Agricultural & Environmental Letters

Commentary

Phosphorus and Soil Health Management Practices

Emily W. Duncan,* Deanna L. Osmond, Amy L. Shober, Laura Starr, Peter Tomlinson, John L. Kovar, Thomas B. Moorman, Heidi M. Peterson, Nicole M. Fiorellino, and Keith Reid

Core Ideas

- Trade-offs exist in nutrient losses for soil health management.
- Combining soil health practices and other BMPs can exacerbate or mitigate P losses.
- There are limitations of soil health practices and reducing P losses.
- Educators should discuss BMP trade-offs associated with P loss.

Abstract: Soil health has gained widespread attention in agronomic and conservation communities due to its many purported benefits, including claims that implementation of core soil health practices (e.g., conservation tillage, cover crops) will improve water quality by curtailing runoff losses of nutrients such as phosphorus (P). However, a review of the existing literature points to well-established findings regarding trade-offs in water quality outcomes following the implementation of core soil health practices. In fact, both conservation tillage and cover crops can exacerbate dissolved P losses, undermining other benefits such as reductions in particulate P (sediment-bound P) losses. Soil health management must be pursued in a manner that considers the complex interaction of nutrient cycling processes and produces realistic expectations. Achieving water quality goals through soil health practices will require adaptive management and continued, applied research to support evidence-based farm management decisions.

Soil health is globally defined by the USDA-NRCS as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA-NRCS, 2019). Operationally, soil health is achieved by following the soil health principles of reducing soil disturbance, improving biodiversity, maintaining soil cover, and maintaining continuous plant growth. A suite of core management practices is promoted by the soil health community to help land managers achieve soil health. Core practices (hereafter referred to as "soil health practices") include conservation tillage, no-till, cover crops, crop rotation, mulching, nutrient management, and pest management (USDA-NRCS, 2019). Implementation of soil health practices over the long term is expected to improve water quality, as well as conserve water, improve air quality, and save renewable resources (USDA-NRCS, 2019).

Some researchers have suggested that soil health practices can result in benefits to the landowner, through reduced fertilizer and pesticide inputs, increased crop yields, improved nutrient cycling, and reduced nutrient and sediment losses (Snapp et al., 2005; González-Chávez et al., 2010; van Kessel et al., 2013; Kuhn et al., 2016). As interest in soil health has grown in recent years, a group of researchers organized a symposium titled "Exploring Soil Health and Phosphorus Connections" as part of the 2018 American Society of Agronomy and Crop Science Society of America Meetings in Baltimore, MD, on 7 Nov. 2018 to express concerns about claims that soil health management can improve water quality by reducing phosphorus (P) losses from agriculture (Smith et al., 2018).

It is well established that eutrophication and harmful algal blooms resulting from agricultural P losses (as particulate or dissolved P in runoff or leachate) negatively affect drinking water, fisheries, recreation, and ecosystem health (Sharpley et al., 1994; Correll, 1998). Scientists recommend a variety of best management practices (BMPs) to reduce the potential for agricultural P losses

Abbreviations: BMPs, best management practices; DRP, dissolved reactive phosphorus; LEB, Lake Erie basin; MB-P, microbial biomass phosphorus.

E.W. Duncan, USDA-ARS Soil Drainage Research Unit, Columbus, OH, 43010 USA; D.L. Osmond, North Carolina State Univ., Raleigh, NC 27695 USA; A.L. Shober, Univ. of Delaware, 531 S. College Ave., Newark, DE 19716 USA; L. Starr and P. Tomlinson, Kansas State Univ., Manhattan, KS 66506 USA; J.L. Kovar and T.B. Moorman, USDA-ARS National Lab. for Agriculture and the Environment, Ames, IA 50011 USA; H.M. Peterson, Sand County Foundation, Stillwater, MN 55082 USA; N.M. Fiorellino, Univ. of Maryland, College Park, MD 20742 USA; K. Reid, Agriculture and Agri Food Canada, 174 Stone Road W. Guelph, ON NIG 4S9 Canada.

Agric. Environ. Lett. 4:190014 (2019)
doi:10.2134/ael2019.04.0014

Received 24 Apr. 2019.
Accepted 13 June 2019.

*Corresponding author (emily.duncan@usda.gov).

(Sharpley et al., 1994). Yet broad assertions that adopting BMPs associated with soil health, particularly conservation tillage and cover crops, will reduce P losses ignore the nutrient loss trade-offs that are associated with these specific practices (Jarvie et al., 2017). Examples of nutrient trade-offs include tillage to incorporate urea to decrease ammonia nitrogen losses at the expense of increased particulate P losses through soil erosion and decreasing particulate P losses with overwintering cover crops at the expense of increasing soluble P losses from the frozen vegetation. In this commentary, we discuss how application of soil health practices influence P cycling and loss from agricultural soils. We also discuss how combining soil health practices with other BMPs (e.g., nutrient placement, drainage management) can either exacerbate or mitigate nutrient trade-offs associated with soil health practices. Overall, we suggest that any responsible discussion of soil health practices must include potential nutrient trade-offs for landowners and other interested parties

Soil Health Practices and Phosphorus Loss

Government agencies began promoting conservation tillage (e.g., strip-till, mulch-till, ridge till, no-till) and cover crops in recent decades to minimize erosion and improve soil health. From a P loss standpoint, these soil health practices are often effective at reducing sediment delivery and the associated particulate P (Butler et al., 2006; Aronsson et al., 2016; Uribe et al., 2018). In contrast, the ability of conservation tillage and cover crops to reduce dissolved P losses in runoff or leaching varies. In a recent literature review, Blanco-Canqui (2018) noted that cover crops effectively decreased sediment and N losses but reduced soluble P losses in fewer than 25% of studies. In some cases, decreased particulate P losses were countered by increased dissolved P losses from the same fields. For example, Uribe et al. (2018) reported smaller sediment loads from potato (*Solanum tuberosum* L.) fields in Colombia managed under conservation tillage (0.31 Mg ha^{-1}) compared with intensive tillage (0.58 Mg ha^{-1}). However, they reported higher total P loads under conservation tillage because soluble P losses increased (0.29 vs. 0.21 kg ha^{-1} for conservation tillage and intensive tillage, respectively). While sediment-bound P is also important to consider, scientists have linked greater dissolved reactive P (DRP) losses under conservation tillage and cover crops to soil P stratification and accumulation (Tiessen et al., 2010; Dodd and Sharpley, 2015; Smith et al., 2016; Jarvie et al., 2017), increased leaching through preferential flow pathways and hydraulic connectivity (Pease et al., 2018), and P leaching from decaying plant tissues (J. Liu et al., 2014).

Phosphorus accumulation in the top layers of soil (5 cm or shallower) is related to surface applications of P (fertilizers and manures) and buildup of plant residues under reduced tillage systems. Deubel et al. (2011) found elevated concentrations of water-soluble P in the surface layer (0- to 5-cm soil depth) of German soils following 16 yr of conservation tillage (109 mg kg^{-1} calcium acetate lactate soluble P) compared with conventional tillage (77.9 mg kg^{-1} calcium acetate lactate soluble P). Similarly, Cade-Menun et al. (2015) compared orthophosphate and phytate concentrations in the top 2.5 cm of soils receiving poultry litter or commercial fertilizer under no-till and conventional tillage; stratification occurred regardless of P source under no-till.

Soil surface layers are the primary interaction zone between precipitation and soil (Sims et al., 2000); therefore, P that accumulates on the soil surface has generally been identified as the principal source of P in both surface runoff and leachate (McDowell and Sharpley, 2001; Kleinman et al., 2011). Several researchers have noted increased DRP in runoff from no-till soils when soil P concentrations reach levels that exceed crop needs (Davis et al., 2005; Vadas et al., 2005; Allen et al., 2006; Kleinman et al., 2009; Wang et al., 2010; Baker et al., 2017). Similarly, surface application of fertilizers and manure can increase P losses in runoff when rainfall events occur shortly after application (Sharpley and Moyer, 2000; Preedy et al., 2001; Kleinman and Sharpley, 2002; Withers et al., 2003; Allen and Mallarino, 2008). Soil health practices are also expected to increase soil microbial biomass, corresponding to a larger pool of microbial biomass P in surface soils (Hallama et al., 2018). This active organic P pool is vulnerable to cell lysis under freeze-thaw or dry-wet cycles that are common in many agricultural regions. As such, the accumulation of a large soil microbial biomass P pool could exacerbate P losses in runoff (Turner and Haygarth, 2001; Blackwell et al., 2010).

Phosphorus uptake by growing cover crops cannot mitigate all dissolved P losses that result from P enrichment at the soil surface. While P uptake by cover crops can reduce P concentration in the soil solution near root surfaces (Wang et al., 2004; Kovar and Claassen, 2009), the soil solution P is generally buffered by a large reservoir of P adsorbed on the solid soil particles. Therefore, even an actively growing cover crop cannot significantly lower solution P concentration. Reducing the leaching potential of dissolved P is only possible via long-term P removal with crop harvest (Schoumans et al., 2014), which often does not occur with cover crops, as residues are left on the soil surface following termination (e.g., winter kill, chemical, or mechanical).

Phosphorus accumulated by the cover crop can be subsequently released as the plant tissue decays, either into the soil to nourish the following crop or into runoff water (Elliott, 2013; K. Liu et al., 2014). The fate of this released P depends on the timing and mechanism of cover crop termination, as well as climatic conditions. The greatest P losses from cover crop biomass are likely to occur when an extended period of frozen soils after cover crop termination is followed by rapid snowmelt or heavy rainfall (Roberson et al., 2007; Liu et al., 2013). Kovar et al. (2011) found that DRP concentrations and loads in runoff increased when rainfall occurred following spring termination of cereal rye (*Secale cereale* L.)–oat (*Avena sativa* L.) cover crop. They noted that the terminated cover crops trapped less sediment and sediment-bound P in spring runoff compared with actively growing cover crops in the fall. In contrast, most of the P will return to the soil if conditions favor infiltration, as was the case with a cover crop trial in southern Ontario (Lozier et al., 2017).

Finally, increasing aggregate stability can increase macropores, ultimately increasing preferential flow pathways that bypass adsorption sites (J. Liu et al., 2014) in the soil matrix that would otherwise reduce DRP concentration. As a result, there may be more DRP than particulate P in shallow groundwater (Shipitalo et al., 2000; Shigaki and Sharpley, 2011) that can be transported to surface waters via tile drains and surface ditches (Sims et al., 1998; Kleinman et al., 2015; King et al., 2017).

Mitigating the Phosphorus Loss Trade-offs Associated with Soil Health Practices

Widespread adoption of conservation tillage and cover crops with the intent of improving soil health can increase P loading to sensitive water bodies in the absence of additional P management. A primary example of this is the Lake Erie basin, where cover crops and conservation tillage could be contributing to an increase in soluble P losses. Researchers speculated that widespread implementation of conservation tillage across the Lake Erie basin in the 1980s and 1990s led to improved water quality due to reduced sediment bound P losses (Boesch et al., 2001; Sharpley et al., 2015; Daryanto et al., 2017; Leinweber et al., 2018). Improvements in water quality that were driven by reduced sediment load were the basis for the Ohio Lake Erie P Task Force to specifically identify soil health practices as an approach to decrease P reaching the lake from agricultural fields (Ohio Phosphorus Task Force, 2013). Yet the Lake Erie basin has recently entered a period of re-eutrophication (Dodd and Sharpley, 2016), resulting in the return of persistent harmful nuisance algal blooms that have long plagued the watershed. Some researchers have linked this water quality reversal to increased DRP losses due, in part, to the wide adoption of conservation tillage; increases in tile drainage; and changes in the amount, placement, and timing of P fertilizers (Meals et al., 2012; Jarvie et al., 2017). Patterns of increased DRP loads are consistent across the watershed, despite localized variations in important determinants like site hydrology, transport pathway, rainfall, and crop species (Baker et al., 2014; King et al., 2017; Pease et al., 2018).

As such, we argue that the core soil health practices of conservation tillage and cover crops must be combined with field-level P (nutrient) management practices such as injecting or banding of fertilizers and manures under no-till. Smith et al. (2017) found that knifing in liquid polyphosphate fertilizer at planting resulted in lower runoff DRP and total P losses when compared to surface applications of granular P fertilizers (i.e., monoammonium phosphate and diammonium phosphate) to no-till fields. Similarly, Johnson et al. (2011) reported decreased runoff DRP losses when dairy slurry was injected into pastures compared with surface application. Kovar et al. (2011) found that low disturbance injection of swine manure into a standing cover crop minimized disturbance, increased P uptake by the cover crop, and reduced P losses.

Cade-Menun et al. (2015) suggested subsurface placement of fertilizers in no-till systems could prevent soil P stratification; however, dealing with existing soil P stratification is a more difficult issue. Some researchers suggest periodic tillage to reduce soil P stratification, but scientific evidence is conflicting on the efficacy of periodic tillage to remediate stratification and reduce P loss. While Sharpley (2003) found that tilling manured soils can reduce P stratification, Smith et al. (2017) demonstrated that disking following the application of diammonium phosphate had the opposite effect, increasing the amount of P stratification. Long-term benefits of periodic tillage are also questionable. Dodd et al. (2014) documented a short-term reduction in subsurface DRP loss of 30 to 70% after tilling a pasture, but no difference in subsurface DRP loads could be detected beyond the first month. The authors hypothesized that preferential pathways reestablished as pasture grasses developed. As such, implementing periodic tillage to reduce stratification would require careful consideration to determine if the benefits outweigh negating the soil health effects of conservation tillage.

Finally, drainage water management may reduce P leaching losses associated with soil health practices in fields with tile or ditch drainage. Zhang et al. (2017) reported that implementing controlled drainage with subirrigation reduced DRP losses in tile flow compared with uncontrolled tile drainage. When controlled drainage was combined with a rye cover crop, total P losses from the field were further reduced. However, the authors noted the importance of monitoring both surface runoff and tile drainage P loss pathways to determine the overall effectiveness of management practices on P losses; in their case, changing practices shifted the balance between surface and subsurface losses and between particulate and DRP losses, but not total P losses. As such, the decision to adopt soil health practices must include an analysis of the whole farm management system to determine the potential for P loss trade-offs.

Recognizing the Limitations of Soil Health Practices to Control Phosphorus Losses

The agroecological benefits of soil health practices such as conservation tillage and cover crops are demonstrable; however, implementation of these soil health practices will not always reduce P loss from agricultural landscapes. Reducing soil disturbance and increasing ground cover decrease sediment leaving the field, but reduced sediment losses do not always translate to meaningful decreases in total P leaving the field (Bullerjahn et al., 2016). While there are positive trade-offs associated with soil health practices relative to N (e.g., cover crops mitigate N leaching), the effects on P losses are more nuanced (Aronsson et al., 2016; Bullerjahn et al., 2016; Jarvie et al., 2017).

To date, claims that soil health practices alone can significantly reduce P losses are not substantiated by peer-reviewed literature; nevertheless, this does not mean that we should stop promoting soil health practices. Both the positive and the negative effects of implementing soil health practices, including nutrient trade-offs, should be discussed with agricultural clientele. If the core principles of soil health do not reduce P losses, are they in fact "soil health" practices? While there is a need for additional meta-analyses to quantify trade-offs associated with the adoption of soil health practices, discussion of these trade-offs and guidance in adjusting existing practices should be available via all educational outlets for soil health information. Ultimately, soil health information presented to agricultural clientele should be science-based and include a consistent message, regardless of who delivers the information. The desire to improve soil health in areas at high risk for P loss must be evaluated holistically, as adjusting other management practices (e.g., nutrient placement, drainage management) may be necessary to achieve soil health objectives without further water quality degradation. Finally, to address water quality goals, there is a need to support development of innovative BMPs that provide multiple ecosystem and environmental benefits, while addressing both particulate and soluble nutrient losses.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

This work was conceived and developed under the auspices of the Southern Extension and Research Activity-17, Innovative Solutions to Minimize Phosphorus Losses from Agriculture, which is funded by the USDA National Institute of Food and Agriculture.

References

Allen, B.L., and A.P. Mallarino. 2008. Effect of liquid swine manure rate, incorporation, and timing of rainfall on phosphorus loss with surface runoff. J. Environ. Qual. 37:125–137. doi:10.2134/jeq2007.0125

Allen, B.L., A.P. Mallarino, J.G. Klatt, J.L. Baker, and M. Camara. 2006. Soil and surface runoff phosphorus relationships for five typical USA Midwest soils. J. Environ. Qual. 35:599–610. doi:10.2134/jeq2005.0135

Aronsson, H., E.M. Hansen, I.K. Thomsen, J. Liu, A.F. Øgaard, H. Känkänen, and B. Ulén. 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. J. Soil Water Conserv. 71:41–55. doi:10.2489/jswc.71.1.41

Baker, D.B., R. Confesor, D.E. Ewing, L.T. Johnson, J.W. Kramer, and B.J. Merryfield. 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky, and Cuyahoga rivers: The importance of bioavailability. J. Great Lakes Res. 40:502–517. doi:10.1016/j.jglr.2014.05.001

Baker, D.B., L.T. Johnson, R.B. Confesor, and J.P. Crumrine. 2017. Vertical stratification of soil phosphorus as a concern for dissolved phosphorus runoff in the Lake Erie basin. J. Environ. Qual. 46:1287–1295. doi:10.2134/jeq2016.09.0337

Blackwell, M.S.A., P.C. Brookes, N. de le Fuente-Martinez, H. Gordon, P.J. Murray, K.E. Snares, J.K. Williams, R. Bol, and P.M. Haygarth. 2010. Phosphorus solubilization and potential transfer to surface waters from the soil and microbial biomass following drying–rewetting and freeze–thawing. Adv. Agron. 106:1–35. doi:10.1016/S0065-2113(10)06001-3

Blanco-Canqui, H. 2018. Cover crops and water quality. Agron. J. 110:1633–1647. doi:10.2134/agronj2018.02.0077

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. J. Environ. Qual. 30:303–320. doi:10.2134/jeq2001.302303x

Bullerjahn, G.S., R.M. McKay, T.W. Davis, D.B. Baker, G.L. Boyer, L.V. D'Anglada, G.J. Doucette, J.C. Ho, E.G. Irwin, C.L. Kling, R.M. Kudela, R. Kurkayer, A.M. Michalak, J.D. Ortiz, T.G. Otten, H.W. Paerl, B. Qin, B.L. Sohngen, R.P. Stumpf, P.M. Visser, and S.W. Wilhelm. 2016. Global solutions to regional problems: Collecting global expertise to address the problem of harmful cyanobacterial blooms. A Lake Erie case study. Harmful Algae 54:223–238. doi:10.1016/j.hal.2016.01.003

Butler, D.M., D.H. Franklin, N.N. Ranells, M.H. Poore, and J.T. Green. 2006. Ground cover impacts on sediment and phosphorus export from manured riparian pasture. J. Environ. Qual. 35:2178–2185. doi:10.2134/jeq2005.0351

Cade-Menun, B.J., Z. He, H. Zhang, D.M. Endale, H.H. Schomberg, and C.W. Liu. 2015. Stratification of phosphorus forms from long-term conservation tillage and poultry litter application. Soil Sci. Soc. Am. J. 79:504–516. doi:10.2136/sssaj2014.08.0310

Correll, D.L. 1998. The role of phosphorus in the eutrophication of surface waters: A review. J. Environ. Qual. 27:261–266. doi:10.2134/jeq1998.00472425002700020004x

Daryanto, S., L. Wang, and P.A. Jacinthe. 2017. Meta-analysis of phosphorus loss from no-till soils. J. Environ. Qual. 46:1028–1037. doi:10.2134/jeq2017.03.0121

Davis, R.L., H. Zhang, J.L. Schroder, J.J. Wang, M.E. Payton, and A. Zazulak. 2005. Soil characteristics and phosphorus level effect on phosphorus loss in runoff. J. Environ. Qual. 34:1640–1650. doi:10.2134/jeq2004.0480

Deubel, A., B. Hofmann, and D. Orzessek. 2011. Long-term effects of tillage on stratification and plant availability of phosphate and potassium in a loess chernozem. Soil Tillage Res. 117:85–92. doi:10.1016/j.still.2011.09.001

Dodd, R.J., R.W. McDowell, and L.M. Condron. 2014. Is tillage an effective method to decrease phosphorus loss from phosphorus enriched pastoral soils? Soil Tillage Res. 135:1–8. doi:10.1016/j.still.2013.08.015

Dodd, R.J., and A.N. Sharpley. 2015. Recognizing the role of soil organic phosphorus in soil fertility and water quality. Resour. Conserv. Recycl. 105:282–293. doi:10.1016/j.resconrec.2015.10.001

Dodd, R.J., and A.N. Sharpley. 2016. Conservation practice effectiveness and adoption: Unintended consequences and implications for sustainable phosphorus management. Nutr. Cycling Agroecosyst. 104:373–392. doi:10.1007/s10705-015-9748-8

Elliott, J. 2013. Evaluating the potential contribution of vegetation as a nutrient source in snowmelt runoff. Can. J. Soil Sci. 93:435–443. doi:10.4141/cjss2012-050

González-Chávez, M.A., J.A. Aitkenhead-Peterson, T.J. Gentry, D. Zuberer, F. Hons, and R. Loeppert. 2010. Soil microbial community, C, N, and P responses to long-term tillage and crop rotation. Soil Tillage Res. 106:285–293. doi:10.1016/j.still.2009.11.008

Hallama, M., C. Pekrun, H. Lambers, and E. Kandeler. 2018. Hidden miners: The roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. Plant Soil 434:7–45. doi:10.1007/s11104-018-3810-7

Jarvie, H.P., L.T. Johnson, A.N. Sharpley, D.R. Smith, D.B. Baker, T.W. Bruulsema, and R. Confesor. 2017. Increased soluble phosphorus loads to Lake Erie: Unintended consequences of conservation practices? J. Environ. Qual. 46:123–132. doi:10.2134/jeq2016.07.0248

Johnson, K.N., P.J.A. Kleinman, D.B. Beegle, H.A. Elliott, and L.S. Saporito. 2011. Effect of dairy manure slurry application in a no-till system on phosphorus runoff. Nutr. Cycling Agroecosyst. 90:201–212. doi:10.1007/s10705-011-9422-8

King, K.W., M.R. Williams, L.T. Johnson, D.R. Smith, G.A. LaBarge, and N.R. Fausey. 2017. Phosphorus availability in Western Lake Erie basin drainage waters: Legacy evidence across spatial scales. J. Environ. Qual. 46:466–469. doi:10.2134/jeq2016.11.0434

Kleinman, P.J.A., and A.N. Sharpley. 2002. Estimating soil phosphorus sorption saturation from Mehlich-3 data. Commun. Soil Sci. Plant Anal. 33:1825–1839. doi:10.1081/CSS-120004825

Kleinman, P.J.A., A.N. Sharpley, R.W. McDowell, D.N. Flaten, A.R. Buda, L. Tao, L. Bergstrom, and Q. Zhu. 2011. Managing agricultural phosphorus for water quality protection: Principles for progress. Plant Soil 349:169–182. doi:10.1007/s11104-011-0832-9

Kleinman, P.J., A.N. Sharpley, L.S. Saporito, A.R. Buda, and R.B. Bryant. 2009. Application of manure to no-till soils: Phosphorus losses by subsurface and surface pathways. Nutr. Cycling Agroecosyst. 84:215–227. doi:10.1007/s10705-008-9238-3

Kleinman, P.J.A., D.R. Smith, C.H. Bolster, and Z.M. Easton. 2015. Phosphorus fate, management, and modeling in artificially drained systems. J. Environ. Qual. 44:460–466. doi:10.2134/jeq2015.02.0090

Kovar, J.L., and N. Claassen. 2009. Plant growth and phosphorus uptake of three riparian grass species. Agron. J. 101:1060–1067. doi:10.2134/agronj2008.0088x

Kovar, J.L., T.B. Moorman, J.W. Singer, C.A. Cambardella, and M.D. Tomer. 2011. Swine manure injection with low-disturbance applicator and cover crops reduce phosphorus losses. J. Environ. Qual. 40:329–336. doi:10.2134/jeq2010.0184

Kuhn, N.J., Y. Hua, L. Bloemertza, J. Heb, H. Lib, and P. Greenwood. 2016. Conservation tillage and sustainable intensification of agriculture: Regional vs. global benefit analysis. Agric. Ecosyst. Environ. 216:155–165. doi:10.1016/j.agee.2015.10.001

Leinweber, P., U. Bathmann, U. Buczko, C. Douhaire, B. Eichler-Löbermann, E. Frossard, F. Ekardt, H. Jarvie, I. Krämer, C. Kabbe, B. Lennartz, P. Mellander, G. Nausch, H. Ohtake, and J. Tränckner. 2018. Handling the phosphorus paradox in agriculture and natural ecosystems: Scarcity, necessity, and burden of P. Ambio 47(Suppl. 1):3–19. doi:10.1007/s13280-017-0968-9

Liu, J.R., R. Khalaf, B. Ulén, and G. Bergkvist. 2013. Potential phosphorus release from catch crop shoots and roots after freeze–thawing. Plant Soil 371:543–557. doi:10.1007/s11104-013-1716-y

Liu, J., B. Ulen, G. Bergkvist, and H. Aronsson. 2014. Freeze-thawing effects on phosphorus leaching from catch crops. Nutr. Cycling Agroecosyst. 99:17–30. doi:10.1007/s10705-014-9615-z

Liu, K., J.A. Elliott, D.A. Lobb, D.N. Flaten, and J. Yarotski. 2014. Nutrient and sediment losses in snowmelt runoff from perennial forage and annual cropland in the Canadian Prairies. J. Environ. Qual. 43(5):1644–1655. doi:10.2134/jeq2014.01.0040

Lozier, T.M., M.L. Macrae, R. Brunke, and L.L. Van Eerd. 2017. Release of phosphorus from crop residue and cover crops over the non-growing season in a cool temperate region. Agric. Water Manage. 189:39–51. doi:10.1016/j.agwat.2017.04.015

McDowell, R.W., and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface and subsurface drainage. J. Environ. Qual. 30:508–520. doi:10.2134/jeq2001.302508x

Meals. D., P. Richards, R. Confesor, K. Czajkowski, J. Bonnell, D. Osmond, J. Spooner, D. Hoag, J. Spooner, and M. McFarland. 2012. Rock Creek, OH: NIFA-CEAP watershed project. In: D. Osmond, D. Meals, D. Hoag, and M. Arabi, editors. How to build better agricultural conservation programs to protect water quality: The NIFA-CEAP experience. Soil and Water Conservation Society, Ankeny, IA.

Ohio Phosphorus Task Force. 2013. Ohio Lake Erie Phosphorus Task Force II final report. Ohio Department of Agriculture, Columbus.

Pease, L.A., K.W. King, M.R. Williams, G.A. LaBarge, E.W. Duncan, and N.R. Fausey. 2018. Phosphorus export from artificially drained fields across the eastern Corn Belt. J. Great Lakes Res. 44:43–53. doi:10.1016/j.jglr.2017.11.009

Preedy, N., K. McTiernan, R. Matthews, L. Heathwaite, and P. Haygarth. 2001. Rapid incidental phosphorus transfers from grassland. J. Environ. Qual. 30:2105–2112. doi:10.2134/jeq2001.2105

Roberson, T., L.G. Bundy, and T.W. Andraski. 2007. Freezing and drying effects on potential plant contributions to phosphorus in runoff. J. Environ. Qual. 36:532–539. doi:10.2134/jeq2006.0169

Schoumans, O.F., W.J. Chardon, M. Bechmann, C.E. Gascuel-Odoux, G. Hofman, B. Kronvang, G.H. Rubæk, B. Ulén, and J.M. Dorioz. 2014. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. Sci. Total Environ. 468–469:1255–1266. doi:10.1016/j.scitotenv.2013.08.061

Sharpley, A.N. 2003. Soil mixing to decrease surface stratification of phosphorus in manured soils. J. Environ. Qual. 32:1375–1384. doi:10.2134/jeq2003.1375

Sharpley, A.N., L. Bergström, H. Aronsson, M. Bechmann, C.F. Bolster, K. Börling, F. Djodjic, H.P. Jarvie, O.F. Schoumans, C. Stamm, K.S. Tonderski, B. Ulen, R. Uusitalo, and P.J.A. Withers. 2015. Future agriculture with minimized phosphorus losses to waters: Research needs and direction. Ambio 44(Suppl. 2):163–179. doi:10.1007/s13280-014-0612-x

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437–451. doi:10.2134/jeq1994.00472425002300030006x

Sharpley, A., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29:1462–1469. doi:10.2134/jeq2000.00472425002900050012x

Shigaki, F., and A. Sharpley. 2011. Phosphorus sources and soil properties effects on phosphorus availability. Soil Sci. 176(9):502–507. doi:10.1097/SS.0b013e318225b457

Shipitalo, M., W.A. Dick, and W.M. Edwards. 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. Soil Tillage Res. 53(3–4):167–183. doi:10.1016/S0167-1987(99)00104-X

Sims, J.T., A.C. Edwards, O.F. Schoumans, and R.R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agriculture management practices. J. Environ. Qual. 29:60–71. doi:10.2134/jeq2000.00472425002900010008x

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293. doi:10.2134/jeq1998.00472425002700020006x

Smith, D.R., T.W. Bruulsema, A.L. Shober, and G. Toor. 2018. Exploring soil health and phosphorus connections. Symposium presented at: Enhancing productivity in a changing climate. 2018 ASA and CSSA Meeting, 7 Nov. 2018. Baltimore, MD. https://scisoc.confex.com/scisoc/2018am/meetingapp.cgi/Session/18123.

Smith, D.R., R.D. Harmel, M. Williams, R. Haney, and K.W. King. 2016. Managing acute phosphorus loss with fertilizer source and placement: Proof of concept. Agric. Environ. Lett. 1:150015. doi:10.2134/ael2015.12.0015

Smith, D.R., C. Huang, and R.L. Haney. 2017. Phosphorus fertilization, soil stratification, and potential water quality impacts. J. Soil Water Conserv. 72(5):417–424.

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agron. J. 97:322–332.

Tiessen, K.H.D., J.A. Elliott, J. Yarotski, D.A. Lobb, D.N. Flaten, and N.E. Glozier. 2010. Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. J. Environ. Qual. 39:964–980. doi:10.2134/jeq2009.0219

Turner, B.L., and P.M. Haygarth. 2001. Biogeochemistry: Phosphorus solubilization in rewetted soils. Nature 411:258. doi:10.1038/35077146

Uribe, N., G. Corzoa, M. Quinteroc, A. van Griensvena, and D. Solomatinea. 2018. Impact of conservation tillage on nitrogen and phosphorus runoff losses in a potato crop system in Fuquene watershed, Colombia. Agric. Water Manage. 209:62–72. doi:10.1016/j.agwat.2018.07.006

USDA-NRCS. 2019. Soil health. USDA-NRCS. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/ (accessed 5 Mar. 2019).

Vadas, P.A., B.E. Haggard, and W.J. Gburek. 2005. Predicting dissolved phosphorus in runoff from manured field plots. J. Environ. Qual. 34:1347–1353. doi:10.2134/jeq2004.0424

van Kessel, C., R. Venterea, J. Six, M.A. Adviento-Borbe, B. Linquist, and K.J. van Groenigen. 2013. Climate, duration, and N placement determine N$_2$O emissions in reduced tillage systems: A meta-analysis. Global Change Biol. 19:33–44. doi:10.1111/j.1365-2486.2012.02779.

Wang, Y.T., T.Q. Zhang, Q.C. Hu, C.S. Tan, I.P. O'Halloran, C.F. Drury, D.K. Reid, B.L. Ma, B. Ball-Coelho, J.D. Lauzon, W.D. Reynolds and T. Welacky. 2010. Estimating dissolved reactive phosphorus concentration in surface runoff water from major Ontario soils. J. Environ. Qual. 39:1771–1781. doi:10.2134/jeq2009.0504

Wang, Z.Y., J.M. Kelly, and J.L. Kovar. 2004. In situ dynamics of phosphorus in the rhizosphere solution of five species. J. Environ. Qual. 33:1387–1392. doi:10.2134/jeq2004.1387

Withers, P.J.A., B. Ulen, C. Stamm, and M. Bechmann. 2003. Incidental phosphorus losses: Are they significant and can they be predicted? J. Plant Nutr. Soil Sci. 166:459–468. doi:10.1002/jpln.200321165

Zhang, T.Q., C.S. Tan, Z.M. Zheng, T. Welacky, and Y.T. Wang. 2017. Drainage water management combined with cover crop enhances reduction of soil phosphorus loss. Sci. Total Environ. 586:362–371. doi:10.1016/j.scitotenv.2017.02.025