doi:10.2489/jswc.2024.0802A

VIEWPOINT

Mapping pollutant source to enhance water quality conservation in agricultural watersheds: Nonpoint no more?

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The term "nonpoint-source pollution" (NPSP) has been used to describe land-sourced, precipitation-driven contamination of surface waters by nutrients, sediment, and land-applied wastes and chemicals since enactment of the US Clean Water Act (CWA, including amendments) in the 1970s. Congress recognized the complexities of NPSP sources, timing, and pathways when writing the CWA and therefore deferred NPSP control to state-administered programs, funded through the US Environmental Protection Agency (USEPA), under Section 319 of the CWA. Braden and Uchtmann (1985) discussed the policy decisions made, funding programs initiated, and roles of federal agencies involved, including the USDA, the US Army Corps of Engineers (USACE), and the USEPA. Renaming the Soil Conservation Service as the Natural Resources Conservation Service was coincident with an expanded role for USDA to help reduce agricultural pollutants in water. Given the importance of agriculture to society and the uncertainties involved in bringing about NPSP reductions, NPSP programs were designed flexibly to give agriculturalists time to gain experience and document success in abating NPSP. Research efforts to understand NPSP transport/delivery processes and mitigation options using soil and water conservation practices began in earnest with passage of the CWA. Sweeten and Reddell (1978) reviewed the then-current knowledge of pollutant sources and early modeling efforts, which focused mostly on erosion and sediment transport. Walter et al. (1979) discussed the principles behind conservation effectiveness in slowing rainfall runoff, as well as transport of soluble and adsorbed agricultural pollutants. The potential importance of lag effects (Braden and Uchtmann 1985) and tradeoffs among pollutants (Walter et al. 1979) were recognized in these early years. Research efforts have continued to the present through extensive field-based experiments and simulation modeling, with the Conservation Effects Assessment Project (CEAP) providing a focus for organizing these efforts within the USDA and among its Land Grant University (LGU) partners since the early 2000s (Moriasi et al. 2020; Osmond et al. 2012).

Landscape-scale variations in soils, terrain, hydrologic flow paths, and agricultural management practices were recognized as challenges to NPSP assessment and control by Duda and Johnson (1985), but they did not see these complexities as a deterrent to taking action, saying:

> We likely will never have enough information on such a dynamic problem or enough funding to prescribe just the right treatment for a watershed to achieve water quality goals—as in a "wasteload" allocation traditionally prepared for point-source discharges. [We ask—was this an early troll of the Total Maximum Daily Load concept?] Instead, a common sense approach must be taken to target implementation of BMPs to the primary pollution-source areas (or hot spots) and then use compliance with water quality standards or removal of use impairment as a measure of how well the pollution control effort fares. [Later they clarify that] the key to cost-effective water quality improvement is targeting to individual hot spots of agricultural pollution, not entire watersheds, not entire counties. . . . These hot spots can often be identified by ephemeral gullies or agricultural activities near ditches and streams.

Duda and Johnson (1985) were calling for conservationists to improve their understanding of the landscape to become better at conservation planning toward water quality improvement. However, after nearly 40 years of subsequent research, planning, and implementation on the use of conservation practices to achieve NPSP control, we can reject this quote's implied assumption that water quality issues can be addressed by treating "hotspots" that are easily identified based on visual observation and professional judgment. In particular, experience in the US Midwest shows that nutrient pollution is virtually ubiquitous across artificially drained agricultural watersheds (Tomer et al. 2008). This is why in-channel treatments (e.g., wetlands and two-stage ditches) are seeing greater emphasis in watershed conservation and research (Kalcic et al. 2018). Additionally, we know that (1) current expenditures are not resulting in water quality improvements when decadal trends are identified (Tomczyk et al. 2023), and (2) current policy may actually disincentivize treatment of hotspots (in favor of maximizing "acres treated") (Stephenson et al. 2022). The problem appears quite thorny, but in our opinion, a part of the solution lies in developing approaches to clearly identifying opportunities for efficiently reducing nutrient and sediment losses actively occurring in each individual watershed. Today, there are technologies that can facilitate this through parsing water quality issues in individual watersheds at a spatial scale that directly supports conservation management decisions and by inventory and ranking of sites suited to specific conservation practices. The purpose of this article is to show that technologies to achieve this are available and, in some places, ready for use in testing and development.

We argue that advances such as high-resolution Light Detection and Ranging (LiDAR) topographic survey data, terrain analyses, remotely sensed crop cover data, modernized soil surveys, and computerized data access and analyses can be lever-

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Received August 2, 2024.

aged to map relative sources of agricultural nutrients and sediments at a scale that is meaningful in watershed- and farm-scale conservation efforts. More specifically, the Agricultural Conservation Planning Framework (ACPF) (Tomer et al. 2013, 2015, 2017) provides three types of layered information for identifying and ranking candidate locations for conservation treatment at the scale of practice implementation—the individual field. These data are already available across most of the Midwest. To address nitrogen (N) losses in this region, land use and by-field crop rotation data can be used to estimate the spatial distribution of fertilizer-N applications, by field and across watersheds (discussed later). Second, high-resolution (ranging from <1 to 3 m) topographic information can be used to map cumulative overland flow pathways by which water moves across the landscape to streams, rivers, and lakes. This level of resolution allows for slope steepness and upstream contributing areas to be mapped in detail across any landscape. Using contributing area and slope distributions, risks of erosion and sediment transport can be mapped at greater resolution than was possible before LiDAR-derived topographic data became available. This means that maps of upslope contributing areas can be weighted to consider estimated by-field nutrient loadings and pathway-specific sediment transport risk, rather than just land area. Third, locations suitable for installation of a range of interceptive conservation practices can be identified using conservation practice placement tools found in the ACPF toolbox, including practices that treat subsurface drainage and others that slow overland flow. With this information, the upstream contributing area to each suggested practice location can be weighted to rank each location based not just on land area but also the proportion of watershed nutrient load intercepted and/or (depending on planning objectives) risk of sediment loss. Overall, these data and geographic analyses can be used to consistently identify locations meeting threshold criteria (i.e., qualifying as a "hotspot"), where a given conservation practice could be installed to provide measurable benefits. The qualified sites can then be ranked according to the costs and benefits of conservation-practice implementation (Bravard et. al 2022). These techniques can provide ranking/prioritization among sites to help watershed coordinators engage landowners in achieving water quality improvement goals.

While this mapping technology is available now, it is not yet fully mature, nor available everywhere. We therefore encourage watershed-scale experimentation to test this approach to rank proposed sites for conservation implementation, as the databases required are developed by state. We hypothesize that the use of by-field crop rotation and high-resolution elevation datasets can be used to enhance the effectiveness of conservation efforts for NPSP control. We encourage testing of this hypothesis in a variety of agricultural landscapes, including naturally and artificially drained, and using a range of conservation practices, alone and in combination. We believe that well designed, paired-watershed experiments (King et al. 2008; Tomer 2018), combined with effective social engagement (Ranjan et al. 2020) and advanced spatial data and analysis approaches, can foster greater success in watershed improvement efforts.

METHODS TO DECIPHER RELATIVE SOURCES OF NUTRIENT AND SEDIMENT

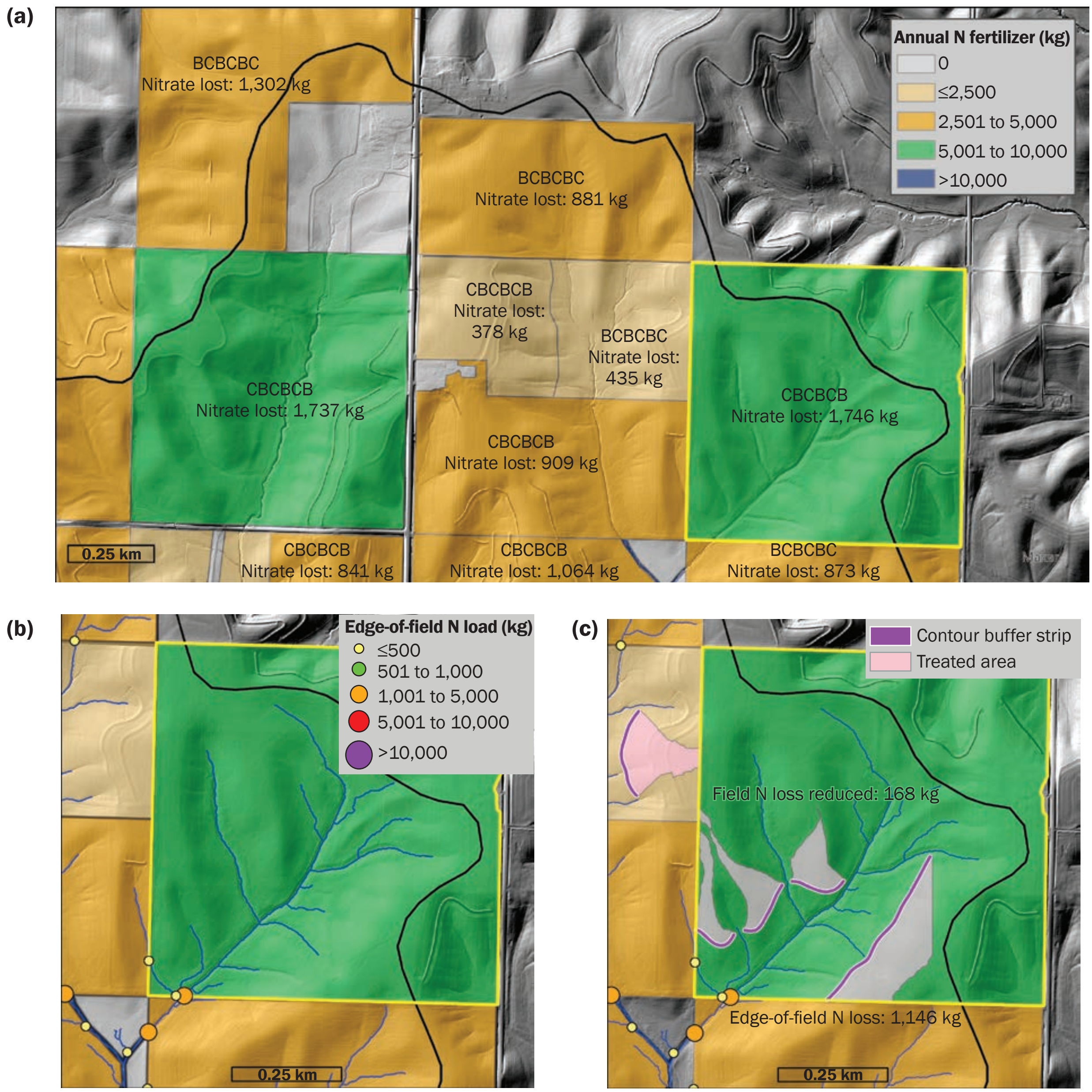
Nitrogen. First, we propose that N applications can be estimated and mapped across watersheds based on field-specific cropping histories. In the ACPF, each field is assigned a sequence of crops observed during the last six years, using the National Cropland Data Layer, which is produced annually by the USDA National Agricultural Statistics Service and based on classified satellite remote-sensing data (Tomer et al. 2017). Each field's cropping history can then be assigned a total amount of N fertilizer applied during the six-year interval, using N application rates for each crop that are based either on rates published by the State Cooperative Extension Service or user-based input values. We focus here on N applications to corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) crops, which are the dominant crops in Iowa; applications to other crops in rotation can be included as necessary.

In our example from Iowa (figure 1), the user has estimated that corn crops that follow corn receive 225 kg N ha^{-1}, while corn crops that follow soybean receive 196 kg N ha^{-1}. Greater N applications to corn following corn are typical and result in greater N leaching losses (Bakhsh and Kanwar 2007; Helmers et al. 2012). Although N fixation by soybean and other legumes, as well as soil N mineralization, certainly contribute to N leaching (Zhu and Fox 2003), the method used here follows the approach used by the Iowa Nutrient Reduction Strategy (INRS 2017) to estimate baseline N losses. The estimated baseline losses allow 45% N reduction targets to be identified by watershed, enabling Iowa to better document progress in mitigating Gulf of Mexico hypoxia. The approach employs a relationship between N application and N leaching that was based on published field-scale observations (Lawlor et al. 2008), which the INRS (2017) applied against stream-discharge versus N-load data from watersheds across Iowa. Watershed estimates of N-fertilizer applications were built using county-level data on crop cover and N-fertilizer use. When annual rainfall was included as an independent variable, a correction was identified to estimate dilution plus pathway-loss (denitrification) effects from "scaling up" between field-level (Lawlor et al. 2008) and watershed-level observations (INRS 2017). The results were grouped by Major Land Resource Area (MLRA) to enable application to nongaged Iowa watersheds by landscape region. See INRS (2017) for further details. This approach was further extended, as described by Bravard (2022), to take these regional relationships back "down" to the field scale. With estimates of by-field N applications and by-field N losses to local streams, the N-loss reductions needed for each field to contribute to the statewide 45% reduction target can be estimated.

This INRS-based approach can be tested and corrected as needed through experimentation, but for now, it provides proxy estimates of N-loss risk by field. A variety of conservation practices can be used to reduce N losses, including improved nutrient management, crop rotational changes, and interceptive practices placed within

Figure 1

Example of by-field estimated nitrogen (N) loss and reductions from an in-field practice. (a) Six-year crop rotations (with C = corn, B = soybean); color coding indicates average annual N-fertilizer applications (i.e., bulk of N applied to whole field) and labels give estimated average annual N losses from each field. (b) Area-weighted N losses assigned to within-field catchments at outlet points located at field-edges. (c) Estimated annual reduction in N loss associated with placement of in-field contour buffers. Once practices are installed, this reduction could be tallied as a contribution to the statewide N-reduction target for reporting purposes.

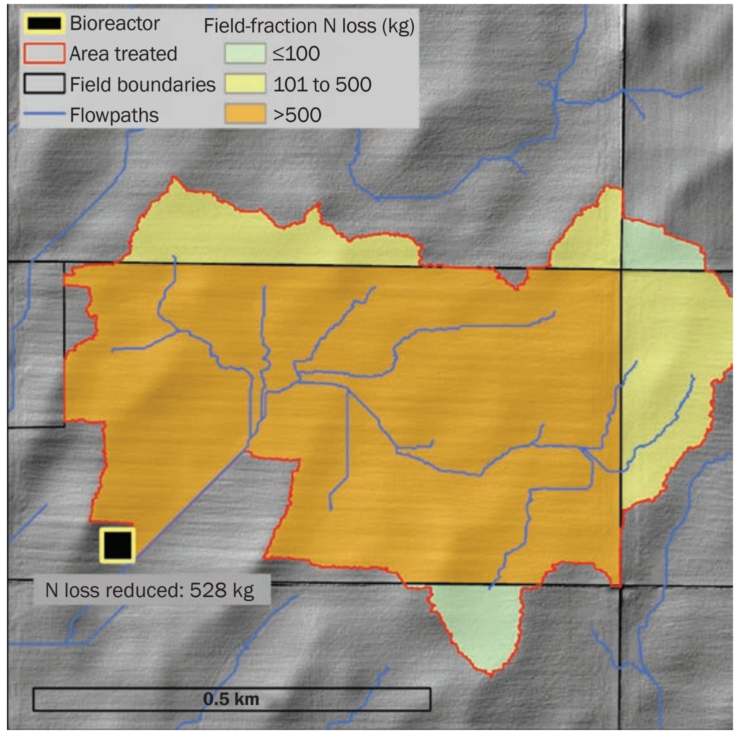


fields and at/below field edges (Tomer et al. 2013). The INRS provides estimates of N-removal efficiency for a wide range of these practices, based on a literature review (INRS 2017). With estimates of N loss by field and practice-specific rates of N removal, conservation-practice placement options identified by the ACPF can be ranked at field and small-catchment scales based on estimated N-loss reductions. Examples from using this approach are illustrated in figures 1 through 3, showing it can be applied to different practices in different landscape settings. The conservation practice placement options evaluated by this approach can be ranked according to the size of the practice catchment (i.e., upslope contributing area) and the expected N-fertilizer applications and losses from each field. Contributing areas above practices can be delineated along overland flow pathways (figure 1), via tile drainage (figure 2), and above riparian segments (figure 3). Among the cautionary notes to this approach, wherever N losses are being delivered by tile drains, the extent and routing of tile drains must be determined to prioritize installation of practices such as edge-of-field bioreactors (figure 2) and saturated riparian buffers (figure 3) that intercept tile drainage.

Because this approach aims to identify a statewide N-loss reduction target, once practices planned through this approach are installed, we propose that the associated N-loss reductions could be tallied as an estimated contribution to that nutrient-loss reduction target. This can assist Iowa state agencies in their efforts to address Gulf of Mexico hypoxia. While the approach needs to be customized by state, consistency of data sources and database structures are available (Tomer et al. 2017) to facilitate the effort in each state. Ongoing persistence in mapping crop rotations, estimating N inputs and associated losses by crop and rotation, and measuring conservation effectiveness for N reduction will allow refinement of this approach over time.

Figure 2

Estimated average annual nitrogen (N)-loss reduction associated with a woodchip bioreactor (edge-of-field practice). The N loss is estimated as a fraction of N applied, then multiplied by practice efficiency (50%) to estimate the N-loss reduction (shown as 528 kg). This reduction could be tallied as a contribution to the statewide N-loss reduction target upon practice installation.



As data on the costs of different conservation practices and their N-loss reduction efficiencies accrue, a framework for working with producers toward achieving a specified (45%) water quality target can emerge. This approach can be refined using experiments aimed at determining how N applications above interceptive practices (e.g., bioreactors and wetlands) impact nutrient loads received and removed by these practices. Experimental results could also provide cost and benefit data to help planners consider economic criteria in ranking treatment options and to support landowner decision-making on practice installations.

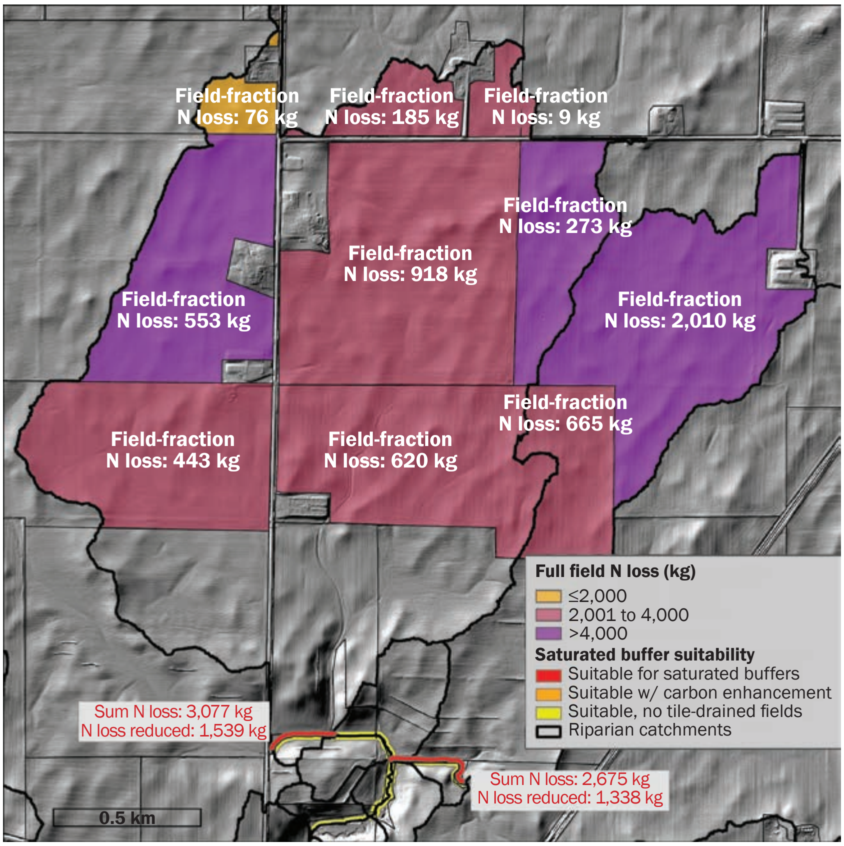
Sediment and Total Phosphorus. This approach to precision watershed conservation could be extended and applied to other contaminants. Delivery of sediment (and total phosphorus [P]) to surface waters occurs dominantly by soil erosion and overland conveyance and through erosion of stream channels and streambanks. Development of watershed sediment budgets would be needed to understand the relative importance of these sources by watershed (Gellis and Walling 2011). However, we already know that streambanks are important sources of sediment in virtually all agricultural watersheds (Simon and Klimetz 2008). Technologies to map streambank erosion, soil erosion, and sediment transport at a fine scale have advanced substantially in recent years (Gelder et al. 2018; Williams et al. 2020). Comparison of aerial photo-images taken in sequence can show the extent of channel movement and provide maps of bank erosion (loss) and deposition (gain). Williams et al. (2020) showed how this information can be combined with topographic data to calculate sediment loads resulting from bank erosion and to identify lengths of eroding bank that can be treated using channel modifications. High-resolution, LiDAR-derived elevation data provide topographic information to identify the distribution of overland flow pathways based on upslope contributing area and local slope. The product of upslope contributing area and slope provides an index of stream power, which can be mapped to show the relative distribution of erosive forces on the landscape. These map results can be used to rank sites being considered for erosion control practices, such as grassed waterways, water and sediment control basins (WASCOBS), and grade-control structures. This approach could be extended within fields to identify the steepest areas being farmed in watersheds, where practices such as no-tillage, prairie strips, or terraces could provide the greatest benefits for erosion control. Again, watershed-scale experiments that demonstrate judicious placement of erosion control practices are suggested to help develop and demonstrate the approach and document success.

SYNOPSIS

Given the scale and complexity of agricultural water quality issues, which continue

Figure 3

Estimated nitrogen (N)-loss reduction from installation of saturated buffers (i.e., riparian practice) during a six-year rotation. Average annual N losses are estimated as a fraction of the N applied, with the reduction from the saturated buffer estimated at 50% of the average annual loss. The N-loss reduction could be tallied as a contribution to the statewide N-loss reduction target upon installation. This planning information would need to be adjusted based on actual tile drainage outlet locations and linear extent of saturated buffer installations.



to be addressed using federal policies enacted nearly a half-century ago, conservationists need tools and data to help them assess opportunities to improve watershed conservation and to engage landowners in taking measures to reduce NPSP. We suggest that those needed tools and data are already available across most of the US Midwest. We need to share these tools and data more widely and use them in an experimental approach, encouraging conservation-citizen science. We may find that, as a result, the term "nonpoint-source pollution" loses its meaning as sources of diffuse agricultural pollution become easier to define, map, and address through conservation measures.

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