JOURNAL OF SOIL AND WATER CONSERVATION
https://doi.org/10.1080/00224561.2025.2492525

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RESEARCH BRIEF

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Combining soil conservation with phosphorus drawdown can confront legacy phosphorus accumulation and transfer

Joshua Mott[a], Zachary P. Simpson[b], Carl H. Bolster[c], Joshua Faulkner[d], Kevin King[e], William Osterholz[e], Mark Williams[f], Brent Dalzell[g], Gary W. Feyereisen[g], Christine L. Dolph[h], Grace L. Miner[a], Lisa F. Duriancik[i], and Peter J. A. Kleinman[a]

[a]USDA Agricultural Research Service (ARS), Soil Management and Sugar Beet Research Unit, Fort Collins, Colorado, USA; [b]USDA ARS, Sustainable Water Management Research Unit, Stoneville, Mississippi, USA; [c]USDA ARS, Food Animal Environmental Systems Research Unit, Bowling Green, Kentucky, USA; [d]Department of Agriculture, Landscape, and Environment, University of Vermont, Burlington, Vermont, USA; [e]USDA ARS, Soil Drainage Research Unit, Columbus, Ohio, USA; [f]USDA ARS, National Soil Erosion Research Laboratory, West Lafayette, Indiana, USA; [g]USDA ARS, Soil and Water Management Research Unit, St. Paul, Minnesota, USA; [h]Department of Ecology, Evolution and Behavior, University of Minnesota, St. Paul, Minnesota, USA; [i]Resource Assessment Branch, Conservation Effects Assessment Project, USDA Natural Resources Conservation Service, Beltsville, Maryland, USA

ABSTRACT

Legacy phosphorus (P) in agricultural soils (i.e., P that derives from historical human activities) can resist conventional nutrient management strategies to improve water quality (e.g., placement, rate, source, and timing of application). Further, soil conservation practices such as reduced tillage, while potentially beneficial for improving soil health and minimizing erosion, can promote dissolved P loss. Comprehensive legacy P management requires targeted mitigation strategies that consider the sources and processes involved in P mobilization and transport. We modeled trade-offs and interactions of nutrient management and soil conservation strategies in legacy P mitigation efforts at three key sites in the northern United States where legacy P contributions to water quality are a concern. The Annual Phosphorus Loss Estimator (APLE) model was used to simulate generalized management scenarios at each site: current site-specific practices, conventional conservation practices (no-till and manure injection), and P drawdown (curtailing fertilizer P additions and extracting P from soils via crop uptake and harvest). Modeled results highlight that the effects of legacy P are not always obvious; even at sites near the range of agronomic optimum, losses of legacy P in runoff can be significant. Phosphorus drawdown via crop uptake and removal offers the potential to deplete legacy P stores but requires dedication and time. In model simulations, no-till reduced total P losses due to reductions in sediment transport. Coupling drawdown strategies with appropriate conservation management to avoid inadvertent P losses can reduce both dissolved and particulate P losses. Focusing on either soil conservation or soil P drawdown alone is insufficient to meet water quality goals. Phosphorus drawdown strategies must be accompanied by practices supporting soil conservation to ensure that legacy P management benefits water quality in the short and long term.

ARTICLE HISTORY
Received September 24, 2024
Revised January 27, 2025
Accepted March 5, 2025

KEYWORDS
agriculture; drawdown; phosphorus; soil conservation; water quality

INTRODUCTION

Efforts to mitigate phosphorus (P) loss in agricultural watersheds are challenged by legacy sources, particularly soil P (Jarvie et al. 2013). In the United States, legacy P from agricultural soils likely contributes to persistent eutrophication within the Lake Erie, Chesapeake Bay, Lake Champlain, Mississippi River, and Snake River watersheds (Joosse and Baker 2011; Kleinman et al. 2019; Wironen, Bennett, and Erickson 2018; Wallington, Cai, and Kalcic 2024). Additionally, watershed management strategies can overlook trade-offs in conservation practices that can inadvertently exacerbate the loss of different forms of P (Kleinman et al. 2022). For example, conservation tillage and cover cropping, while beneficial for improving soil health and minimizing erosion, can promote dissolved P loss through, among other things, increased vertical stratification of P in topsoil (Duncan et al. 2019). Thus, agricultural P management requires targeted

CONTACT Joshua Mott joshua.mott@usda.gov
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

mitigation strategies that consider the sources and processes involved in P mobilization and transport (McDowell et al. 2024).

Conventional P management tends to focus on managing P inputs (e.g., the 4 "R"s of nutrient stewardship) (Johnston and Bruulsema 2014), reducing incidental P loss (Preedy et al. 2001; Osterholz et al. 2024), and reducing soil erosion to prevent losses of particulate P (Sharpley et al. 2015). In contrast, legacy P management prioritizes practices that reduce persistent sources of dissolved and particulate P (Kleinman et al. 2011). For example, deep tillage of P-stratified soils dilutes legacy P (Sharpley 2003), but this practice brings its own agronomic and soil conservation trade-offs (Kleinman et al. 2022). As a result, drawdown strategies (i.e., the cessation of fertilizer P application combined with the extraction of soil P through crop harvest over time) remain key to decreasing P concentrations in soils and runoff water (Liu et al. 2019; Svanback et al. 2015; Schelfhout et al. 2019; Van Der Salm et al. 2009).

Legacy P management can be specific to the nuances of agricultural fields as well as the wider watershed setting (Sharpley et al. 2013). Our primary objective was to model surface runoff water quality trade-offs associated with management strategies targeting legacy P in field soils. In particular, we sought to assess the soil and water quality outcomes of conventional management as well as drawdown strategies aimed at addressing legacy P.

MATERIALS AND METHODS

Study site descriptions

Three sites participating in the USDA Legacy Phosphorus Assessment Project (USDA ARS 2023) representing a diversity of conditions in the northern United States and having at least five years of edge-of-field water quality data available were identified: Lake Champlain, Western Lake Erie, and Le Sueur River (Table 1). Lake Champlain and Western Lake Erie followed an official USDA Natural Resources Conservation Service (NRCS) nutrient management plan (CPS-590) during the monitoring period. Briefly, the Lake Champlain field occupies sloping soils

Table 1. Field management information. Average climatic data (past 30 years) sourced from Daymet (Oak Ridge National Laboratory).

Variable	Location: Lake Champlain	Location: Le Sueur River	Location: Western Lake Erie Basin
Mean annual temperature (°C)	8.25	7.57	9.75
Mean annual precipitation (mm)	1,010	907	1,030
Field drainage area (ha)	2.35	14.3	6.8
Slope (%)	3.0	3.0	0.5
Mean annual runoff (mm)	143	52	77
Observed annual total P loss (kg ha^{-1})*	0.63 (0.29)	0.43 (0.29)	0.83 (0.43)
Observed annual dissolved P loss (kg ha^{-1})*	0.56 (0.26)	0.17 (0.10)	0.32 (0.31)
Mean sediment delivery (Mg ha^{-1})	0.03	0.24	0.83
Years monitored	7	6	5
Tile drained	Yes	Yes	Yes
Prevailing management			
Crop rotations present	Legume–hay	Soybean–corn	Corn–soybean–double crop wheat
Historic external P source	Liquid dairy manure (broadcast)	Swine manure (injected); inorganic P (banded)	Swine manure (injected)
Average annual P addition (kg ha^{-1})	10.1	20.4	24.1
Average annual crop P uptake (kg ha^{-1})	16.1	25.1	26.9
Tillage	No-till	Chisel; turbo till	Vertical; rip
Nutrient management plan	Yes	No	Yes
Soil characteristics			
Drainage class	Poorly drained	Very poorly drained	Very poorly drained
Initial soil test P (mg kg^{-1})	4.2 (Modified Morgan's P)	38 (Bray-1 P)	85 (Mehlich-3 P)
Clay (%)	30	32	33
Organic matter (%)	4.55	6.5	3.68
Bulk density (g cm^{-3})	1.45	1.43	1.25

*Annual phosphorus (P) losses are presented as mean (standard deviation).

(3% gradient) on a dairy farm, managed as part of perennial forage rotation with historical broadcast application of dairy manure to meet crop nutrient requirements. The Le Sueur River field is under soybean (*Glycine max* [L.] Merr.)–corn (*Zea mays* L.) production, with injected swine manure and synthetic fertilizer serving as sources of applied P. The Western Lake Erie Basin field includes wheat (*Triticum aestivum* L.) as a small grain (corn–soybean–wheat), with injected swine manure as the principal source of nutrients. Notably, the three sites differ in the intensity of tillage, with vertical and rip tillage at Le Sueur River and chisel tillage occurring at Western Lake Erie. Soils data for the three farms included in this study were collected from published and unpublished datasets (MDA 2021; Osterholz et al. 2023; White et al. 2021). Unreported soil characteristics (e.g., bulk density, soil texture, and drainage class) needed for simulations were gathered from SSURGO via the FedData package (Bocinsky et al. 2024).

Water quality monitoring

Edge-of-field runoff monitoring data were provided by each site at relatively similar resolutions. Generally, flow was continuously monitored at each site and water samples were collected on a flow-weighted basis. Detailed descriptions of runoff monitoring setup, sample collection, processing, and analysis are outlined in MDA (2021) for Le Sueur River, Williams et al. (2016) for Western Lake Erie, and White et al. (2021) for Lake Champlain.

Annual Phosphorus Loss Estimator model description

The Annual Phosphorus Loss Estimator (APLE) (Vadas, Joern, and Moore 2012) was used to predict edge-of-field P loss and differentiate between legacy and recent sources of P (Bolster et al. 2017; Fiorellino et al. 2017b). For each site, measured soil properties and site-level data on annual precipitation and crop uptake were input. Inputs for sediment loss and runoff volume must be measured, calculated using the curve number method, or derived from other sources to estimate edge-of-field P loads (Bolster and Vadas 2022). In the current study, we used Revised Universal Soil Loss Equation Version 2 (RUSLE2) (USDA ARS 2014) to predict changes in runoff and erosion under different management practices.

We found that the equation relating soil test P to the labile P pool in APLE, which is influential on model behavior (estimation of total P in soil and dissolved P in runoff per soil test P value) (Sharpley et al. 2002; Vadas et al. 2005; Vadas and White 2010), was biased for these three sites. Therefore, we used measured soil test P and labile P from these regions (Simpson, Mott, and Kleinman 2024) to employ region-specific equations, while also noting the default model behavior in the results.

Model assessment metrics

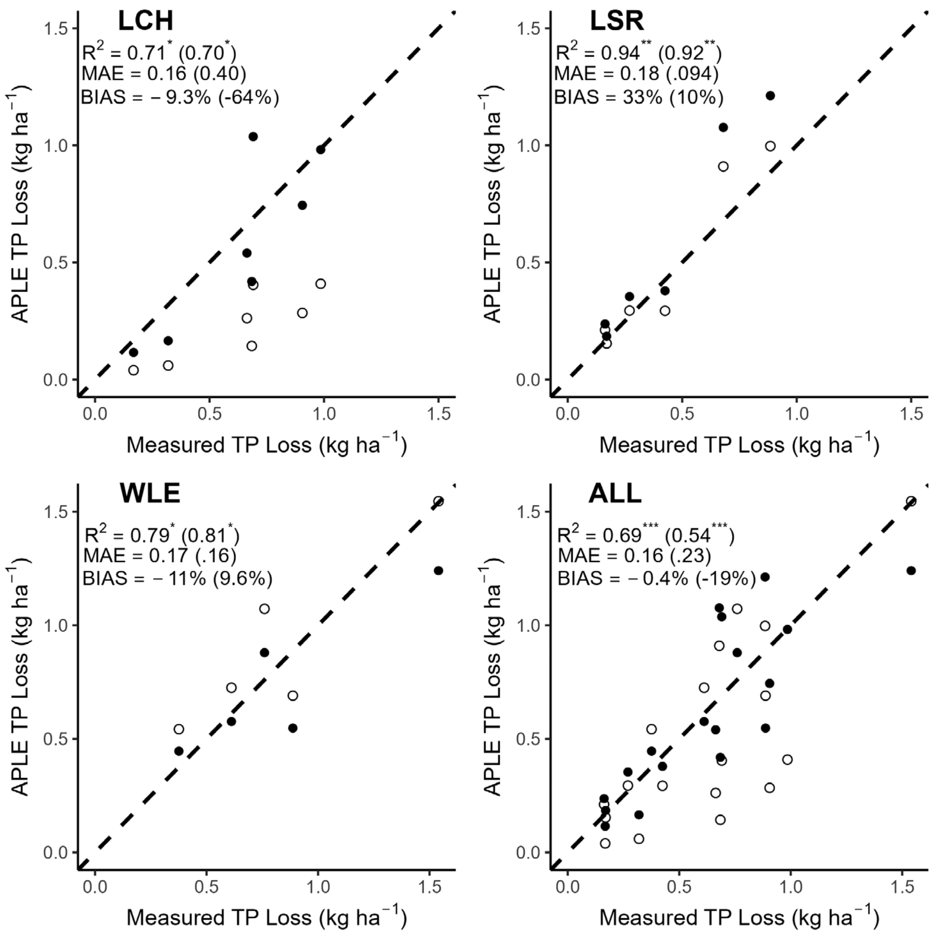
To corroborate the model prior to evaluating scenario simulations, we compared APLE-predicted P runoff loss with measured P runoff loss data collected from each site. Model predictions were evaluated using the coefficient of determination (R^2), mean absolute error (MAE, kilograms per hectare), and percentage bias (BIAS; Figures 1 and 2). All performance metrics were performed in R Statistical Software (v4.3.3; R Core Team 2024) and calculated using the complete period of record.

Simulated management scenarios

Multiple scenarios were developed for each site. Model inputs such as organic matter, bulk density, annual precipitation, and crop uptake were assumed static for modeling purposes and held constant, despite their nonstatic nature and likelihood to vary with management. Similar to previous scenarios implemented in Vadas et al. (2018), we simulated the following:

1. Prevailing management: Annual P additions and tillage practices remain constant throughout a 20-year simulation period. For Lake Champlain and Western Lake Erie, the prevailing management scenario followed their current nutrient management plan, while Le Sueur River continued typical P applications and a tillage regimen.

Figure 1. Observed annual total phosphorus (TP) loss versus Annual Phosphorus Loss Estimator (APLE)-predicted TP loss for each site in this study (Lake Champlain [LCH], Le Sueur River [LSR], Western Lake Erie [WLE], and all sites combined [ALL]). Coefficient of determination (R^2), mean absolute error (MAE, kg ha^{-1}), and percentage bias (BIAS, %) are calculated for each site individually and displayed as insets of each plot. Filled circles (black) represent APLE predictions with site-specific empirical relationships. Default model performance metrics are presented in parentheses. A 1:1 line (dashed) is included on each plot. A single asterisk (*) is significant at the 0.05 probability level; two asterisks (**) is significant at the 0.01 probability level; and three asterisks (***) is significant at the 0.001 probability level.



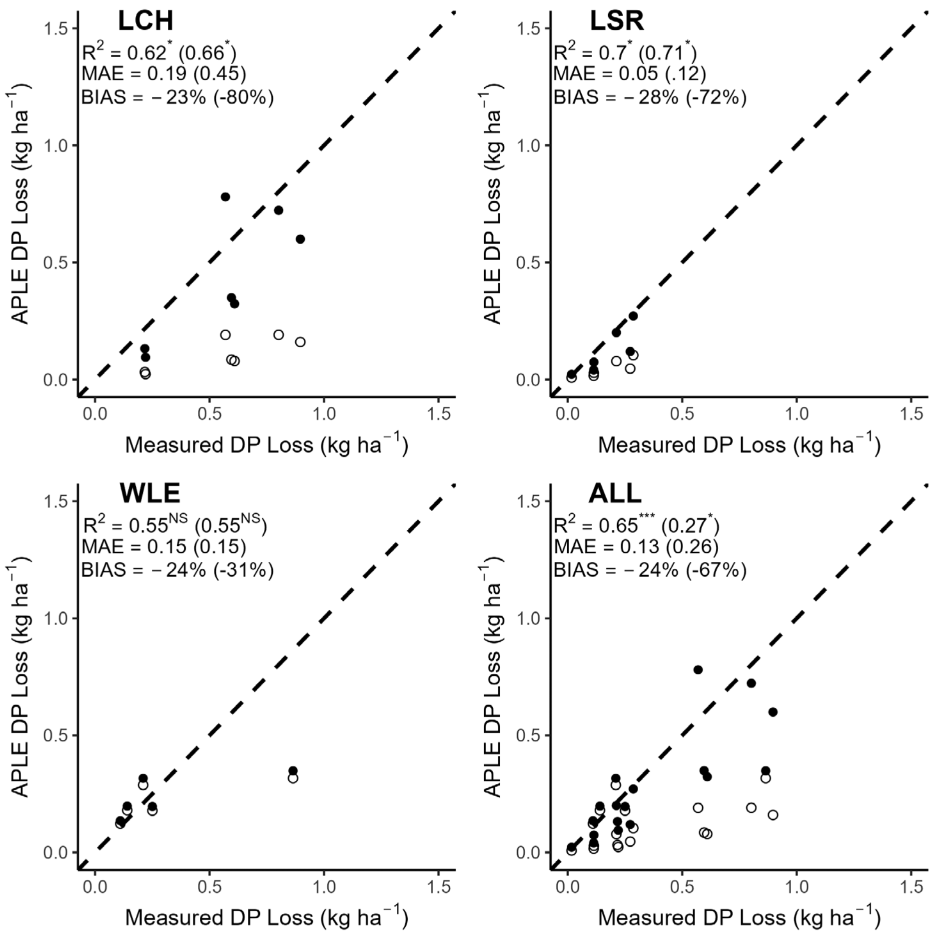
2. Manure injection: Changing surface application to a subsurface injection with low disturbance (10 cm depth).
3. No-till: Moving from prevailing management to minimal/no-till in accordance to NRCS conservation practice standards (USDA NRCS 2016).
4. Drawdown: Ceases all P applications; prevailing tillage continues. Once the soil test P reaches the site-specific critical level, P additions resume at crop removal rates.
5. Drawdown with no-till: Same as the drawdown scenario, but soil disturbance is based on NRCS standards.

RESULTS AND DISCUSSION

Annual Phosphorus Loss Estimator predictions and measured phosphorus loss

The region-specific empirical relationships for estimating labile P generally improved model performance (Figures 1 and 2). Even so, the default APLE model generally captured the temporal dynamics of P transport. For example, peaks in total P loss for years with heavy tillage, multiple P applications, and/or higher precipitation were similar to measured losses. Similarly, predicted dissolved P losses trended proportionately with soil test P and increased with runoff volumes.

Figure 2. Observed annual dissolved phosphorus (DP) loss versus Annual Phosphorus Loss Estimator (APLE)-predicted DP loss for each site in this study (Lake Champlain [LCH], Le Sueur River [LSR], Western Lake Erie [WLE], and all sites combined [ALL]). Coefficient of determination (R^2), mean absolute error (MAE, kg ha^{-1}), and percentage bias (BIAS, %) are calculated for each site individually and displayed as insets of each plot. Filled circles (black) represent APLE predictions with site-specific empirical relationships. Default model performance metrics are presented in parentheses. A 1:1 line (dashed) is included on each plot. A single asterisk (*) is significant at the 0.05 probability level; two asterisks (**) is significant at the 0.01 probability level; three asterisks (***) is significant at the 0.001 probability level; and NS is not significant.

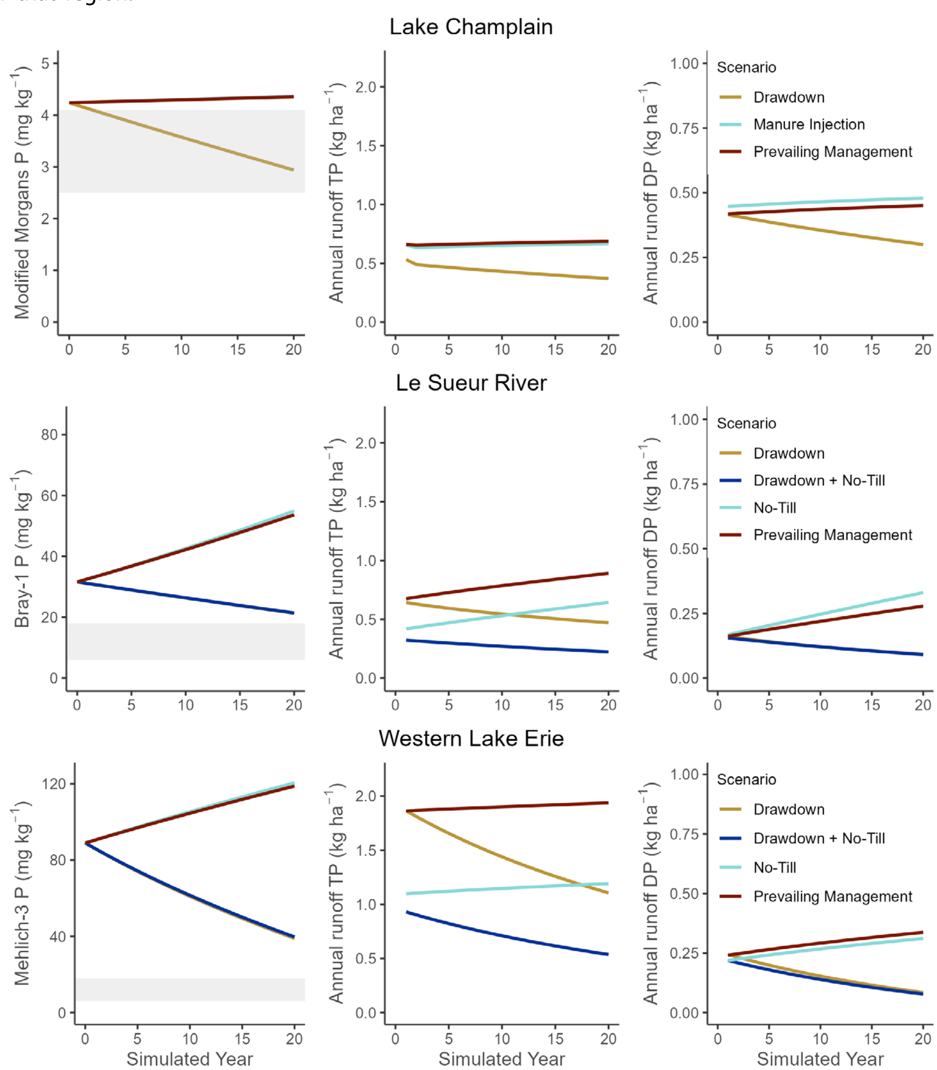


Across the three fields, observed annual total P losses in runoff ranged from 0.16 to 1.5 kg ha^{-1} while dissolved P losses ranged from 0.02 to 0.89 kg ha^{-1}. Total and dissolved P loss predictions in runoff correlated well with the observed losses (total: R^2 = 0.69, $p < 0.001$; dissolved: R^2 = 0.65, $p < 0.001$). Furthermore, all field-specific correlations for total and dissolved P in runoff were at least moderately strong (R^2 > 0.55); however, with respect to the Western Lake Erie field, the correlation of predicted to observed dissolved P losses was not statistically significant. Across fields, mean absolute error was relatively low (total: 0.16 kg ha^{-1}, dissolved: 0.13 kg ha^{-1}). Notably, while there was not a consistent trend in prediction bias for total P losses (i.e., −9% to 33% across fields), dissolved P losses were consistently underpredicted by the APLE model with a bias of −24% across all sites. However, given the intended use of this model (i.e., providing insight into the magnitude of potential surface P losses), we conclude that APLE can provide reasonable estimates for the screening of conservation practices in these fields.

Managing soil test phosphorus as an indicator of legacy phosphorus stores

Differences in initial soil P concentrations, as measured by locally relevant agronomic soil tests, reflect the unique management contexts in the three watersheds. Each region has distinct thresholds for soil test P identified as the agronomic optimum for the crop or cropping system. The row-cropped fields simulated in Le Sueur River and Western Lake Erie had initial soil test P concentrations two- to threefold greater than the soil test values identified as the agronomic optimum for the crops grown in the region (38 mg kg^{-1} Bray P and 85 mg kg^{-1} Mehlich-3, respectively; Figure 3), pointing to excesses in field P budgets due to historical management of swine manure and fertilizer (Sharpley, Daniel, and Edwards 1993). In contrast, the hayfield at Lake Champlain had an initial soil test P slightly above agronomic optimum (4.2 mg kg^{-1} Modified Morgan's P), pointing to extensive dairy productions systems with P balances closer to the crop requirement (Harrison et al. 2021). When simulating prevailing management, soil test P increased by 105% and 30% over 20 years at Le Sueur River and Western Lake Erie, respectively; at Lake Champlain, soil test P remained roughly level over the 20 years. Importantly, implementation of conservation practices for all sites (manure injection and no-till) had no influence on soil test P accumulation relative to prevailing management.

Figure 3. Twenty-year Annual Phosphorus Loss Estimator (APLE) simulations of soil test phosphorus (P) and surface runoff P losses. The columns (left to right) display simulated soil test P (mg kg^{-1}), annual total P (TP) loss (kg ha^{-1}), and dissolved P (DP) loss (kg ha^{-1}) from each field (rows). The shaded box in each soil test P graph represents the agronomically optimal (top of shaded box) P level and a critical soil test P value for 90% relative yield or "medium" soil test P value (bottom of shaded box) for that region.



The implementation of P drawdown alone, or in combination with the conservation practice of no-till, resulted in a ~50% decrease in soil test P over the 20-year simulation at the Western Lake Erie and the Le Sueur River sites. At a constant drawdown rate, it would take ~20 years at the Le Sueur River site and ~30 years at the Western Lake Erie site to reach agronomic optimums. Even the field at Lake Champlain retained soil test P concentrations above the medium soil test value for crop production for at least 20 years under drawdown. These APLE simulations are consistent with experimental studies concluding that greater initial soil test P necessitates a longer duration of drawdown to achieve environmental objectives (Fiorellino, Kratochvil, and Coale 2017a; Lasisi et al. 2023; McDowell et al. 2020).

Trade-offs in runoff phosphorus losses

Results of APLE simulations point to the general ineffectiveness of adding manure injection to prevailing practices in the Lake Champlain field. Although manure injection virtually eliminated direct losses of manure P to runoff (i.e., incidental transfers) (Preedy et al. 2001), increases in soil disturbance from the injector negated these reductions by adding more particulate-bound P to total P losses. Nevertheless, continued P application to this field, regardless of placement, indicated legacy P accumulation, resulting in substantial and sustained runoff P losses.

At the Western Lake Erie and Le Sueur River fields, simulated no-till reduced total P losses, supporting the conservation benefits of this practice, but dissolved P losses gradually increased over time, indicating legacy P accumulation in soils. At Le Sueur River, no-till lowered predicted sediment loss in runoff by 65% (Table 2). As a result, the initial reduction in total P loss was 62% under no-till alone. However, under the no-till alone scenario, dissolved P loss increased by 150% (0.06 to 0.15 kg P ha^{-1}) over the 20-year simulation period, resulting in total P loss returning to starting values under prevailing management. Similarly, at Western Lake Erie, sediment loss decreased by 57% and runoff decreased by 9% under no-till. At Western Lake Erie, no-till initially reduced total P loss by 52% but, as P applications continued, dissolved P loss increased by 40% (0.20 to 0.28 kg P ha^{-1}). Buildup of soil test P, hence legacy P, in any simulation presented here led to increased dissolved P losses. This relationship is borne out empirically, such as in studies of increased soil P stratification (common for tilled and no-till soils alike) (Smith, Huang, and Haney 2017; Simpson, Mott, and Kleinman 2024) correlating to greater dissolved P losses (Baker et al. 2017; Jarvie et al. 2017).

At each of the three fields, the implementation of soil P drawdown alone was shown to effectively target legacy P stores; however, comprehensive management of legacy P is best administered through combining soil conservation and soil P drawdown. For Le Sueur River, dissolved P losses decreased by about 60% under both drawdown scenarios (sole and combined with no-till); however, the greatest reduction in total P losses was realized in the combined drawdown and no-till scenario, which saw a 65% decrease in end-of-simulation total P loss compared to the drawdown-only scenario. Similar to Le Sueur River, dissolved P loads at Western Lake Erie decreased by about 65% in both drawdown scenarios, but the combination of drawdown and no-till resulted in the greatest reduction of losses

Table 2. Average annual runoff and sediment loss from each field under each management scenario.

	Prevailing management		Drawdown		Manure injection		No-till		Drawdown + no-till	
Site	Runoff (mm)	Sediment loss (Mg ha^{-1})	Runoff (mm)	Sediment loss (Mg ha^{-1})	Runoff (mm)	Sediment loss (Mg ha^{-1})	Runoff (mm)	Sediment loss (Mg ha^{-1})	Runoff (mm)	Sediment loss (Mg ha^{-1})
Lake Champlain	142	0.032	143	0.014	153	0.065	—	—	—	—
Le Sueur River	52	0.24	52	0.24	—	—	54	0.085	50	0.058
Western Lake Erie	77	0.83	78	0.84	—	—	70	0.36	70	0.28

for total P (1.09 versus 0.51 kg ha^{-1}) and dissolved P (0.08 versus 0.07 kg ha^{-1}) by the conclusion of the simulation. Additionally, at the Lake Champlain field, the cessation of manure applications on the already well-conserved soil resulted in an initial reduction in total P loss of 20% (0.66 to 0.53 kg ha^{-1}). By the conclusion of the drawdown scenario at Lake Champlain, total P loss was further reduced to 0.37 kg ha^{-1} and dissolved P loss decreased from 0.41 to 0.30 kg ha^{-1}. The persistence of elevated dissolved P losses, in the fields represented here and elsewhere, is central to the legacy P problem (Joosse and Baker 2011).

SUMMARY AND CONCLUSIONS

There are several limitations of the model simulations presented here. Notably, our analysis did not consider subsurface P losses in detail, the trade-offs of alternative P-free fertilizer sources, or the limitations of no-till in colder climates. These factors must be considered when implementing P drawdown. Furthermore, while APLE model predictions were generally improved when using site-specific empirical relationships, estimations of dissolved P losses were still consistently underpredicted. This suggests that further improvements need to be made to the APLE model to improve the accuracy of P loss predictions in a variety of contexts (i.e., where P loss pathways are more complex, such as artificially drained fields). Additionally, users of the APLE model should be aware of this consistent underestimation of dissolved P losses when utilizing the model to make future management decisions.

Even so, these three studied sites are illustrative of the context-specific challenges of legacy P management. Each site presented P loss concerns, yet all were not necessarily "high" in soil test P. This emphasizes that, even for soils near the range of agronomic optimum, losses of legacy P in runoff can be significant. Conventional conservation practices may not, on their own, sufficiently prevent P losses in legacy P contexts and, in some cases, may promote P accumulation in surface soils. Despite their other conservation benefits, these practices can present the trade-off of unmitigated, or even intensified, P losses. However, the drawdown of soil P clearly offers the potential to deplete legacy P stores. The timescale for drawdown depends on initial soil P and can often be decades long. However, when coupled with appropriate conservation management to avoid inadvertent P losses, drawdown can reduce both dissolved and particulate P losses. In one example of such pairing, the well-established conservation practice of no-till prevents sediment transport (and thus a major particulate P loss) while drawdown confronts legacy P stores, mitigating the buildup of P in topsoil and therefore reducing dissolved P losses. Where current conservation practices alone would lead to mitigating one P loss pathway for the sake of exacerbating another, coupling a P drawdown strategy offers a path to overcoming trade-offs in P management.

DISCLOSURE STATEMENT

The authors declare no conflict of interest. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. USDA is an equal opportunity provider and employer.

FUNDING

This project was funded by USDA Natural Resources Conservation Service (NRCS) for this work through the support of the Conservation Effects Assessment Project Watershed Assessment Studies and the USDA Legacy Phosphorus Assessment Project (NRCS Agreement #NRC21IRA0010879).

NOTES ON CONTRIBUTORS

Joshua Mott is a research soil scientist with the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Soil Management and Sugar Beet Research Unit in Fort Collins, Colorado, USA.

Zachary P. Simpson is a research hydrologist with the USDA ARS Sustainable Water Management Research Unit in Stoneville, Mississippi, USA.

Carl H. Bolster is a research hydrologist with the USDA ARS Food Animal Environmental Systems Research Unit in Bowling Green, Kentucky, USA.

Joshua Faulkner is a research associate professor for the Department of Agriculture, Landscape, and Environment and interim director of the Center for Sustainable Agriculture at the University of Vermont, in Burlington, Vermont, USA.

Kevin King is a supervisory research agricultural engineer with the USDA ARS Soil Drainage Research Unit in Columbus, Ohio, USA.

William Osterholz is a research soil scientist with the USDA ARS Soil Drainage Research Unit in Columbus, Ohio, USA.

Mark Williams is a research agricultural engineer with the USDA ARS National Soil Erosion Research Laboratory in West Lafayette, Indiana, USA.

Brent Dalzell is a research soil scientist and Gary W. Feyereisen is an agricultural engineer with the USDA ARS Soil and Water Management Research Unit in St. Paul, Minnesota, USA.

Christine L. Dolph is a researcher with the Department of Ecology, Evolution and Behavior at the University of Minnesota in St. Paul, Minnesota, USA.

Grace L. Miner is a research agronomist with the USDA ARS Soil Management and Sugar Beet Research Unit in Fort Collins, Colorado, USA.

Lisa F. Duriancik is a natural resources specialist and watershed lead of the Conservation Effects Assessment Project with the Natural Resources Conservation Service in Virginia, USA.

Peter J. A. Kleinman is a supervisory research soil scientist with the USDA ARS Soil Management and Sugar Beet Research Unit in Fort Collins, Colorado, USA.

ORCID

Joshua Mott http://orcid.org/0000-0002-5598-5383
Zachary P. Simpson http://orcid.org/0000-0001-8075-810X
Carl H. Bolster http://orcid.org/0000-0001-6646-0921
Joshua Faulkner http://orcid.org/0000-0002-4695-5334
Kevin King http://orcid.org/0000-0002-3843-9591
William Osterholz http://orcid.org/0000-0003-2218-9396
Mark Williams http://orcid.org/0000-0002-8081-8018
Brent Dalzell http://orcid.org/0000-0001-9710-6562
Gary W. Feyereisen http://orcid.org/0000-0003-2785-4594
Christine L. Dolph http://orcid.org/0000-0003-3667-7809
Grace L. Miner http://orcid.org/0000-0001-5936-2979
Lisa F. Duriancik http://orcid.org/0000-0002-0442-9352
Peter J. A. Kleinman http://orcid.org/0000-0002-5093-3736

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