Assessment and Synthesis of 50 Years of Published Drainage Phosphorus Losses

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Abstract

The prevalence of anthropogenic drainage systems in intensively cropped areas across North America combined with the degradation of important freshwater resources in these regions has created a critical intersection where understanding phosphorus (P) transport in drainage waters is vital. In this study, drainage-associated nutrient load data were retrieved and quantitatively analyzed to develop a more comprehensive understanding of the P loading and crop yield impacts of agronomic management practices within drained landscapes. Using the Drain Load table in the MANAGE (Measured Annual Nutrient loads from AGricultural Environments) database, the effect of factors such as soil characteristics, tillage, and nutrient management on P loading were analyzed. Across site-years, generally less than 2% of applied P was lost in drainage water, which corroborates the order of magnitude difference between agronomic P application rates and P loadings that can cause deleterious water quality impacts. The practice of no-till significantly increased drainage dissolved P loads compared with conventional tillage (0.12 vs. 0.04 kg P ha^{-1}). The timing and method of P application are both known to be important for P losses, but these conclusions could not be verified due to low site-year counts. Findings indicate there is a substantial need for additional field-scale studies documenting not only P losses in drainage water but also important cropping management, nutrient application, soil property, and drainage design impacts on such losses.

Core Ideas

- Used the MANAGE water quality database to evaluate factors affecting drainage P loss.
- Generally less than 2% of applied P was lost in drainage across all studies.
- P application timing/method are important, but sparse data limited the assessment.
- The scarcity of drainage P data relative to N is a critical gap in understanding.

PHOSPHORUS (P) is an element essential for life (Correll, 1998; Sharpley and Menzel, 1987). A low level of P is required for primary production in lakes and rivers (Correll, 1998), and P levels exceeding that required for natural cycling can result in waters that become easily impaired. In terms of agricultural impacts on water quality, literature historically indicates that surface runoff poses a greater risk of both sediment and P transport compared with subsurface agricultural drainage, which has even been proposed as a management practice to reduce P transport (Algoazany et al., 2007; Ball Coelho et al., 2012; Bengtson et al., 1995; Blann et al., 2009; Bottcher et al., 1981; Eastman et al., 2010; Schwab et al., 1973; Sharpley and Syers, 1979; Sharpley and Withers, 1994; Sims et al., 1998; Skaggs et al., 1994). However, as major P-related water impairments continue to generate headlines and stir regulatory interest (Moore et al., 2011; Ohio Legistlative Service Commission, 2014; Scavia et al., 2014), there is an increasing need to better quantify the contribution of P loads transported via both surface and subsurface flow pathways in anthropogenically drained agricultural landscapes (Ball Coelho et al., 2012; Gächter et al., 1998; McDowell et al., 2001; Ruark et al., 2012).

Phosphorus concentrations reported in previous drainage studies ranged as high as 20 mg P L^{-1} (Duxbury and Peverly, 1978; Miller, 1979), with some of these high values strongly influenced by spatial or temporal effects (i.e., 9.7 mg total P [TP] L^{-1} in tile drainage near a milk house [Fleming, 1990] or 6.14 mg TP L^{-1} under spring high-flow conditions in a drainage ditch [Sallade and Sims, 1997]). Several observed average P concentrations are above the critical limits known to impair freshwater (Ahiablame et al., 2011; Sallade and Sims, 1997; Xue et al., 1998). In-stream and in-lake total P concentrations of less than 0.025 to 0.030 mg TP L^{-1} are recommended to avoid algal growth (Dodds et al., 1997; Fleming, 1990), although some suggest as low as 0.010 to 0.020 mg TP L^{-1} (Correll, 1998; Daniel et al., 1998). The USEPA has recommended 0.015 and 0.076 mg TP L^{-1} as limits for lakes/reservoirs and streams/rivers, respectively, in the Midwestern Corn Belt region (USEPA, 2002).

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The form and extent of subsurface (tile) drainage P losses depends upon the interaction of factors including climate, soil, hydrology, land management, P application strategies, and drainage design (Culley et al., 1983; Dils and Heathwaite, 1999; King et al., 2015; Sims et al., 1998; Skaggs et al., 1994). Many of these factors are also relevant for surface drainage P losses. Sites prone to preferential flow, sites with high organic matter soils, and sites with historically high P applications and/or soil P concentrations are primary concerns for subsurface P leaching (Blann et al., 2009; Hansen et al., 2002; Miller, 1979; Sims et al., 1998). Soils containing iron ores or aluminum with high P fixing potential may have minimal P leaching losses (Hansen et al., 2002; Sims et al., 1998). The importance of soil type and properties means the site specificity of the potential for P transport in drainage is extremely important (Sims et al., 1998).

Human and environmental health concerns associated with P-related algal blooms (e.g., the Lake Erie Toxic bloom in the summer of 2014) necessitate increasing attention be paid to mitigating drainage P loads. There is a need to assemble and further analyze drainage-associated P studies to enhance understanding across drained landscapes. Recently, information from nearly 1300 drainage N and P study site-years was compiled in a free, publically available database (Christianson and Harmel, 2015a). The Drain Load table in the MANAGE (Measured Annual Nutrient loads from AGricultural Environments) database provides comprehensive P load data from peer-reviewed studies across North America. MANAGE is hosted by the USDA, Agricultural Research Service, Grassland, Soil, and Water Research Laboratory in Temple, Texas (Harmel et al., 2006, 2008; USDA–ARS, 2015). The objectives of this study were (i) to update the MANAGE database to include data from agricultural drainage P-transport studies and (ii) to use the pooled drainage data in a large-scale analysis to better define the water quality and yield impacts of P fertilizer management strategies. Special emphasis was placed upon better understanding the impacts of the 4Rs approach to nutrient management (i.e., applying the right nutrient source at the right rate, right time, and right place). Although specific statistically defined meta-analytical methods were used, small treatment populations complicated these analyses. Thus, this study is most appropriately termed a "compilation and synthesis" rather than a meta-analysis (Arnqvist and Wooster, 1995; Hedges et al., 1999).

Materials and Methods

A literature review encompassing over 400 agricultural drainage publications focused on nutrient loads (both surface and subsurface drainage) was conducted between April and October 2014. Although it is acknowledged that drainage ditches are not solely for surface drainage and that they can be a primary method of subsurface drainage in many coastal areas, for simplicity of terminology here, studies reporting monitoring of drainage ditches were coded in the database as "surface drainage," and tile drainage studies were coded as "subsurface drainage." Ninety-one of these peer-reviewed publications were deemed suitable for inclusion in the MANAGE Drain Load table. Studies suitable for inclusion in the Drain Load table had to (i) be peer reviewed, (ii) be from study areas of at least 0.009 ha with a single land-use in North America, (iii) not be a rainfall simulation or lysimeter study, and (iv) include

data from at least 1 yr (i.e., studies only containing event specific drainage loadings were not sufficient; multiple-year studies were recorded as multiple site-years). Although this selection process excluded some publications, particularly international drainage studies, excluded works were used to inform the discussion surrounding this analysis. In general, information on each site-year's location, drainage and cropping systems, nutrient application, yield, precipitation, and citation were retrieved and added to the database. Retrieved categories of P loss in drainage waters included "dissolved P" (reported in literature as dissolved reactive P via both ascorbic acid and molybdate methods, orthophosphate, PO_4–P, Ortho-P, dissolved P, soluble inorganic + organic P, soluble inorganic P, soluble P via both ascorbic acid and colorimetric methods, solution P, soluble reactive P, and total dissolved P), "particulate P" (reported as particulate P [PP] and sediment P), and "total P" (reported as TP and simply "phosphorus"). Duplication of site-years was avoided by cross referencing the sites and years to ensure data would not be represented twice in the database even if the same data happened to be published in multiple publications. If only a mean nutrient load was reported, for example, for a 3-yr period rather than three individual values, the mean was entered into the database as three individual site-year records. Every attempt was made to capture true "annual" loading values in the database; however, for studies for which this was not clear (i.e., actual dates were not reported) or for studies where monitoring equipment was winterized, reported loading values were recorded along with notes reflecting the nature of what was reported as the "annual" period. Data Thief software was used to extract information from figures and graphs when necessary. Development of MANAGE's Drain Load table has previously been described (Christianson and Harmel, 2015a), as have the nitrogen (N) load data (Christianson and Harmel, 2015b).

Study objectives involved better understanding the water quality impacts of P management; thus, the four factors of the 4R Nutrient Stewardship approach (source, rate, timing, placement/method) were integral to this work. Within the database, nutrient application source, timing, and method were recorded separately for up to two individual formulations for a given site-year. Application timings were grouped into one of four options: (i) at planting (within 1 wk of plant), (ii) out of season (>2 mo before plant), (iii) pre-plant (2 mo to 1 wk before plant), or (iv) side/top dress (>1 wk after plant). The intent with these groupings was to differentiate between nutrient applications close to planting but before plant growth (at planting), much before plant growth (pre-plant), out of season from plant growth (out of season), and when plants were present and taking up nutrients (side/top dress). Application placements were also grouped: "surface applied" (including broadcast), "incorporated" (including broadcast incorporated); "injected" (including knifed and injected); and "banded" (generally by the seed). Because MANAGE has an annual focus, one P application rate (i.e., the summed total of each reported formulation's application rates) was reported for a given site-year. Application rates were standardized to kg P ha^{-1}.

In addition to the impacts of the 4Rs strategies, the effects of soil test P level, soil drainage class, and tillage on drainage P losses were assessed. The USDA defines a soil's natural drainage class based on "the frequency and duration of wet periods under conditions similar to those under which the soil developed"

(USDA–NRCS, 2016). Classes range from "excessively drained" to "very poorly drained," with much of the Midwest's tile-drained landscape corresponding to "poorly drained" and "somewhat poorly drained" drainage classes (Jaynes and James, 2016). Tillage practices were coded as "conventional tillage," including moldboard plow and literature reports of "conventional tillage"; "conservation tillage" including ridge till, chisel plow, and reports of "conservation tillage"; "no till"; and "pasture." The majority of the data were non-normally distributed and thus were first analyzed using Kruskal–Wallis one-way ANOVA tests. Then, Dunn's test was used to evaluate all pairwise multiple comparisons (Sigma Plot 12.5).

Results and Discussion

The MANAGE Drain Load table included 225, 50, and 242 dissolved, particulate, and total P site-years from 26, 4, and 19 studies, respectively, from the complete set of 1279 site-years (91 studies). Not every Drain Load site-year record contained drainage P loads; many only contained N loads. Site-years reporting dissolved, particulate, and total P loads spanned 1968 to 2010, 1976 to 2004, and 1961 to 2009, respectively. The North American geographies covered by these P data ranged from southern and Mid-Atlantic coastal drainage states, to eastern Canadian provinces, to Midwestern states where climate differences within the region affect drainage nutrient loss trends (e.g., drainage ceasing in the winter due to frozen soils is more prevalent in Iowa than in southern Indiana) (Fig. 1). The majority of P load site-years were from Ontario, which contributed 33 and 41% of dissolved and total P site-years, respectively (Fig. 1). The mean field/plot size across site-years where a P load was reported was 4.4 ± 11.7 ha (median, 0.2 ha; range, 0.03–113.4 ha; n = 311), the mean slope was 2.3 ± 1.7% (median, 2.0%; range, 0.1–13%; n = 79), and mean precipitation was 902 ± 210 mm (median, 923 mm; range, 334–1811 mm; n = 202). Corn (including seed, silage, and white corn [*Zea mays* L.]) was the most prevalent crop across the Drain Load database, representing 53% of site-years, followed by soybean [*Glycine max* (L.) Merr.] and alfalfa (*Medicago sativa* L.) at 27 and 6%, respectively. Other crops each represented less than 2% of site-years: oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), cabbage (*Brassica oleracea* L.), carrot (*Daucus carota* L.), citrus, cotton (*Gossypium* spp.), onion (*Allium cepa* L.), pea (*Pisum sativum* L.), peanut (*Arachis hypogaea* L.), potato (*Solanum tuberosum* L.), rye (*Secale cereal* L.), snap bean (*Phaseolus vulgaris* L.), sugarcane (*Saccharum officinarum* L.), wheat (*Triticum aestivum* L.), prairie grasses, miscanthus (*Miscanthus x giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoize), and switchgrass (*Panicum virgatum* L.).

The greatest load reported across the database was 36.8 kg dissolved P ha^{-1} (Miller, 1979), with 15 site-years reporting loads greater than 10 kg P ha^{-1} (subsurface drainage loads from
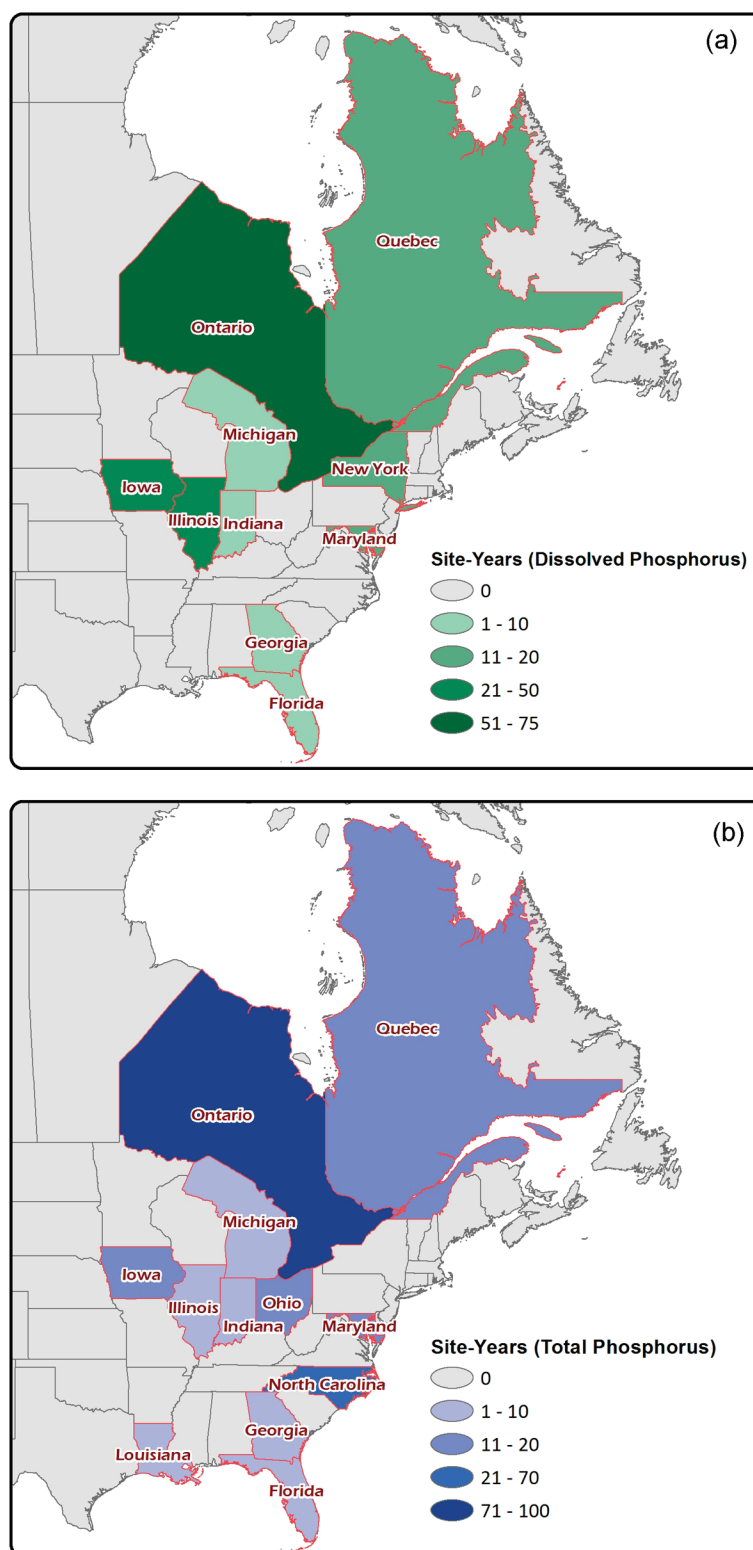

Fig. 1. Locations of dissolved (a) and total (b) P load site-years in the Drain Load database.

Miller [1979] and Duxbury and Peverly [1978]; surface drainage loads from Kleinman et al. [2007]). A general comparison showed surface drainage site-years reported significantly greater P loads than subsurface (Fig. 2). Because there were relatively few P loads reported from surface drainage studies, the remainder of this analysis focused on subsurface drainage (i.e., tile drainage).
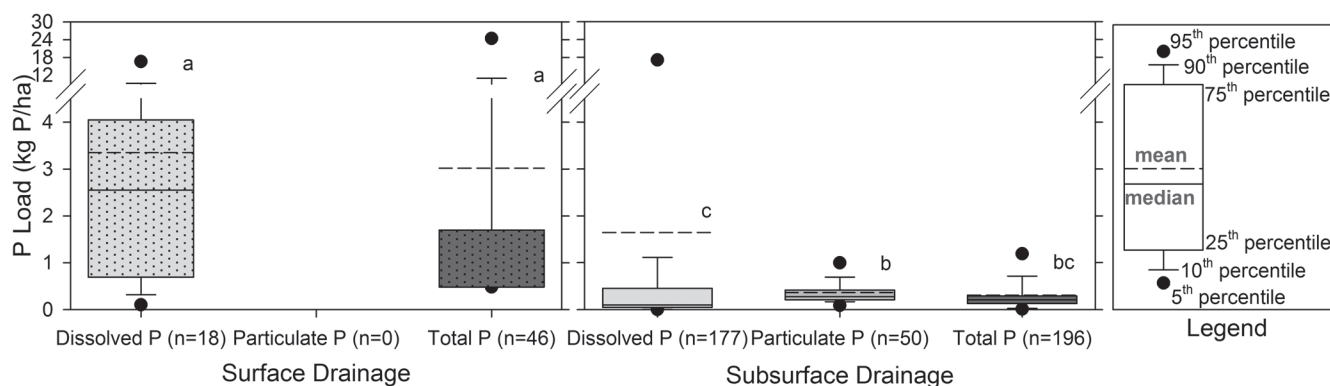
Fig. 2. Range of surface and subsurface drainage P loads with legend defining box plot symbols. Bars followed by the same lowercase letters are not significantly different.

P Species and Hydrology

Historically, more emphasis has been placed on documenting soluble P loads in subsurface drainage flows compared with particulate P, although they are both related to the total P load (dissolved P, $n = 68$; particulate P, $n = 15$) (Fig. 3). Eighty-six percent of the total P load could be identified as sediment-bound P when both values were reported in a given site-year (only 15 site-years; slope of dashed line in Fig. 3), whereas 40% of the total load was due to dissolved forms when both dissolved and total P loads were reported (solid line in Fig. 3). Only two studies reported all three P forms (dissolved, particulate, and total), indicating a potential gap in understanding of P forms in drainage water. Generally, the P form present in drainage water is largely a function of the contact time (or travel distance) between infiltrating water and the soil (Addiscott et al., 2000; Sharpley and Syers,

1979; Williams et al., 2016), and the form and therefore the fractions of P can change during transport through the complex soil ecosystem (McDowell et al., 2001).

Neither annual precipitation nor drainage discharge values collected in the MANAGE Drain Load database were strongly correlated with dissolved, particulate, or total P loads, indicating that drainage P loads were not dependent upon yearly cumulative hydrology factors (Fig. 4; $R^2 < 0.10$ for all six possible regressions in Fig. 4a and 4b; regressions with p values <0.05 are shown). Within a given year, high–flow rate P-transporting events are primarily associated with macropore flow (Macrae et al., 2007; Vidon and Cuadra, 2011), and such preferential flow paths have been identified as potential conduits for P (Scott et al., 1998; Simard et al., 2000; Stamm et al., 1998; Vidon and Cuadra, 2011; Wesström and Messing, 2007). Nevertheless, matrix
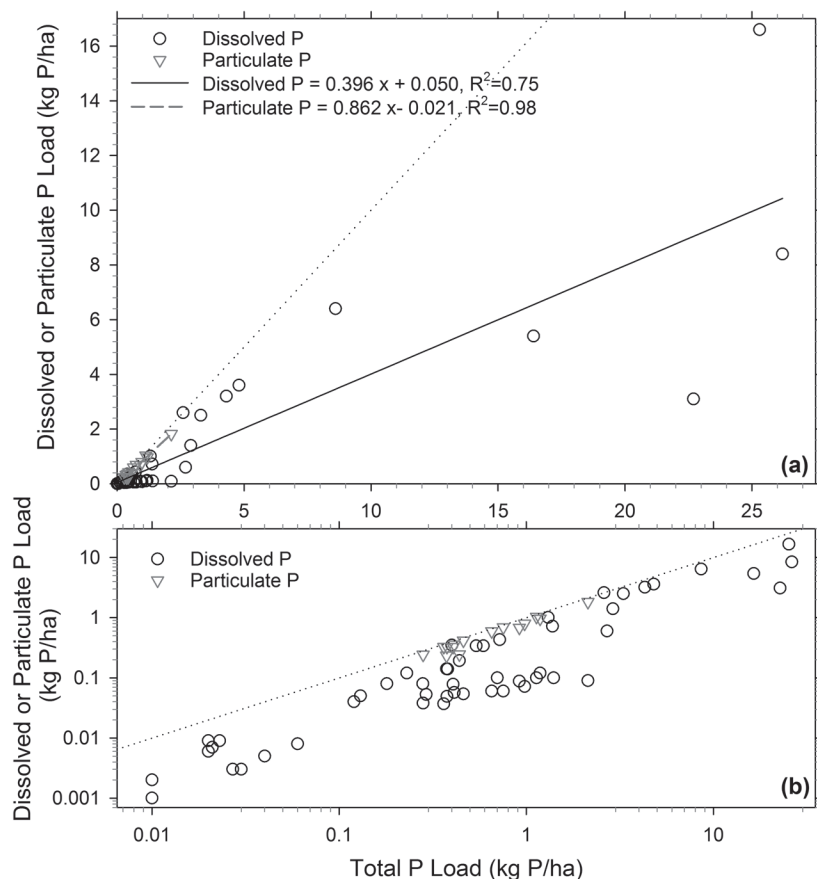

Fig. 3. Relationship between soluble P and total P loads as well as particulate P and total P loads that are recorded in the MANAGE Drain Load database. The 1:1 relationship is shown with the dotted line. To better highlight low-end values, data are presented in linear scale (a) and in log scale (b).
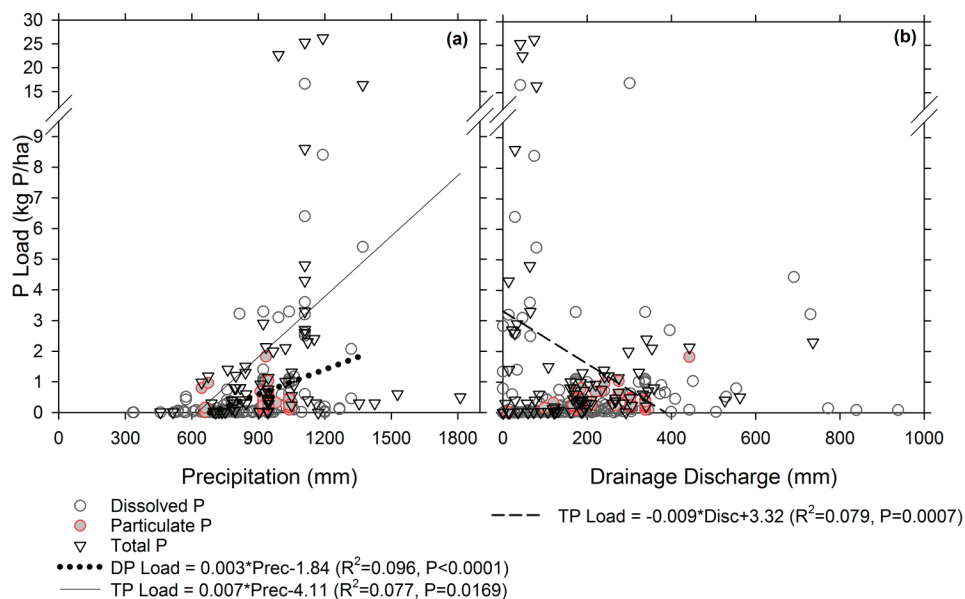
Fig. 4. Dissolved, particulate, and total P loads versus annual precipitation (a) and drain discharge (b). Four high-discharge outliers were removed from (b). All possible regressions had $R^2 < 0.10$, but the three regressions with $p < 0.05$ are shown. DP, dissolved P; TP, total P.

Legend for figure:
- ○ Dissolved P
- ● Particulate P
- ▽ Total P
- •••• DP Load = 0.003*Prec−1.84 (R^2=0.096, P<0.0001)
- — TP Load = 0.007*Prec−4.11 (R^2=0.077, P=0.0169)
- — — TP Load = −0.009*Disc+3.32 (R^2=0.079, P=0.0007)

flow is not to be ignored, as McDowell and Sharpley (2001a) observed increased dissolved P concentrations in drainage water a year after manure applications that indicated slow transport via matrix flow paths. Although storm discharge flowrates have been positively correlated with both particulate and dissolved P concentrations (Djodjic et al., 2000; Gächter et al., 1998; Gentry et al., 2007), the extent of soluble P contribution to total P loads may vary with the size of the precipitation event and extent of macropore flow (Vidon and Cuadra, 2011). Because MANAGE is aggregated at the annual time step, the values compiled in the Drain Load database may not be the most useful to evaluate temporal effects on drainage P transport, which appears to be event driven. The source data from individual studies could be useful for this purpose, and this will be pursued in future work.

Soil Test P Level

Soil test P (STP) and available P levels, particularly in subsoils, are known to be significant factors for drainage P loads (Hanway and Laflen, 1974; Klatt et al., 2003; Sharpley et al., 1977; Smith et al., 1998; Watson et al., 2007; Xue et al., 1998). Dissolved P in drainage is particularly thought to be influenced by STP,

and there has been much interest in attempts to identify a STP "change point" above which P is relatively more easily leached (Carefoot and Whalen, 2003; Heckrath et al., 1995; Hesketh and Brookes, 2000; McDowell and Sharpley, 2001a; McDowell and Sharpley, 2001b). Nevertheless, some have reported that STP and P losses in drainage are not always correlated due to variability in year-to-year hydrologic conditions (Haq et al., 2011; Watson et al., 2007). Maguire and Sims (2002) noted that "Soil testing alone cannot be expected to answer all questions about the potential for subsurface P losses as every agricultural field will have variable chemical ... and hydrologic properties..." During the review to create the Drain Load database, it was found that STP is often not reported in drainage studies, and when STP was reported, critical sampling details were often missing. Of the 148 MANAGE Drain Load site-years reporting STP values, very few simultaneously reported a corresponding dissolved, particulate, or total P load (n = 31, 15, and 26, respectively). Additionally, comparisons between studies were complicated by use of differing STP methods (Bray 1, n = 105 but no corresponding P loads; Mehlich 3, n = 25; Olsen/bicarbonate P, n = 14).

Table 1. Soil series recorded in the MANAGE Drain Load database by USDA natural drainage classification and the median tile spacing by class.

Natural drainage class	Soil series in MANAGE Drain Load database†	Tile spacing
		m
Excessively drained	Rubicon	13.0 (n = 2)
Somewhat excessively drained	–	–
Well drained	Cecil; Marshall-Monona-Ida-Napier	2.5 (n = 4)
Moderately well drained	Kenyon; Normania; Ste. Rosalie-Suffield-Bedford; Sharpsburg; Willowemoc	28.5a‡ (n = 86)
Somewhat poorly drained	Commerce; Dana-Flanagan- Blackberry; Floyd-Kenyon-Readlyn; Nicollet; Sabina and Xenia; Floyd; Londo	28.5a (n = 133)
Poorly drained	Brookston; Clarion-Webster; Clermont; Oldsmar; Taintor-Kalona; Webster; Webster-Nicollet; Othello; Drummer-Flanagan	19.2b (n = 178)
Very poorly drained	Hoytville; Kossuth-Ottosen-Harps-Okoboji; Nicollet-Webster-Canisteo; Rensselaer; Rensselaer-Wolcott-Gilford; Toledo; Wabash; Webster-Canisteo; Lauderhill-Terra Ceia; Pahokee; Quindocqua-Othello-Kentuck	7.6c (n = 175)

† When multiple soil series were reported for a given site, the coded drainage class was the least well drained class (e.g., a reported Webster-Nicollet soil was classified as poorly drained; Webster = poorly drained, Nicollet = somewhat poorly drained).

‡ Medians with the same letters are not statistically significantly different based on a Kruskal–Wallis one way analysis of variance for drainage classes with greater than 5 site-years.
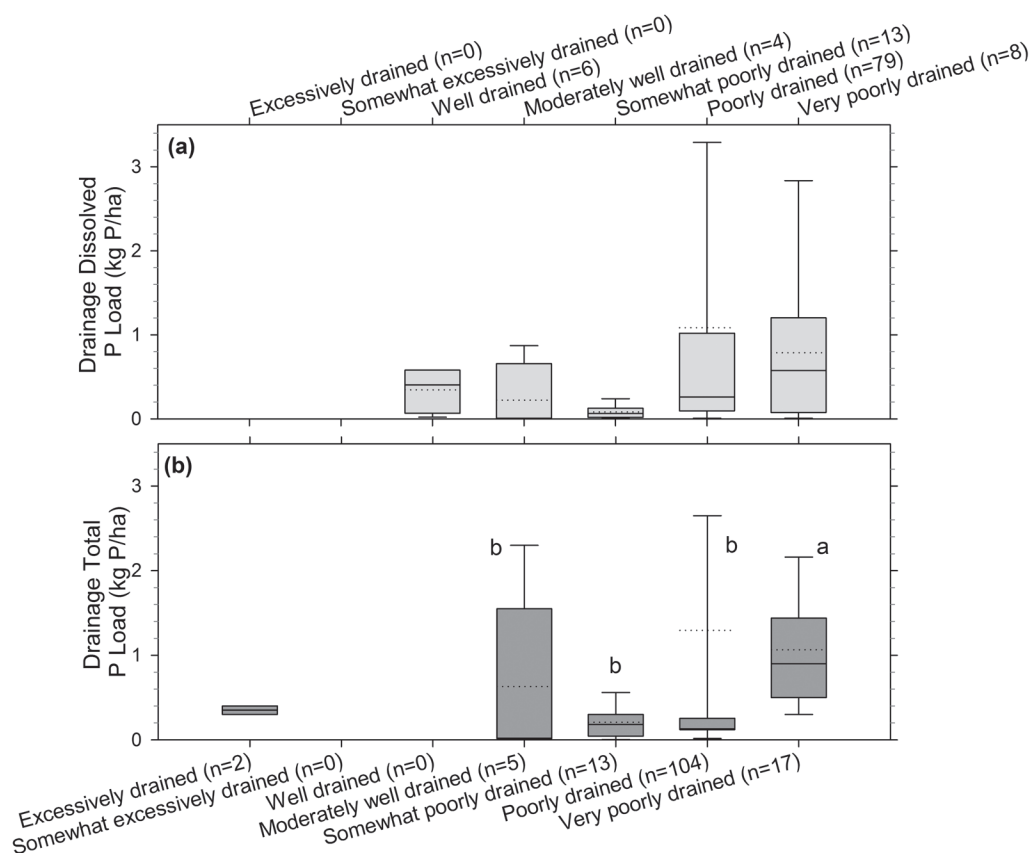
Fig. 5. Drainage dissolved (a) and total (b) P loads by soil drainage class. Drainage class total P difference significant at *p* < 0.001, and dissolved P was not statistically significantly different; n describes the site-years within a given drainage class. Total P bars followed by the same lowercase letters are not significantly different. The box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dotted line represents the mean, and the whiskers show the 10th and 90th percentiles (see Fig. 2 for legend).

Soil Drainage Class

Soil type, texture, and properties are important determinants of P movement to drainage systems (Eastman et al., 2010). When soil types were sorted by USDA natural drainage classes (Table 1), the more poorly drained soils tended to have greater drainage P loads (Fig. 5). Excluding the well-drained soil, which only represented 6 site-years (Burwell et al., 1974; Endale et al., 2010), the median dissolved P values increased as soils were categorized as increasingly poorly drained (medians for moderately well, somewhat poorly, poorly, and very poorly were 0.0075, 0.064, 0.26, and 0.58 kg dissolved P ha^{-1}, respectively) (Fig. 5a). Although this trend was not significant for dissolved P, there were significant differences between drainage classes for total P (Fig. 5b; significant at *p* < 0.001). This comparison, however, was limited by the fact that most of the soil types reported in

the Drain Load database were somewhat poorly, poorly, or very poorly drained.

Tillage

In the Drain Load database, no-tillage site-years had statistically greater dissolved P loads than conventional tillage site-years, but there were very few particulate and total P site-years to further assess tillage impacts (Table 2; total P and particulate P excluded from statistical analysis due to small sample size). The dissolved P finding was consistent with the general consensus that tillage systems that incorporate surface residues are more susceptible to loss of sediment-associated pollutants, whereas lower disturbance tillage systems will be more prone to transport of dissolved pollutants (Zhao et al., 2001). Brye et al. (2002) reported greater dissolved P concentrations in drainage from a no-till system, although their chisel plow treatment always resulted in greater

Table 2. Median of precipitation, drainage discharge, corn yield, and P loads by tillage type.

Tillage type	Precipitation†	Drainage discharge	Corn yield	Dissolved P load	Particulate P load‡	Total P load‡
	——— mm ———		Mg ha^{-1}	——————— kg P ha^{-1} ———————		
Conservation	790 (*n* = 132)	140b§ (*n* = 156)	9.9a (*n* = 53)	0.04ab (*n* = 29)	0.81 (*n* = 2)	0.42 (*n* = 4)
Conventional	789 (*n* = 406)	200a (*n* = 378)	8.1b (*n* = 226)	0.04b (*n* = 52)	0.37 (*n* = 4)	0.36 (*n* = 35)
No till	770 (*n* = 129)	170ab (*n* = 151)	8.7b (*n* = 68)	0.12a (*n* = 21)	0.88 (*n* = 4)	1.18 (*n* = 5)
Pasture	756 (*n* = 20)	78b (*n* = 19)	–	0.08 (*n* = 5)‡	0.33 (*n* = 5)	0.41 (*n* = 5)

† No significant difference between treatments (*p* = 0.719).

‡ Excluded from statistical analysis due to small sample size.

§ Medians followed by the same lowercase letters are not significantly different.

discharge. Djodjic et al. (2000) observed greater dissolved P losses from a no-till versus a tilled plot, but tillage treatments may not always result in an observable water quality impact (Djodjic et al., 2002). Conservation tillage may reduce drainage discharge (Gaynor and Findlay, 1995) but increase overall P loads compared with conventional tillage potentially due to altered crop residue mineralization and less retention of mineralized P in the soil (Gold and Loudon, 1989). This was observed here with significantly lower drainage volumes from conservation compared with conventional tillage and a greater median total P load from the conservation tillage treatment, although a more robust statistical comparison was precluded by small sample sizes (Table 2). Conservation tillage may provide an economic benefit because this treatment returned 14 and 22% increases in corn yield compared with no-till and conventional tillage, respectively (Table 2). There will likely be water quality and economic tradeoffs for tillage practices because reduced macropore connectivity can reduce soluble P transport to drainage tiles but may increase sediment-bound P loads in surface runoff (Kleinman et al., 2009).

4Rs P Application Strategies

Source

Phosphorus nutrient sources were divided between eight general categories for all site-years (Supplemental Fig. S1). Custom blends and unspecified P sources (where an application rate was reported but the formulation was not) were the most predominant (140 and 112 site-years, respectively). At 121 combined site-years, organic sources of P (e.g., manure and litter) also proved popular ($n = 121$). Liquid swine manure was the most commonly reported organic P source in the Drain Load database (67 site-years).

Across P application site-years, organic versus inorganic applications did not result in significantly different dissolved or total P drainage losses (Fig. 6c and 6d), although this conclusion for total P losses may be limited by a small sample size (organic total P load; $n = 7$). Studies comparing the drainage P load impact of

organic versus inorganic P applications sometimes show that higher P loads may occur from organic applications (Delgado et al., 2006; Phillips et al., 1981; Macrae et al., 2007; Haq, et al., 2011). Although this may not always be the case (Gangbazo et al., 1997), such differences may depend upon legacy P in the soil and the history of P management at the site. Organic P applications increased corn yields over inorganic, although manure and litter sources were generally applied at significantly greater rates than inorganic P sources (Fig. 6a and 6b). Application of different organic nutrient sources may result in varying magnitudes of drainage P losses (Dukes and Evans, 2006), but there were not sufficient site-years to make such comparisons here.

Rate

There is an obvious distinction between the level of P required to contribute significantly to agronomic production and the level of P loading that begins to impair water quality (Heathwaite and Dils, 2000; Schelde et al., 2006). Compared with drainage N losses, drainage P losses often do not occur at levels of economic relevance to farmers (Daniel et al., 1998; Owens and Shipitalo, 2006). Nitrogen losses in drainage are generally on the order of 15 to 20% of the applied N in a given year (Christianson and Harmel, 2015b). When P losses are expressed in similar terms, values tend to be less than 5% of the applied P, although they can be greater than 20% (Algoazany et al., 2007; Baker and Laflen, 1982; Culley et al., 1983; Sharpley and Withers, 1994; Withers et al., 2003). Across the Drain Load database, the P concentration was usually less than 1% (total P median; Fig. 7), with particulate P losses tending to be a relatively greater percentage of the applied P than soluble P losses (median, 1.0 vs. 0.2%). Nevertheless, conclusions should not be drawn too deeply on this "annual % applied" basis because P accumulated in soils can be transported years later (Kröger et al., 2008; Sharpley et al., 2013). Nor should comparisons be drawn too closely between this "annual % applied" metric for N and P because levels of P required for agronomic production and crop response to P can both be highly variable.
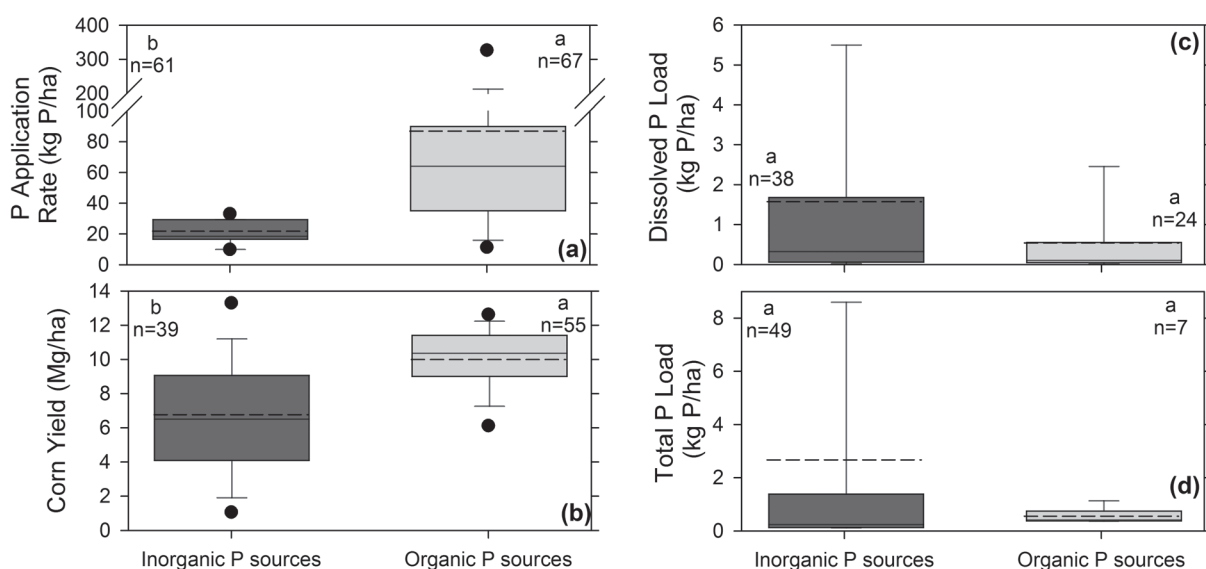

Fig. 6. Drain Load database P application rate (a), corn yield (b), and dissolved and total P loads (c, d) by nutrient source. Organic or inorganic P source impacts on dissolved and total P loads were not statistically different at $p = 0.219$ and $p = 0.095$, respectively. Bars followed by the same lowercase letters are not significantly different. The box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dashed line represents the mean, and the whiskers show the 10th and 90th percentiles (see Fig. 2 for legend).
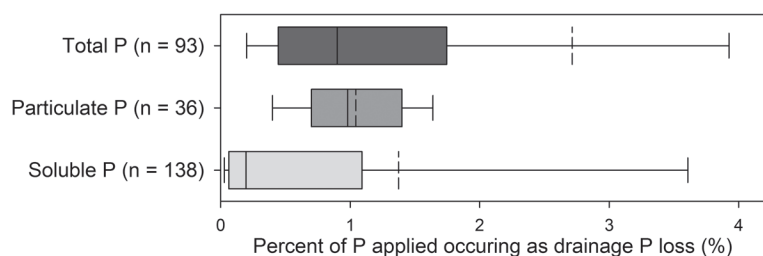
Fig. 7. Percent of P applied lost in drainage as total, particulate, or dissolved P from the Drain Load database. The box boundaries represent the 25th and 75th percentiles, the solid line represents the median, the dashed line represents the mean, and the whiskers show the 10th and 90th percentiles (see Fig. 2 for legend).

A correlation between P application rate and P losses in drainage water has been reported for both inorganic (Algoazany et al., 2007; Culley et al., 1983; Hawkins and Scholefield, 1996; Watson et al., 2007) and organic P sources (Hergert et al., 1981; Hodgkinson et al., 2002). However, the rate effect for P in drainage may not be as strongly observed as the rate effect for N in drainage (Christianson and Harmel, 2015b; Schwab et al., 1980) and may not become apparent until excessive P fertilization levels are reached (Izuno et al., 1991). This lack of a significant correlation seemed to be the case here (Fig. 8). Dissolved, particulate, and total P loads showed an increasing trend at increasing application rates but were generally much less than 1 kg P ha^{-1} across most reasonable P rates. The 37 inorganic and 50 organic site-years also showed that P rate exerted an impact, albeit weak, on corn yield (i.e., P application rate vs. yield for inorganic and

organic sources had $R^2 = 0.25$ and 0.14, respectively; data not shown). This response was likely weak because crop yield response to P is also known to be affected by plant-available P in the soil (Brady and Weil, 2002).

Timing

Because multiple fertilizer formulations are often applied at or in a given site-year, up to two fertilizer formulations/methods/timings could be recorded in the Drain Load table for each record (i.e., Fertilizer 1 and 2). Recording of a "Fertilizer 2" in the database indicated a side-dressed application in some site-years but was also used to record cases where different fertilizer formulations were applied at different times (e.g., UAN applied pre-plant and anhydrous ammonia applied at planting; anhydrous ammonia would be recorded as Fertilizer 2) or when different formulations were applied at the same time (e.g., two products applied at planting; the second product reported in the study was recorded as Fertilizer 2). This terminology of Fertilizer 1 and 2 was considered to be the simplest method to capture a range of application possibilities during the development of MANAGE. If a P application rate was given for a site-year, application of Fertilizer 1 most often occurred at planting, with out-of-season and pre-plant applications also common (41, 28, 24% of Fertilizer 1's 176 total site-years, respectively) (Supplemental Fig. S2a). If the P application occurred as the second fertilizer reported, it was most often a pre-plant application (46% of Fertilizer 2's 74 total site-years) (Supplemental Fig. S2a). None of the site-years in the Drain Load database reported side-dressed P applications.

Analysis of application timing from corn site-years where only one fertilizer was reported (to avoid confounding effects of Fertilizer 1 vs. 2) showed the most common source/timing combinations for corn were custom P blends applied at-planting, pre-plant application of superphosphate (single superphosphate or triple superphosphate), and out-of-season liquid swine manure application (Supplemental Fig. S2b). These data revealed the out-of-season and pre-plant applications resulted in greater corn yields, although they also received significantly greater P rates (Table 3). There was no significant drainage P loss difference between application timings, although comparisons were limited by very small sample sizes (Table 3). This lack of differences confounds any viable conclusion about fall versus spring P applications, and the unavailability of side-dressed site-years negated any possible conclusions about split applications. Nevertheless, across the literature, temporal factors related to P application are known to be important. Timing of P applications, particularly
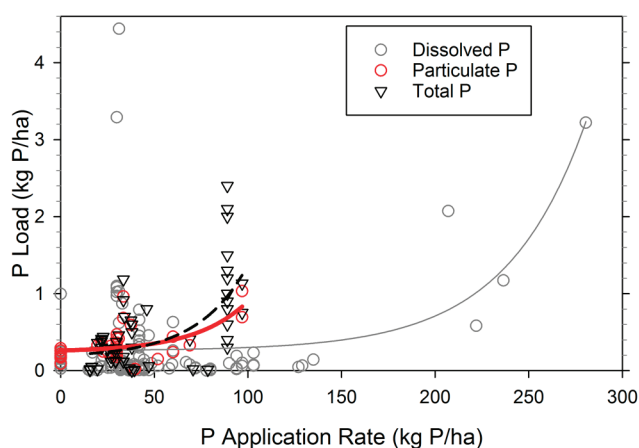

Fig. 8. Dissolved ($n = 145$; gray line) ($R^2 = 0.18$), particulate ($n = 48$; heavy red line) ($R^2 = 0.35$), and total P ($n = 79$; black dashed line) ($R^2 = 0.41$) loads versus P application rate.

Table 3. Median P application rate, corn yield, drainage discharge, and P loads by P application timing for corn site-years where only one P source was reported in the Drain Load database.

Application timing	P application rate	Corn yield	Drain discharge†	Dissolved P load†	Particulate P load	Total P load†
	kg P ha^{-1}	Mg ha^{-1}	mm		—————kg P ha^{-1}—————	
At planting (within 1 wk of planting)	19b‡ ($n = 63$)	6.0b ($n = 47$)	138 ($n = 53$)	0.03 ($n = 9$)	–	0.18 ($n = 3$)
Out of season (>2 mo before planting)	47a ($n = 31$)	9.0a ($n = 27$)	151 ($n = 31$)	–	–	–
Pre-plant (2 mo to 1 wk before planting)	32a ($n = 48$)	9.9a ($n = 18$)	131 ($n = 48$)	0.03 ($n = 28$)	0.82 ($n = 2$)	1.05 ($n = 2$)

† No significant difference between treatments (discharge, $p = 0.631$; dissolved P, $p = 0.338$; total P, $p = 0.105$).

‡ Medians followed by the same lowercase letters are not significantly different.

manure, has seasonal relevance due to climate, soil moisture, and soil freezing conditions (Gentry et al., 2007; Geohring et al., 2001; Hodgkinson et al., 2002; Klausner et al., 1976; Macrae et al., 2007).

Method

The method of P application was strongly related to the P source for several placement types. Banded and injected applications were nearly entirely (>90%) comprised of custom formulations and liquid swine manure, respectively (Supplemental Fig. S3b). Injected liquid manure applications pose a particular concern for leaching of nutrients directly to tile lines, although this is a recommended practice for odor management and nutrient usage (Shipitalo and Gibbs, 2000). The Drain Load dataset also showed that a relatively similar mix of P sources was applied via incorporation and surface application, with the former proving more than twice as prevalent (Supplemental Fig. S3b). Plowing-in or significantly incorporating solid manures is a recommended practice to reduce P loss in drainage because these methods disrupt the hydraulic conductivity of soil macropores (Geohring et al., 2001; Hodgkinson et al., 2002; Kleinman et al., 2009). However, Feyereisen et al. (2010) reported their highest total P leaching loss was from a subsurface incorporated litter treatment (0.48 kg P ha^{-1}), which was more than 1.5 times greater than the P loss from either their broadcast or broadcast incorporated treatments.

From this selected dataset, there were no significant differences in corn yield, drainage discharge, or dissolved P load, although greater application rates were reported for incorporated and injected methods (Table 4). There were no particulate or total P loads reported in the dataset for this corn site-year only analysis. Similar to P application timing conclusions, P application placement/method conclusions were limited due to a low number of site-years across the Drain Load database.

Conclusions

The widespread prevalence of drainage systems in intensively cropped areas across North America overlain with the degradation of freshwater resources in these regions has created a critical intersection where understanding drainage P transport is vital. Historically, dissolved N loads in subsurface drainage have received much greater attention than P loads, and this now presents a large gap in knowledge. This work serves as a call to increase the number of field-scale studies documenting not only drainage P losses but also important cropping management, nutrient application, soil property, and drainage design impacts on such losses. We further implore future studies to include multiple species of P, such as dissolved reactive P, particulate P, and total P, to assist in advancing our knowledge of fate and transport processes.

The order of magnitude difference between agronomic P application rates and P loadings that can cause ecological damage presents a serious environmental challenge, especially compared with N. Across the Drain Load database, generally less than 2% of applied P was lost in drainage water flow in a given site-year, and total P losses were less than 1 kg ha^{-1} across most P application rates. Reduced forms of tillage showed increased drainage dissolved P loads, which was consistent with the literature. However, conservation tillage, based on our dataset, improved corn yields compared with conventional tillage, which indicated that further evaluation of drainage water quality/economic tradeoffs may be necessary. The timing and method of P application are both known to be important for drainage P losses (King et al., 2015), but these conclusions could not be verified due to a low number of site-years across the database. The scarcity of drainage P information is a critical gap in scientific understanding, and improved knowledge of P transport in drainage can help facilitate improved use and targeting of practices such as P-sorbing soil amendments and drainage filters, drainage water management, and cover crops. Moving forward, although more field-scale studies are needed, the Drain Load database may itself need to be further developed to better capture important P loss criteria (e.g., add peak flowrate information or create a Drainage Concentration table to supplement the Drain Load table).

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Table 4. Median P application rate, corn yield, drainage discharge, and dissolved P load by P application method for corn site-years where only one P source was reported in the Drain Load database.

Application method	P application rate	Corn yield†	Drainage discharge†	Dissolved P load†
	kg P ha^{-1}	Mg ha^{-1}	mm	kg P ha^{-1}
Banded	18c‡ (n = 21)	8.4 (n = 15)	223 (n = 18)	–
Incorporated	50a (n = 27)	10.6 (n = 11)	124 (n = 23)	0.02 (n = 14)
Injected	57ab (n = 38)	9.6 (n = 31)	151 (n = 35)	0.04 (n = 3)
Surface applied	3b (n = 16)	–	155 (n = 16)	0.03 (n = 16)

† No significant difference between treatments (yield, p = 0.066; discharge, p = 0.076; dissolved P, p = 0.147).

‡ Medians followed by the same lowercase letters are not significantly different based on a Kruskal–Wallis one-way ANOVA on ranks.

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