station locations were then compared to watershed-scale (HUC-8) nutrient inventory estimates for agricultural fertilizer and livestock manure inputs. From this assessment, we found that many, but not all, of the nation's most agriculturally intensive areas are under-monitored, and often unmonitored. While it is well-known that the Midwest is the epicenter of agricultural production in the U.S., our results reveal it is poorly monitored relative to its agricultural nutrient inputs. Other regions, like the California Central Valley and parts of the southeastern Coastal Plain were also coarsely monitored relative to nutrient inputs. Conversely, some agriculturally intensive watersheds were moderately-to-well monitored (e.g., western Lake Erie basin, eastern North Carolina, and the Delmarva Peninsula), with these basins largely having established Total Maximum Daily Loads and discharging to prominent waterways. In closing, we argue that sparse monitoring across many of the nation's most agriculturally intensive areas motivate a need to re-envision nutrient monitoring networks, and that increased resources and advanced technologies are likely required to enable effective nutrient source identification throughout the nation.



KEYWORDS: *nitrogen, phosphorus, Clean Water Act, Federal Water Pollution Control Act, nutrient inventory*

■ INTRODUCTION

Across the range of environmental issues, Americans are most concerned about water pollution, with over half of polled respondents indicating they are concerned "a great deal" about the quality of drinking water, rivers, and lakes.[1,2] Yet, water quality impairment remains pervasive, particularly with regards to nutrient pollution (i.e., nitrogen and phosphorus). In the U.S., over 40% of lakes and river/stream miles are in poor condition due to elevated nutrients, and about two-thirds of the national estuarine area has fair or poor eutrophication conditions.[3−5] To help improve water quality, the Clean Water Act (CWA) of 1972 was created "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" and is the primary legislation regulating surface water quality in the U.S.[6] The original CWA instituted permitting requirements for pollutant discharges to navigable waters from point sources, such as wastewater treatment plants and industry, and largely exempted discharges from nonpoint sources, like from agricultural and developed areas. In 1987, the reauthorization of the CWA included expanded provisions

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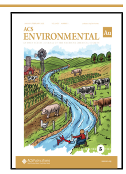

for stormwater management,[7,8] providing additional regulation of urban discharges.

Though difficult to measure its effects, the CWA is believed to have driven widespread decreases in pollutants from point sources and urban areas but has not substantially affected nutrient pollution from agriculture. For example, Keiser and Shapiro[9] analyzed over 50 million measurements collected between 1962 and 2001 from 240,000 monitoring locations across U.S. surface waters and found significant declines in many pollutants following CWA enactment, but noted that some nutrients, specifically nitrate, remained steady. Similarly, Stets et al.[10] analyzed observations from locations across the U.S. from 1992 to 2012 and reported total phosphorus was highest in urban sites in 1992 but decreased over time; by 2012, agricultural sites were associated with the highest total phosphorus concentrations. These trends indicate that CWA regulations on discharges from point sources and stormwater successfully mitigated nutrient pollution from urban areas, while leaving it unchecked from agriculture. Stets et al.[10] also found that agricultural sites had the highest total nitrogen, total phosphorus, and nitrate concentrations as compared to sites in undeveloped and urban areas, a finding that is echoed in other studies.[11,12] In addition, studies have linked high agricultural nutrient inputs to elevated watershed nutrient discharges across the nation, though such discharges are also controlled by spatial trends in precipitation, geology, and land management.[13−16]

Despite a lack of regulation on agricultural discharges, substantial money and efforts have been spent to control pollutants originating from agricultural lands over the past several decades. The establishment of the Soil Conservation Service (now the Natural Resources Conservation Service) in response to the Dust Bowl led to widespread implementation of voluntary agricultural conservation programs.[17,18] While many of the early programs focused on paying farmers to take land out of production, more money and effort have gone into funding conservation on working lands since the 1990s.[18] These agricultural practices are primarily funded through programs originating from the Farm Bill, but have also received support from state, local, and private programs. For example, 4.14% of the current 5-year Farm Bill budget is assigned to the Conservation Title, which represents $58 billion dollars from the federal level to address environmental concerns on agricultural lands.[19] In addition to public investments, private entities are also funding agricultural conservation as part of their own climate initiatives.[20] However, because most of these programs are voluntary and lack comprehensive monitoring, there have been issues with continued implementation and compliance,[21] as well as a lack of substantial improvements in outcomes like water quality and erosion.[22,23]

Our understanding of policy successes and failures in preventing water pollution comes from analysis of long-term monitoring data, the availability of which varies across the country. Under section 303(d) of the CWA, states must identify impaired and threatened waterways and develop Total Maximum Daily Loads (TMDLs) for these systems, and such requirements led to the creation of water quality monitoring networks. While there are U.S. Environmental Protection Agency (EPA) guidelines informing how routine monitoring networks should be established,[24] state monitoring programs differ.[25,26] Monitoring is also conducted by the U.S. Geological Survey, which collects ambient water quality observations across the country in addition to other hydrologic data, and the U.S. EPA conducts intensive and short-term monitoring of different systems (e.g., rivers and streams, lakes, wetlands, coasts) every few years through their National Aquatic Resource Surveys. In total, the patchwork of state and federal data collection results in a national water quality monitoring network that is extensive, but not uniformly distributed. While some areas are intensively sampled over space and time, others are devoid of monitoring altogether.[26−28]

Since the highest nutrient concentrations in surface waters are often associated with agricultural production, it would be reasonable to expect more frequent water quality monitoring in agricultural regions given the greater likelihood of eutrophication-related waterway impairment in these areas. However, thus far, the validity of this expectation remains untested. Further, prior findings on monitoring patterns put into question the degree to which surface waters in agricultural areas are effectively monitored. For example, in the U.S. South Atlantic-Gulf Region, unmonitored areas are more likely to be socially vulnerable,[27] and agricultural areas in this region have high or very high social vulnerability.[29] Similarly, water quality monitoring density is correlated with population density, with monitored and unmonitored watersheds having 14.3 and 1.2 persons/km^2, respectively.[26] Given that agricultural areas are largely rural (e.g., 88% of farming-dependent counties in the U.S. are outside of metropolitan areas[30]), correlations between monitoring and population density indicate agricultural areas receive less monitoring effort.

Building on this background, we explore in this Perspectives article whether the nation's water quality observation programs are monitoring agricultural watersheds with intensive nutrient inputs. In this work, we first evaluate the current state of nutrient monitoring in surface waters of the contiguous U.S. (CONUS) relative to agricultural nutrient inputs (i.e., fertilizer and livestock manure) to assess how monitoring effort varies across agriculturally intensive areas. We then discuss broader implications of the existing monitoring system in the U.S.

■ CURRENT STATE OF SURFACE WATER NUTRIENT MONITORING IN CONUS

To characterize spatial trends in nutrient monitoring of surface waters in relation to agricultural nutrient inputs, we combined monitoring location data from the U.S. Water Quality Portal with national nutrient inventory estimates. The U.S. Water Quality Portal includes data from over 1.5 million stations that are owned, operated, and maintained by more than 400 local, state, and federal agencies.[31] From the portal, we downloaded all surface water locations in CONUS where at least 40 sampling activities yielded at least 40 concentration observations of any nitrogen or phosphorus species logged from January 1, 2012, to December 31, 2021 (10 years), which amounts to approximately seasonal or quarterly data collection (i.e., 4 observations per year). We note that around 50−100 observations are often recommended to estimate pollutant loads in streams over decadal time periods,[32] as uncertainties increase substantially for smaller sample sizes.[33] For some applications, more samples may be needed; for example, at least 200 observations over 20 years are recommended for studying long-term trends using Weighted Regressions on Time, Discharge, and Season (WRTDS).[34] When downloading observations from the portal, we did not screen the results to determine how the observations were spread over the decadal period (e.g., if they were from locations that had short-term/intensive or long-term/routine observations), as we consider

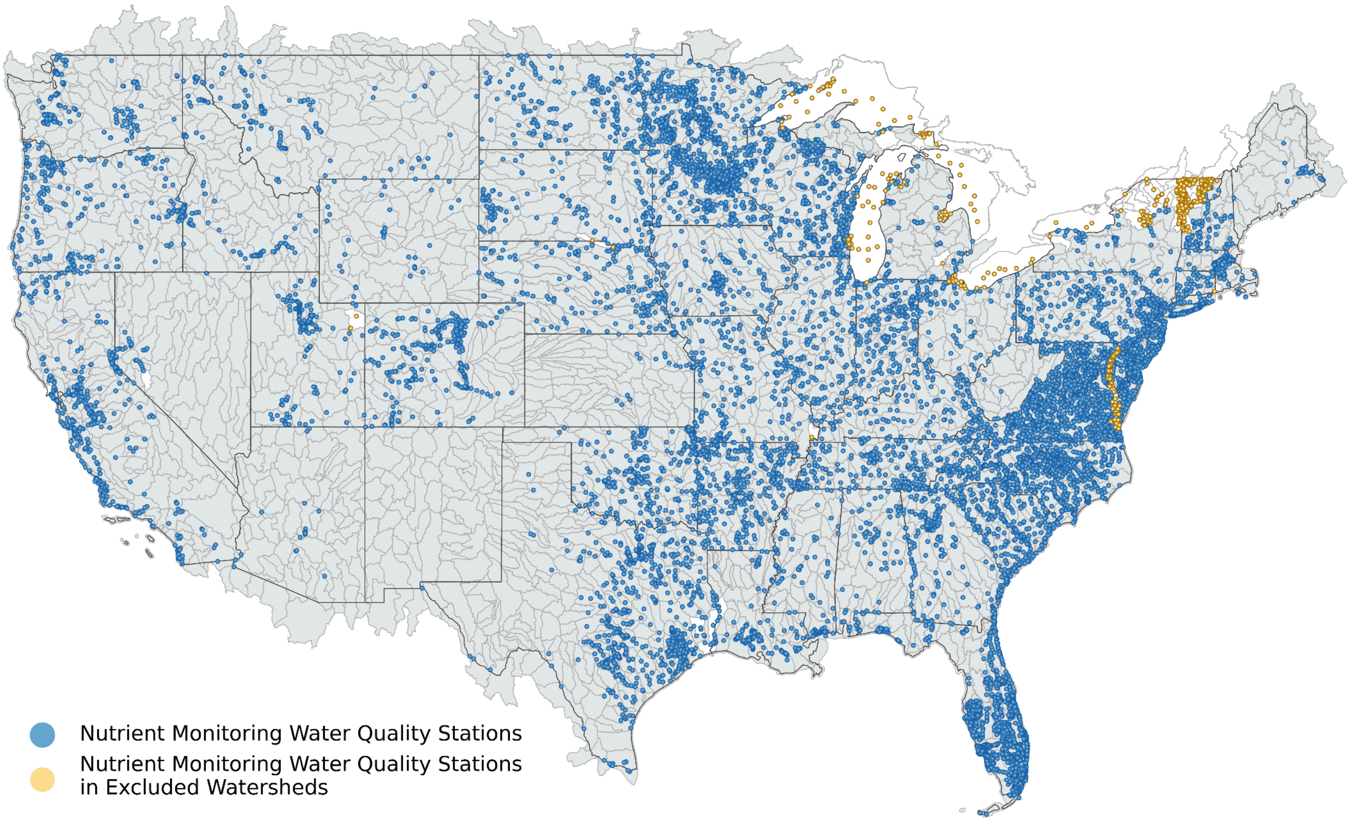

Figure 1. Distribution of nutrient monitoring station locations across the U.S. where there were at least 40 sampling activities that yielded at least 40 observations collected in 2012−2021 (n = 16,377). The gray polygons with medium gray outlines are watersheds (HUC-8); watersheds for which nutrient inventory data were unavailable (n = 41) are shown in white. State boundaries are shown as dark gray lines. Blue and yellow points correspond to water quality stations that were (n = 15,824) and were not (n = 553) considered in the study, respectively; excluded stations fell outside of watershed boundaries (e.g., Great Lakes, Chesapeake Bay) or within watersheds for which nutrient inventory data were missing.

both approaches to reflect monitoring effort, and either approach can potentially be used to assess waterway impairment. From this portal query, there were 16,377 stations with at least 40 nutrient observations over 10 years (Figure 1). Across CONUS, 34.5% of watersheds (HUC-8) have zero stations that met our inclusion criteria, and 81.8% have ten or fewer stations that met our inclusion criteria (Figure 2). Nutrient monitoring varies throughout the country, with the upper Midwest, Mid-Atlantic, Florida, and parts of some southern central states having many monitoring locations, while the rest of the country had fewer stations. New Mexico had no stations. Of the states with monitoring stations that met our criteria, Arizona, Kansas, and Nevada have the fewest stations relative to area (21, 25, and 37 stations or 7.1×10^{-05}, 1.2×10^{-04}, 1.3×10^{-04} stations per km^2, respectively), while New Jersey, Delaware, and Florida have the most (615, 155, and 2520 stations or 0.032, 0.031, and 0.018 stations per km^2, respectively).

To understand how monitoring locations relate to agricultural nutrient sources, watershed-scale (HUC-8) estimates of nitrogen and phosphorus inputs from fertilizer and recoverable livestock manure were accessed from Sabo et al.,[35,36] who compiled fertilizer and livestock manure data from other sources.[37−40] Of all the watersheds in CONUS, there were 41 for which at least one of the nutrient inventory inputs was missing, and these watersheds were excluded from subsequent analysis. In the nutrient inventories, fertilizer inputs were estimated from fertilizer sales and expenditures data, and inputs from livestock manure were modeled using livestock counts, excretion constants, and estimates of recoverability. While the inventories include multiple years of nitrogen and phosphorus input estimates, we only considered estimates from 2012, as this was the most recent year of data in both inventories and the first year of the time period considered when screening monitoring locations (i.e., 2012−2021; Figure 3). Ideally, nutrient inventory data would be available for multiple years in our study period, as the use of nutrient inventory data from only the first year of our study period adds uncertainty to our analysis. While agricultural land in CONUS has remained remarkably stable over the past few decades (U.S. farmland area only declined 6.2% from 2002 to 2022[41]), fertilizer sales can vary considerably on an annual basis due to volatility in markets and other exogenous drivers.[42] Livestock production has varied more than farmland area (e.g., there was an approximately 12%, 1%, and 13% increase in the national hog, cattle, and chicken inventory from 2012 to 2022, and a 22% and −7% change in hogs and cattle, respectively, from 2002 to 2022[43]); however, livestock production has grown increasingly concentrated,[44] and some manure management technologies have improved over time.[45] Overall, while imperfect, we believe the 2012 estimates provide a reasonable characterization of agricultural variability across CONUS over our period of analysis (2012−2021).

Nitrogen and phosphorus inputs from fertilizer and recoverable livestock manure were spatially joined with monitoring locations to produce maps summarizing station density within a watershed in relation to nutrient inputs (Figure 4). Analyses were conducted using the Python

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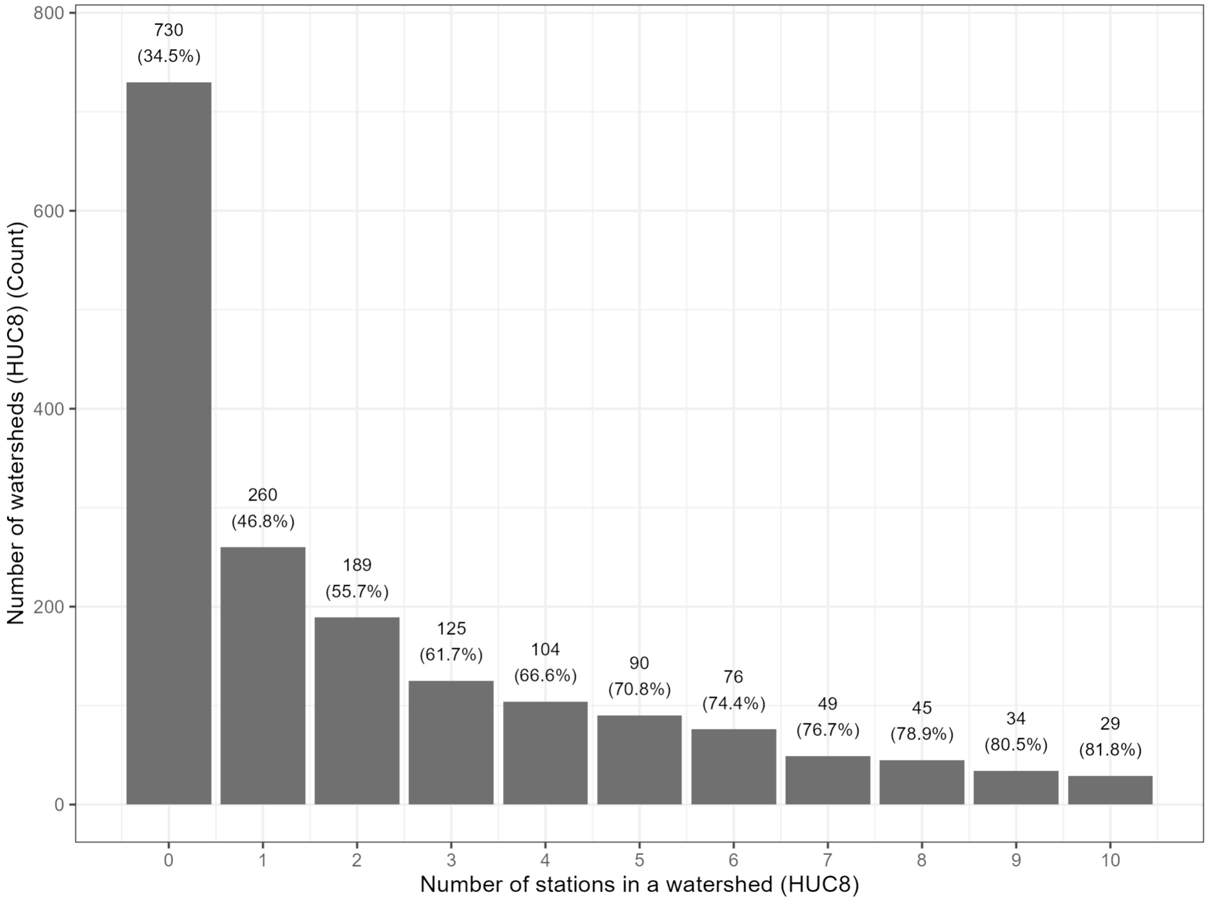

Figure 2. Number of watersheds (HUC-8s) that have 0−10 stations with at least 40 nitrogen and/or phosphorus sample observations from 2012 to 2021. The numbers atop each bar are of the corresponding number of watersheds, and the percentages in parentheses show cumulative percentages of watersheds (i.e., 46.8% of basins had 0−1 stations, and 81.8% of basins had 0−10 stations).

packages GeoPandas[46] and Pandas.[47] To create the maps, watersheds were assigned to one of nine categories created from combinations of two variables: the (annual) agricultural nutrient source input per watershed area (kg/km^2 for 2012), and the number of monitoring stations per watershed area (i.e., station density). The agricultural nutrient input variables were divided into terciles (top 1/3, middle 1/3, bottom 1/3), and station density was divided into three bins (unmonitored, low monitoring, medium-to-high monitoring; Table 1). To determine the breakpoints for the station density bins, we visually inspected a histogram of watershed station density (Figure S1). The combinations of bins from the nutrient input and station density variables created nine categories in total. We consider watersheds with high nutrient inputs and no or low monitoring to be under-monitored agricultural areas in CONUS, and watersheds with high nutrient sources and medium-to-high monitoring to be moderately-to-well monitored. Importantly, we define under-monitored and moderately-to-well monitored in relative terms and not in reference to a benchmark of what is adequate, as such a benchmark depends on location-specific factors and monitoring objectives.

Based on results shown in Figure 4, we identified areas with varying levels of monitoring effort relative to agricultural nutrient sources. The Mississippi River Basin, California's Central Valley, Inland Northwest, and many of the coastal watersheds along the Gulf Coast were under-monitored relative to fertilizer inputs. Much of the Atlantic coast was moderately-to-well monitored with regards to fertilizer inputs, meaning these areas receive large amounts of nutrients via fertilizer but also have relatively high surface water monitoring for nutrients. Many of the watersheds with high nutrient inputs from fertilizer also had high inputs from livestock manure (e.g., parts of the Midwest, California's Central Valley, southeastern Coastal Plain), with greater variability among neighboring watersheds. Together, these maps illustrate that many, but not all, of the nation's most agriculturally intensive areas are under-monitored.

While it is well-known that the Midwest is the epicenter of agricultural production in the U.S., our results reveal that it is under-monitored, and unmonitored in some areas, relative to its nutrient contributions. Under-monitoring in the Midwest is particularly noteworthy given the area has attracted substantial federal investments for nutrient load mitigation in response to the eutrophication-caused dead zone in the Gulf of Mexico.[48] For example, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force was established in 1997 in response to the dead zone, and the task force created action plans in 2001 and 2008 that both include nutrient monitoring as a critical need.[49,50] However, while Action 5 of the 2001 Action Plan called for expanded monitoring to allow for better understanding of nutrient contributions from individual sub-basins, the 2008 Action Plan reported that monitoring had not significantly increased and that some long-term monitoring stations had actually been discontinued. Further, the 2008 Action Plan reasserted the need for greater monitoring, particularly of smaller rivers and streams. Among other

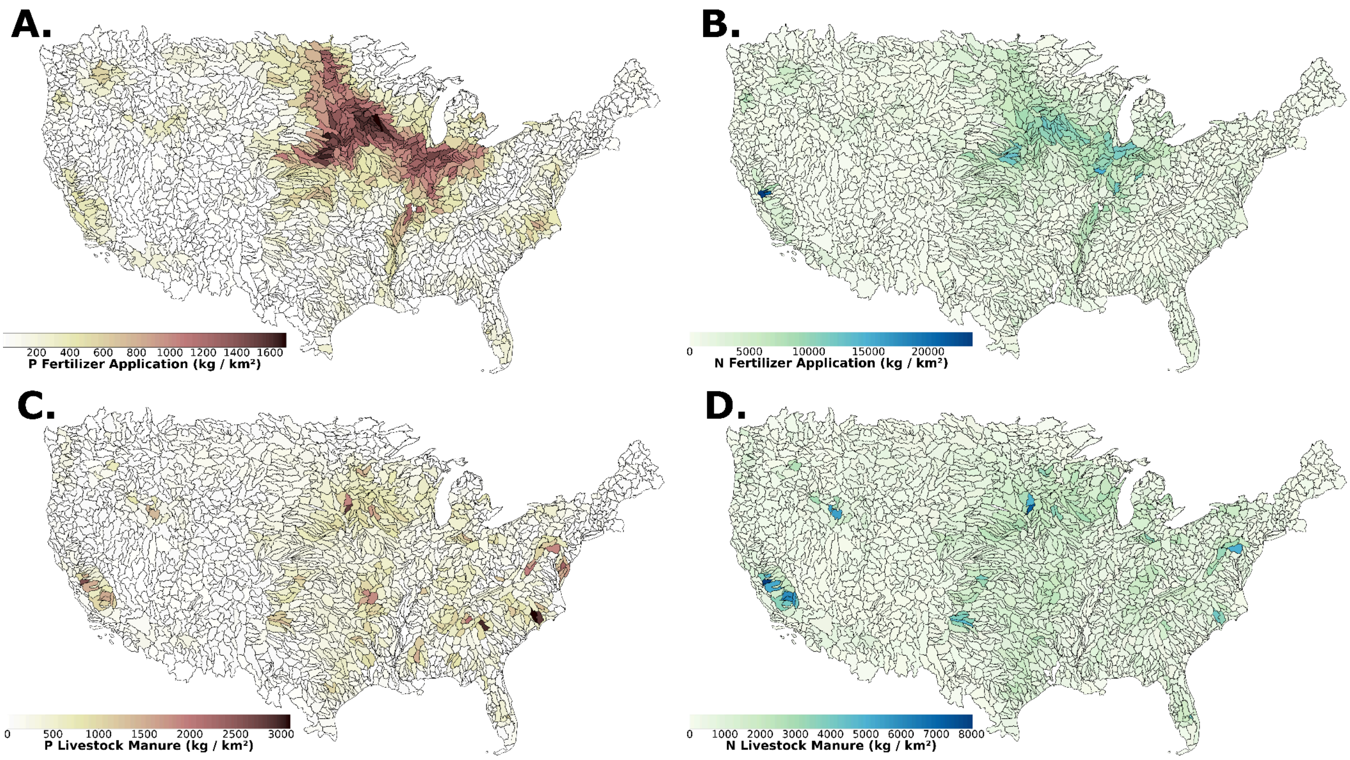

Figure 3. Watershed-scale phosphorus and nitrogen inputs from fertilizer application (A, B) and livestock manure production (C, D), normalized by watershed area. Data from Sabo et al.,[35,36] representative of conditions from 2012.

reasons, the lack of monitoring in this region could relate to logistical challenges associated with sampling in rural areas, such as having to drive long distances to either collect samples or deliver collected samples to a lab for analysis.

Conversely, some agriculturally intensive areas were moderately-to-well monitored. For example, the Delmarva Peninsula (including Delaware and parts of Maryland and Virginia), the western Lake Erie basin, and eastern North Carolina have dense livestock populations and extensive field crops, and these areas also have considerable surface water monitoring efforts. In the case of the Delmarva Peninsula, much of the land area is part of the larger Chesapeake Bay watershed, which is home to locally- and federally-supported efforts to restore the Chesapeake Bay. The Chesapeake Bay Monitoring Program was established in 1984 and has supported expanded surface water monitoring, with data from this monitoring network playing a pivotal role in informing restoration actions and documenting successes.[22,51,52] Key commonalities of these moderately-to-well monitored agricultural areas are that they all discharge to prominent waterways like the Chesapeake Bay, Lake Erie, and the Pamlico Sound with established TMDLs for nutrients.[53−55] Political and societal pressures may contribute, among other factors, to surface waters in these agriculturally intensive regions receiving greater attention via monitoring, although additional research is needed to confirm this.

While our findings present clear trends in nutrient monitoring patterns across the country, our data analysis approach has limitations. Nutrient inputs were aggregated by watershed area and binned into equal thirds, and the delineation between low and medium-to-high station density was based on a visual assessment of the data distribution (Figure S1); thus, other thresholds and categorizations could lead to somewhat different visualizations relative to Figure 4. However, there were 135−152 watersheds (6−7% of all watersheds in CONUS) that had high inputs for at least one agricultural nutrient source and zero monitoring stations, demonstrating a clear under-monitoring issue. Additionally, we did not consider placement of stations within a watershed. In some areas, monitoring stations may be clustered near urban centers, providing little information on nutrient export from agricultural lands. Moreover, high station densities in agriculturally intensive watersheds will not always reflect stronger monitoring. For example, a monitoring network of 10 sparsely monitored stations near headwaters may provide less useful information than one intensively monitored station at the watershed outlet.

A potential extension of the presented analysis is to move beyond evaluating monitoring needs as a function of nutrient inventory inputs, and to consider hydrologic nutrient exports (i.e., instream loads) and concentrations when evaluating the adequacy of existing monitoring networks. Water quality impacts are most strongly associated with surface water concentrations or instream loads, rather than terrestrial inputs. At a local scale, nutrient concentrations are typically the most important determinant of water quality, with algal concentrations increasing roughly proportionally to the concentration of the limiting nutrient.[56] However, downstream environmental impacts in large waterbodies, such as harmful algal blooms in Lake Erie or hypoxia in the Gulf of Mexico, typically respond most strongly to cumulative nutrient loading.[57,58] Fortunately, standard approaches to analyzing instream nutrient data provide both average concentrations and loads.[34] Given that load is the product of concentration and flow, we would expect a load-based evaluation (e.g., load per station) to suggest greater monitoring needs in wetter portions of the nation. Indeed, precipitation influences both the spatial and temporal variability in nutrient loading across the U.S.[13,14]

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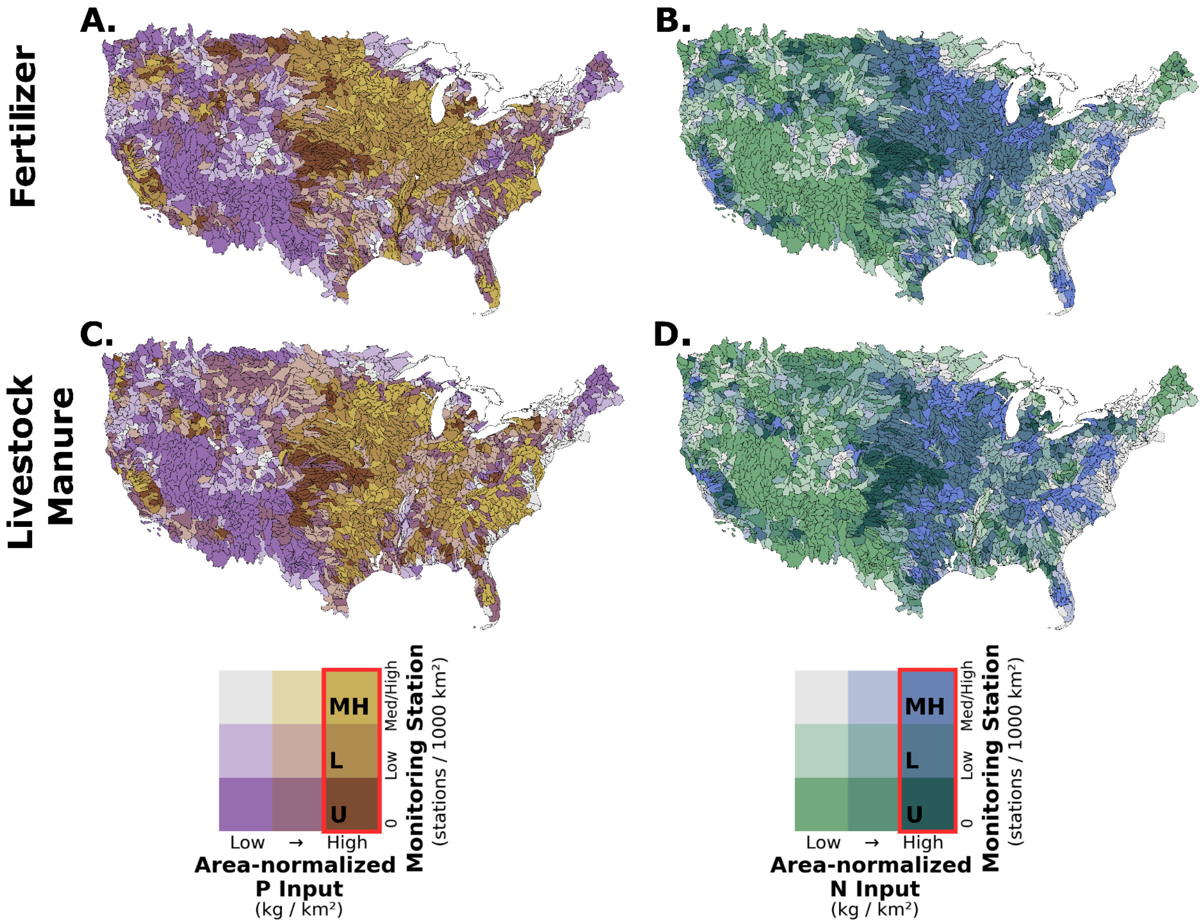

Figure 4. Bivariate maps of watersheds (HUC-8) colored based on the area-normalized agricultural phosphorus (left column: A, C) and nitrogen (right column: B, D) input and station density in the watershed. Panels A and B show inputs from fertilizer application, while panels C and D show inputs from livestock manure production. On the legends, "U", "L", and "MH" denote colors used for basins with high agricultural nutrient inputs and no (i.e., unmonitored), low, or moderate-to-high surface water monitoring, respectively. In the text, "under-monitored" is used to refer to U and L basins. In the legend, the bins outlined in red are those that are interpreted further in the text. Basins with no fill (n = 41) have missing nutrient inventory information.

Table 1. Bin Limits for Nutrient Inventory (Area-Normalized) and Station Density Variables[a]

Variable	Low	Medium	High
Fertilizer, phosphorus (kg km^{-2})	$0.02 < x \leq 30.2$	$30.2 < x \leq 149.6$	$149.6 < x \leq 1696.4$
Fertilizer, nitrogen (kg km^{-2})	$-0.001 < x \leq 221.2$	$221.2 < x \leq 1128.5$	$1128.5 < x \leq 23745.9$
Livestock manure, phosphorus (kg km^{-2})	$-0.001 < x \leq 65.5$	$65.5 < x \leq 233.1$	$233.1 < x \leq 3102.0$
Livestock manure, nitrogen (kg km^{-2})	$-0.001 < x \leq 235.3$	$235.3 < x \leq 699.8$	$699.8 < x \leq 8037$
Station density (stations per 1000 km^2)	0 (unmonitored)	$0 < x \leq 2$ (low monitoring)	$2 < x$ (medium-to-high monitoring)

[a]Each variable was divided into three bins.

Instream concentrations may also be affected by precipitation patterns, though in less consistent ways, due to localized flow-concentration relationships.[59] At the same time, it is important to note that surface waters aggregate nutrients from urban, agricultural, and other sources. In the context of our objectives, the agricultural component can potentially be isolated using results from large-scale source attribution studies.[14,60]

IMPLICATIONS OF UNDER-MONITORING IN AGRICULTURALLY INTENSIVE REGIONS

Challenges stemming from the CWA's inability to mitigate agricultural nutrient pollution are further exacerbated by coarse nutrient monitoring of surface waters in many agricultural watersheds of the U.S. Without sufficient monitoring that accounts for geospatial and temporal variation, there is limited information from which to develop effective pollution mitigation strategies, calibrate and validate process-based models, and track mitigation action successes and failures. Thus, we join a chorus of other researchers calling for expanded water quality monitoring,[61−63] and specifically highlight the need for greater nutrient observations in under-monitored and agriculturally intensive watersheds, including the areas highlighted in this work.

Expanded monitoring in agriculturally intensive areas would provide several benefits, particularly by helping to identify critical source areas that disproportionately contribute pollutants.[64] In many cases, critical source areas are relatively small. For example, in an analysis of six watersheds over seven years, White et al.[65] found that 5% of the land area contributed 34% of the watersheds' phosphorus load. Frei et al.[66] analyzed nutrient observations collected across CONUS over 20 years and estimated that 2−8% of the total land area generated 75%

of the observed nutrient flux, with the largest nutrient fluxes associated with watersheds less than 250 km^2. Nutrient observations collected from monitoring locations represent the corresponding drainage area (surface and subsurface); thus, when monitoring data are spatially sparse, small critical source areas can be lumped with larger watershed areas, preventing their identification. Though process-based models like the Soil and Water Assessment Tool (SWAT) and SPAtially Referenced Regression On Watershed attributes (SPARROW) can be used to estimate critical source areas when observational data are sparse, their predictions are often highly uncertain[67−70] and only as detailed as the available model inputs.[71−73] Models are critically important for filling gaps in observational data and providing mechanistic explanations, but they cannot fully substitute or replace observations.

Ultimately, identifying critical source areas is key to developing and implementing efficacious and cost-effective mitigation actions, particularly since surface water pollution remediation is costly. From 1970 to 2014, $2.83 trillion (in 2017 USD) was spent in the U.S. to reduce surface water pollution,[2] not including measures specifically targeted at improving drinking water quality. Though expanded monitoring will require financial support, we argue that resources spent on monitoring are worthwhile given observations support identification of specific critical source areas, leading to more efficient spending on larger-scale projects targeting load reductions. Expanded monitoring would not only help to identify areas best suited for pollution mitigation actions, but would also support nutrient recovery efforts as well as create opportunities to address existing social inequities in the current placement of nutrient monitoring stations.[26−28]

When considering monitoring expansion, the temporal resolution of sampling—and not just the number and placement of sampling locations—must also be considered. Particularly in cases when monitoring data are used to track downstream impacts of restoration actions or adopted best management practices, more frequent monitoring data are needed to resolve time-varying trends and account for confounding effects, such as from flow variation.[34] While we identified 16,377 stations with at least 40 sampling activities that yielded at least 40 observations over 10 years, we expect far fewer would have sufficient temporal resolution for resolving long-term trends. For example, in their assessment of water quality trends from 1992 to 2012 across CONUS, Stets et al.[10] analyzed all monitoring stations for which there were sufficient data to run WRTDS. In total, they analyzed data from 159 locations for total nitrogen and 230 for total phosphorus, demonstrating that few stations have sufficient temporal resolution for trend analyses; however, we also note that WRTDS requires continuous streamflow data to accompany discrete water quality observations, and the streamflow requirement imposes an additional constraint that likely resulted in other relatively intensely monitored stations not being considered. While we focused on the spatial distribution of monitoring stations, additional research is needed to understand spatial variation in the temporal frequency of monitoring, and whether monitoring intensity correlates with geographic patterns in agricultural production.

Overall, we recognize that expanding water quality monitoring programs will require substantial investments at both federal and state levels, and these investments may be within increasingly resource-constrained fiscal contexts. At the same time, environmental monitoring has been shown to be among the most cost-effective strategies for managing and making decisions regarding environmental contaminants.[74,75] Because monitoring in rural areas poses challenges (e.g., fewer laboratories and personnel, longer driving times), alternative approaches to grab sampling for nutrient analysis should be explored, such as monitoring through the use of field-deployable sensors[76] and uncrewed aerial vehicles for sample collection.[77] Satellite remote sensing could also provide insights on areas in need of greater monitoring effort, such as waterways affected by harmful algal blooms[78,79] or high sediment loads. In some cases, existing monitoring investment may need to be shifted to prioritize areas of greater need. Lessons can also be learned from monitoring programs outside of the U.S., such as the European Union Water Framework Directive (WFD)[80] and related legislation.[81−83] The founding of the WFD led to extensive water quality monitoring across European Union nations, with Belgium, Czech Republic, and France being notable in terms of the spatiotemporal coverage and number of pollutants analyzed across their networks.[84]

■ CONCLUSION

In closing, the CWA has led to meaningful reductions in point source and urban discharges to surface waters, but its exemptions for agriculture have contributed to agriculture's growing dominance as a nutrient pollution source. To support the CWA's aim to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters",[6] we argue for expanded nutrient monitoring in agriculturally intensive areas to allow for more accurate and efficient identification of critical source areas, which could then be targeted for nutrient load reduction actions. To support this argument, we characterized the current state of nutrient monitoring in surface waters relative to agricultural nutrient inputs (i.e., fertilizer and livestock manure) across the U.S. and highlighted mismatches between nutrient sources and monitoring across many of the nation's most agriculturally intensive areas, such as the Midwest. While some agriculturally intensive watersheds were well monitored, increased resources and improved monitoring technologies are likely required to enable effective nutrient source identification throughout the nation. Importantly, we do not include recommendations as to how expanded monitoring networks should be implemented, as local monitoring efforts should reflect monitoring objectives and knowledge of location-specific factors, such as expected or known spatial variability in water quality and management practices.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsenvironau.4c00060.

Histograms of the stations per area in a watershed (PDF)

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Notes

The authors declare no competing financial interest.

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